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Fishing Sea-bed Habitat Risk Assessment

(A framework towards the quantitative assessment of trawling impact on the sea-bed and benthic ecosystem)

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SUMMARY

A framework to assess the impact of mobile fishing gear on the seabed and benthic ecosystem is presented. The framework that can be used at regional and local scales considers the physical effects of trawl gears on the seabed, on marine taxa and the functioning of the benthic ecosystem. A reductionist approach is applied that breaks down a fishing gear in its components and distinguishes a number of biological traits that are chosen to determine the vulnerability of benthos for the impact of a gear component or to provide a proxy for their ecological role. The approach considers a wide variety of gear elements, such as otter boards, twin trawl clump and ground-rope, and, sweeps that herd the fish. The physical impact of these elements on the seabed, comprising scraping of the seabed, sediment mobilisation and penetration, are a function of the mass, size and speed of the individual component. The impact of the elements on the benthic community are quantified using a biological-trait approach, that considers the vulnerability of the benthic community to trawl impact (e.g. sediment position, morphology), the recovery rate (e.g. longevity, maturation age, reproductive characteristics) and the ecological role. The framework is explored to compare the indicators for pressure and ecological impact of bottom trawling in three main seabed habitat types in the North Sea. Preliminary results show that the sublittoral mud habitat is impacted most due to the combined effect of an intensive fishing and high proportions of long-lived taxa.

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1 INTRODUCTION

Fishing is one of the important anthropogenic activities affecting marine ecosystems (Jennings and Kaiser, 1998; Halpern et al., 2008). Continental shelf areas are heavily exploited by bottom trawls towed over the seabed. Benthic ecosystems on the continental shelf provide important ecosystem goods and services. They provide fisheries production and the food for bottom dwelling fish species, which comprise about 23% of the global fisheries yield (FAO, 2009), but also play a vital role in the functioning of marine ecosystems, while they support a wide diversity of species. The bottom trawl fisheries typically use heavy otter boards or shoes to maintain contact with the seabed, and ground ropes and chains to herd fish into the net. Physical disturbance from such fisheries can cause significant changes in the seabed ecosystem, mortality among the animals encountered and affect the biogeochemical processes of the sediment – water interface (Dayton et al., 1995; Watling and Norse, 1998; Jennings and Kaiser, 1998; Auster et al., 1996; Thrush and Dayton, 2002). The widespread use of bottom trawls has raised concerns about possible adverse impacts on biodiversity, ecosystem functioning and ecosystem goods and services (Dayton et al., 1995; Watling and Norse, 1998; Jennings and Kaiser, 1998; Auster et al., 1996; Burridge et al., 2006; Pitcher et al., 2009).

Although it has been widely accepted that the Ecosystem Approach to Fisheries Management (EAFM) can lead to mitigation of the adverse effects of fishing on the ecosystem, there is no accepted answer to the question how the benthic ecosystem can be incorporated in the EAFM (Botsford et al., 1997; Pikitch et al., 2004). To assess the current impact and advice on management plans to mitigate adverse impacts, methods are required to assess sensitivity of the various seabed habitats for the different fishing methods used. These methods should be quantitative, validated, repeatable and applicable at the scales of impact and management (Hiddink et al., 2007). Several recent studies have assessed the sensitivity of benthic habitat – gear combinations (Eno et al., 2013; Grabowski et al., 2014). The sensitivity matrices established in these studies were based on a combination of a review of the scientific literature and expert judgement, and were subjected to peer review to obtain consensus among stakeholders. One of the problems encountered was how to extrapolate results to habitat and gear combinations not directly examined. A second problem with such an approach is that although the subjective assessments of the impact is successful in ranking impacts by gear and habitats, it is unsuitable for examining cumulative impacts of different gears and for assessing the effects of gear substitutions and redistribution of fishing effort.

The European Union adopted the Marine Strategy Framework Directive (MSFD) to promote a more effective protection of the marine environment and aims to achieve good environmental status (GES) by 2020 (EC, 2008). The status of the marine environment, and the human pressures acting upon it, are described by eleven qualitative descriptors of which the descriptor on seafloor integrity (or D6) states that "the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected". Quantitative indicators and reference levels are required to assess progress towards GES. As fishing is considered the main human activity impacting the seafloor (Eastwood et al., 2007; Foden et al., 2011), an EAFM needs to explicitly consider this and a framework for the assessment of the impact of mobile bottom gears is required with indicators that capture the differences in the sensitivity of seabed habitats for a variety of fishing gears deployed. The indicators need to be able to assess the status of the seabed on regional scales, and can therefore not be tested solely using data acquired through sampling programmes.

The objective of the current study is to develop an assessment framework that can be used to assess the benthic impacts of trawl fisheries and to inform managers how to trade-off different options for mitigating the adverse impacts of bottom trawling. In order to be able to extrapolate to habitat and gear combinations not directly examined, we adopt a mechanistic approach that incorporates both the understanding of benthic ecosystem processes and the mechanisms by which fishing gears interact with the benthic ecosystem. Our approach considers multiple scales ranging from the scale at which the gear interact with the seabed to the scale at which both the fisheries operate and they are managed. Some simplifying assumptions are made to allow scaling up the assessments to these larger spatial scales. The report starts with a brief outline of how bottom trawling affects seabed habitats, benthos species composition and benthic ecosystem functioning (Figure 1). This review highlights the processes that will need to be understood to allow an assessment of the large scale effects of trawling on benthic ecosystems. Based on these dominant effects of trawling, we then develop a number of indicators that quantify the impact of trawling on the benthic ecosystem that are generic and can be applied to different benthic habitats and the various gears used in bottom trawl fisheries. The framework is explored in a preliminary assessment of the impact of bottom trawling in three dominant habitat types in the North Sea.

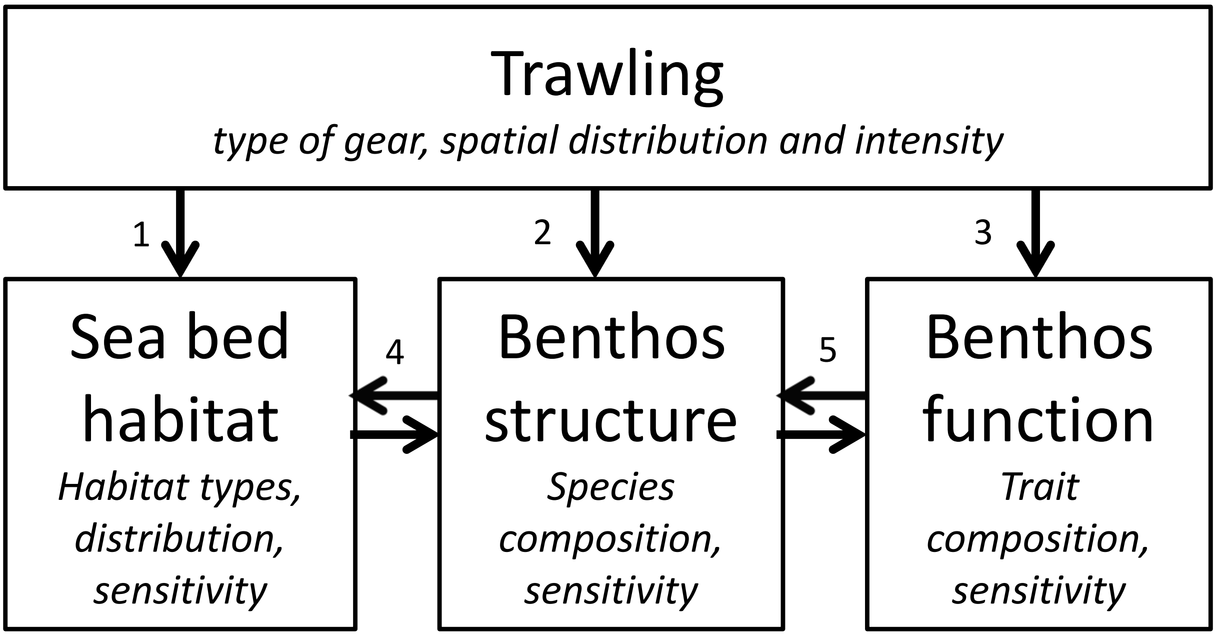

***Figure 1**. Components of the framework to assess the impact of trawling on the sea bed and benthic ecosystem. Trawling effects are dependent of the type of gear and the distribution and intensity. Sea bed habitats and benthic communities differ in their spatial distribution and sensitivity for trawling. Benthic ecosystem function is dependent on the composition of the functional traits, which may differ in their sensitivity for trawling.*

2 TRAWLING IMPACT

Any gear that aims to catch demersal fish, crustaceans or shellfish needs to be in contact with the seabed. Fishermen have developed a variety of trawl gears to maximise catch efficiency and their ability to operate on the different types of seabed habitats (Eigaard et al., 2014). As a result, bottom trawls differ in their design and dimensions, in particular in ground rope design and the methods used to spread the trawl horizontally (beam trawl, otter trawl, seine) (Valdemarsen, 2001). We distinguish between the physical effects of the gear on the seabed and the effects of the gear on marine organisms and the functioning of the benthic ecosystem (Figure 1).

2.1 Physical effects

The physical interaction of fishing gears with the seabed is extremely complex. The degree of contact of the trawl with the seabed depends on the design and rigging of the gear, the speed at which the gear is towed and the characteristics of the seabed (Buhl-Mortensen et al., 2013; He and Winger, 2010). On soft sediments there can be compression, shearing and associated displacement of the sediment (O'Neill and Ivanovic, this volume) and mobilisation of sediment (O'Neill and Summerbell, 2011). Some parts of the gear can penetrate and disturb the seabed to depths of >5 cm or more (e.g. otter trawl doors, dredges, tickler chains), while other gear components may only skim the surface (e.g. sweeps) (Eigaard et al. 2015, in press IJMS).

Bottom trawls will scrape the sea floor and may reduce habitat complexity by smoothing out the ridges and depressions generated by natural or biological processes (Watling and Norse, 1998; Thrush et al., 2006; Hewitt et al., 2010). Trawling may also dislodge benthic taxa anchored in soft sediments or displace taxa attached to hard substrate into an unfavourable position (Buhl-Mortensen et al., 2013). On harder substrates stones may become dislodged from the sediment by the action of tickler chains, rakes or foot rope, and may subsequently be turned over or end up in the net and be displaced or even removed. Gear components may crush or break biogenic structures or material, such as dead shells, which may result in a reduction of the substrate for epibenthic species (Collie et al., 2000; Kaiser et al., 2006). Sediment disturbance may further affect the flux of nutrients from the sediment to the overlying water (Almroth-Rosell et al., 2012).

2.2 Collision

The collision of a gear element with an object or biogenic structure on the seabed can be described in terms of the impulse or change in momentum that takes place. The momentum of an object is defined to be its mass times velocity, and one way to view it is as a measure of how difficult it would be to bring that object to rest. The impact that takes place when gear components collide with objects and structures in their path can be described in terms of their change of momentum. In general this instantaneous quantity will be difficult to measure, particularly when the dynamic interaction between adjacent components and the restrictions to movement of a component is considered. As a first approximation, however, the impulse momentum to characterise and rank the potential effect that a gear component may have on the seafloor may be used.

2.3 Sediment mobilisation

Bottom trawls will mobilise sediment in the wake of the gear (De Madron et al., 2005). As finer particles will settle more slowly than the larger particles and may be transported further away from the trawl track by the prevailing bottom currents, trawling will influence the sorting of the sediments in trawled areas (Brown et al., 2005). Enhanced total organic carbon concentrations have been observed after the start of bottom trawling likely due to the uplift from deeper sediments (Pusceddu et al., 2005), but in chronically trawled grounds, organic matters appears to be reduced. Chronically trawled sediments along the continental slope of the north-western Mediterranean Sea are characterized by significant decreases in organic matter content (Pusceddu et al., 2014). A strong decrease in the mud fraction and an increase in the fine sand fraction was observed over a period of 35 years in the sediments of the Bay of Biscay (Hily et al., 2008). With the sediment mobilisation, pore water and its nutrients will be exchanged with the overlying water (De Madron et al., 2005). Changes in sediment structure due to trawling may make benthic habitats more sensitive for natural disturbance.

The amount of sediment that is mobilised is primarily determined by the particle size distribution of the sediment and the hydrodynamic drag of the gear components (O'Neill and Summerbell, 2011). Because the hydrodynamic drag of the gear is determined by the square of the towing speed and by the frontal surface area of the gear components, the impact of bottom trawls on the sediment mobilisation can be estimated from the towing speed and the size of the gear components (O'Neill and Ivanovic, 2015, in press IJMS).

2.4 Penetration

On soft sediments, heavy components of the gear, such as the doors of an otter trawl or the shoes of a beam trawl, will penetrate in the seabed and create a furrow by pushing aside the sediment (Schwinghamer et al., 1996; Smith et al., 2007; Buhl-Mortensen et al., 2013; Depestele et al., 2015, in press IJMS; O'Neill and Ivanović, 2015, in press IJMS). Rakes or a series of tickler chains running in front of the ground rope, will penetrate and enhance the mixing in the impacted layer and disturb the sediment sorting and damage the tubes and burrows of infaunal species.

Penetration depends on the pressure force (weight per unit area) exerted by a gear component but is largely independent of the towing speed. Recent trials suggest that components may penetrate less with increasing speed (O'Neill pers comm), however, fishers will adjust the weight of the gear elements and/or alter their rigging to ensure bottom contact is maintained if towing speed increases. In the flatfish fisheries in the North Sea, beam trawl fishers increased the engine power of their vessels to use larger and heavier gear at higher towing speeds (Rijnsdorp et al., 2008). The increase in towing speed made it necessary to increase the weight of the gear to compensate for the increase in upward lift (Fonteyne, 2000).

3 SEABED HABITAT

Sediment characteristics such as grain size, mud content and presence of gravel or boulders, along with food, light and shear bed stress, are important determinants of the benthic community (Gray and Elliot, 2009; Hiddink et al., 2006b; van Denderen et al., 2014). Furthermore, the topography of the seabed influences benthos at different spatial scales (Buhl-Mortensen et al., 2010). For example, distinct gradients in benthic biomass and species composition occur between the valleys and the crest of sand waves due to small scale hydrodynamics that influence feeding opportunities (Ramey et al., 2009).

The benthic fauna itself may also influence seabed habitats by forming 3-dimensional structures on and within the seabed. Biogenic structures formed by ecosystem engineers, such as coral reefs and sponge gardens, provide structures that influence the habitat and determine its suitability for other species (Buhl-Mortensen et al., 2010). Dense populations of epibenthic species may form mats or beds that structure the seafloor (e.g. mussels), while infaunal species, such as spionid worms, create burrows or tubes (Bolam and Fernandez, 2003; Braeckman et al., 2014; Rabaut et al., 2007). High densities of such species have been shown to directly affect sediment characteristics and faunal assemblage structure or indirectly via alterations to near-bed hydrodynamic conditions.

In order to develop an impact assessment framework, information on the distribution of seabed habitats is required. Seabed habitats can be classified according to the combination of physical factors. In European waters, such a classification has been developed (EUNIS habitat classification, see Davies et al., 2004). At the EUNIS level 3, this classification approach takes into account depth, sediment grain size, light and level of disturbance by hydrodynamic forces. Since habitat maps based on these factors are available for large parts of European seas (http://www.emodnet-seabedhabitats.eu/), they provide a starting point for an impact assessment.

4 ECOSYSTEM EFFECTS

Trawling may reduce benthic community biomass and biodiversity and may shift the size and species composition towards short-lived, smaller species due to differences in direct mortality and recovery rates among taxa (Jennings et al., 2005; Tillin et al., 2006). The comprehensive review by Collie et al. (2000) and Kaiser et al. (2006) showed how mortality imposed by the passage of a trawl is habitat specific and differs between benthic species groups and types of trawl gear. The most severe impact occurred in biogenic habitats (sessile epifaunal species) in response to scallop-dredging, followed by the effect of beam trawls in sandy habitats and otter trawls in muddy habitats. In sandy sediments, deposit feeding macrofauna were reduced by approximately 20% by beam trawls and otter trawls and 40% by scallop dredges, whereas suspension feeders declined by 70% by beam trawls, 45% by scallop dredges and 5% by otter trawls.

As benthic taxa differ in their ecological role, trawling-induced changes in species composition have implications for ecosystem function, such as benthic-pelagic coupling, processing organic carbon and remineralisation of nutrients (Thrush et al., 2001; Olsgard et al., 2008). Suspension feeders transfer organic carbon from the pelagic system to the benthic food web, enhancing the rate of biodeposition (Graf and Rosenberg, 1997; Gray and Elliott, 2009). Benthic invertebrates may play a role in the bioturbation of sediments (Aller, 1994; Reise, 2002). Some species such as the sea urchin *Echinocardium cordatum* and the annelid worm *Scoloplos armiger* are diffusive mixers, physically mixing the sediment whilst moving (Lohrer et al., 2005). Other species transport organic material downwards (e.g. *Thyasira flexuosa* and *Echiurus echiurus*) as they feed on the surface and defecate in the sediment (downward conveyors), while species like *Antalis entalis*, transport organic carbon upwards by sub-surface feeding and defecating on the surface (upward conveyors) (Queirós et al., 2013). Others feed on dead organisms (scavengers), predate or parasite on benthic organisms. Many provide food for other benthic invertebrates, fish, birds or marine mammals (Bolam et al., 2010).

Biological Trait Analysis (Bremner, 2008; Bremner et al., 2006) has proved to be a useful approach to assess the vulnerability of taxa for trawling disturbance as well as their recovery rate. Bolam et al (2014) indicated how differences in direct mortality among species groups are related to characteristics such as the position in the seabed profile, morphology (exoskeleton, crustose, soft bodied) and body size. Furthermore, differences in the recovery rate among species was related to life history characteristics such as the longevity, larval development and egg development. Morphological traits have been demonstrated to be important in determining a species presence in a trawled habitat. Organisms covered by a hard shell, for example, have been observed to be less vulnerable to trawling than those with other morphological traits (Bergman and van Santbrink, 2000; Blanchard et al., 2004). Others found that filter-feeding, attached and larger animals were relatively more abundant in lightly trawled areas, while areas with higher levels of trawling were characterised by a relatively high biomass of mobile animals and infaunal and scavenging organisms (e.g. Kaiser and Spencer, 1994; Tillin et al., 2006). Biological Traits Analysis can also be used as a proxy to examine changes in the ecological function, based on the observed changes in the species composition due to trawling. For example, an assemblage dominated by suspension-feeders will transport carbon and energy between the seabed and the overlying water column differently from one dominated by sub-surface deposit feeders (Rosenberg, 1995), while assemblages dominated by individuals that recruit via planktonic larvae are likely to recolonize more rapidly following large-scale physical disturbance than those reliant on benthic or lecithotrophic larvae (Thrush and Whitlatch, 2001; Bolam et al., 2014).

Sediment mobilisation due to bottom trawling may have important ecological consequences. Deposit feeding benthos may be negatively affected by trawling due to a loss of surficial sediments and a reduction of the food quality (Watling et al., 2001; Mayer et al., 1991). Sediment mobilisation may also reduce the available light for primary producers and hence reduce primary production.

5 ASSESSMENT FRAMEWORK

Table 1, summarises the indicators developed in the following sections to estimate the pressure, the physical impact on the seabed and the impact on the functional composition of the ecosystem.

Table 1*. Overview of the indicators developed to estimate the pressure of trawling, the impact on the sea bed habitat and the impact on the structure and functioning of the ecosystem.*

Pressure indicators

P1	Proportion of the habitat that is not trawled during a year
P2	Proportion of the habitat that is trawled less than once in a year
P3	Proportion of the habitat where 90% of the trawling effort is concentrated.

Indicators for the physical impact on the sea bed	
Ip	penetration depth of the gear component
Ic	impulse momentum of the collision of the gear element
Is	sediment mobilisation
Indicators for the ecological impact	
E	Reduction in the surface area where the community, or a specific functional group, is in its undisturbed reference state

5.1 Trawling pressure

It is well established that bottom trawling is patchy and that this patchiness needs to be taken into account to assess the impact of trawling on the benthic ecosystem (Rijnsdorp et al., 1998; Lee et al., 2010a; Ellis et al., 2014). Figure 2a gives a hypothetical example of the distribution of bottom trawling frequencies. Intense trawling occurs in a relative small proportion of the habitat as compared with the habitat that is trawled at a low frequency or that not trawled.

The information contained in this graph can be condensed in three indicators of trawling pressure that highlight different aspects (Figure 2a). The first indicator gives the proportion of habitat that is not trawled. The untrawled area comprises the surface areas of the grid cells where no fishing was recorded plus the untrawled part of the grid cells which were trawled less than once a year. The second indicator gives the proportion of habitat that was trawled less than once a year. The third pressure indicator estimates the surface area of the most intensively trawled grid cells, in our example encompassing 90% of the annual fishing effort.

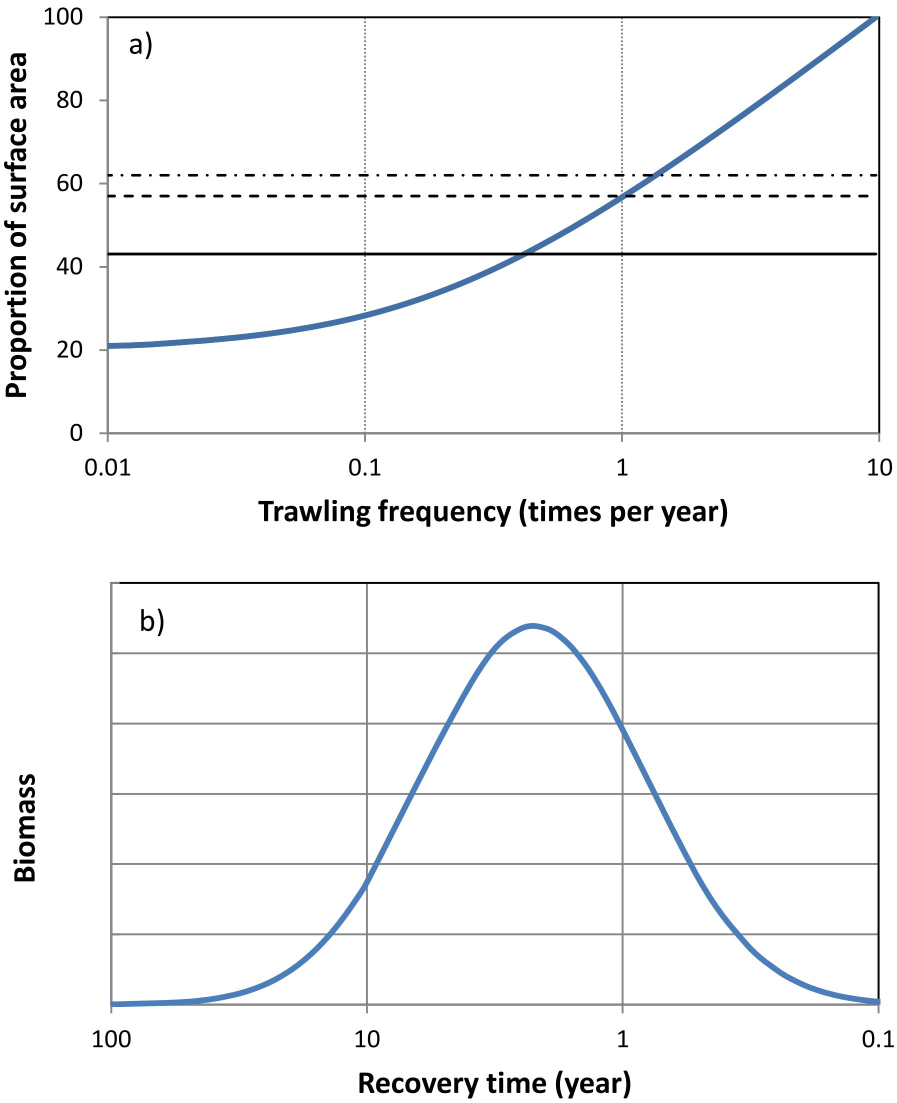

Figure 2 *a) Hypothetical relation of the heterogeneous distribution of bottom trawling showing the proportion of the surface area that is trawled less than a certain trawling frequency. Horizontal lines show the proportion of untrawled habitat (grey line), the surface area trawled less than one time per year (---) and the surface area encompassing the lightly (heavily) trawled areas representing 10% (90%) of the total fishing effort (-.-.-.-). The untrawled area comprise the untrawled grid cells (0.05) and the untrawled surface of the grid cells trawled less than one time per year. The area above the dotted – hatched line represent the main fishing grounds where 90% of the total effort is deployed.* ***b)*** *Hypothetical distribution of biomass over the recovery time of the benthic taxa of an undisturbed community. The recovery time and trawling frequency are related via the reciprocal of the trawling frequency which gives the average interval between two trawling events.*

5.2 Impact on seabed habitat

The physical impact of trawling gear is related to the penetration of gear elements, the collision impact and the sediment mobilisation.

The penetration impact will be a function of the mass of the gear component (M) and the inverse of the component's surface area that is in contact with the seabed (A):

$$I_p \sim f(MA^{-1})$$

The collision impact of a gear element (*Ic*) will, as a first approximation, be a function of the mass of the gear component (*M*) and the towing speed (*U*):

$$I_c \sim f(MU)$$

Sediment mobilisation is a function of the hydrodynamic drag, which is dependent on the product of U^2 and the frontal surface area of the gear element S, that generates the turbulence. Hence, as a first approximation, sediment mobilisation (*Is*) can be written as:

$$I_s \sim f(SU^2)$$

The extent to which a component penetrates into the seabed and the amount of sediment mobilised will depend on the sediment type. On finer sediments, gear components are likely to put more sediment into the water column and penetrate further. Hence, *Ip* and *Is* will also be influenced by the particle size distribution of the sediment.

5.3 Impact on benthos community composition and ecosystem function

The trawling frequency (f) determines the probability that an organism will be hit by a bottom trawl during a year. If we assume that trawling is random at the level of the grid cell, we can calculate the average time interval between two trawling impacts ($D=f^{-1}$) indicating the time for benthic invertebrates to recover. Whether a taxa will fully recover is determined by their recovery time (R). If the recovery time is less or equal to the trawling interval, the taxa will be able to recover. For each taxa a maximum trawling frequency ($f=R^{-1}$) can be defined where the taxa will be able to recover. If trawling frequency is below the threshold, the population will be temporarily reduced by bottom trawling. If the trawling frequency is above the threshold, the population will be permanently reduced.

At the level of the community, we can link the trawling frequency distribution (Figure 2a) with the recovery characteristics of the benthic community (Figure 2b). In the hypothetical example, the taxa with a recovery time of 10 years will be in a reference state in about 30% of the habitat where trawling frequencies are less than 0.1 $year^{-1}$. Taxa with a recovery time of 1 year will be in a reference state in almost 60% of the habitat where trawling frequencies are less than 1 $year^{-1}$.

We can calculate an index of trawling impact (I) on the benthic community from the reduction in the surface area of the habitat where taxa are in reference state. Let p_t gives the proportion of the surface area of a habitat where recovery class t is in reference state, and b_t gives the biomass of the benthos with a recovery time of t. The impact is than given by

$$I = \frac{\sum_{t=t_{min}}^{t_{max}} p_t b_t}{\sum_{t=t_{min}}^{t_{max}} b_t}$$

If we want to compare the impact of different fisheries (*f*), a scaling term s_f can be included that expresses the relative impact rescaled to the gear with the largest impact.

$$I = \frac{\sum_{f=1}^{fmax} s_f \sum_{t=t_{min}}^{t_{max}} p_{ft} b_t}{\sum_{t=t_{min}}^{t_{max}} b_t}$$

The trawling impact indicator I estimates the status of the benthic community as the surface area of a particular habitat where the different recovery classes are in reference state. A value of 1 reflects a situation where trawling has no impact on the benthos. A value of 0 reflects a situation where none of the recovery classes are in their reference state.

Besides assessing the impact measure for the whole community, we can apply the above method for a particular functional group of benthos to estimate the impact of trawling on a selected ecosystem function.

6 APPLICATION TO REAL DATA

The framework is explored in a preliminary assessment of the impact of bottom trawling on three seabed habitats in the North Sea. The habitats assessed are A5.1 sublittoral coarse sediment, A5.2 sublittoral sand, and A5.3, Sublittoral mud; which comprise 12%, 69% and 10% of the North Sea down to 200 m depth.

6.1 Trawling frequency

The distribution of trawling frequencies was estimated from the VMS recordings of fishing activities of all bottom trawlers for the period 2010-2012 at a resolution of 1 minute longitude x 1 minute latitude (Eigaard et al., in prep). The analysis took account of the differences in footprint of the various metiers distinguishing between surface and subsurface footprint (Eigaard et al., 2015, in press IJMS). Trawling frequencies were estimated for each grid cell as the ratio of the total swept area over the surface area of the grid cell (1.7 km^2 at 60°N).

Figure 3 shows the trawling frequency distribution curves for the three habitats. The results show that the bottom trawl pressure increases from coarse sediments to mud. The proportion of seabed trawled less than once a year was lowest (33%) for the sublittoral mud habitat (A5.3) and increased to 66% for the intermediate grain size (A5.2) and to 75% for the coarse sediment (A5.1). The proportion of untrawled habitat (P1) was lowest in sublittoral mud, and highest in coarse sediments. Subsurface effects of bottom trawling were smaller than the surface effects as reflected in the lower subsurface proportions trawled at a certain frequency (Figure 3b). The differences in surface and subsurface impacts between habitats are similar up to a trawling frequency of about 0.5 $year^{-1}$ but disappear at higher trawling frequencies.

6.2 Benthos

Benthos data were available from a number of investigations that studied the changes in infaunal benthic community composition along a trawling gradient in different study sites covering the three main habitats of the North Sea (Table 2). Benthos data were collected with replicates at each of the sampling locations, except for the Dutch coarse sediment (Dutch CS) and fine sediment (Dutch FS) data which had many more stations that were sampled over multiple years (Table 2). Benthos data were sampled using a Day grab (Fladen Ground), a Hamon grab (Dogger Bank and Long Forties) or a Reineck box corer (Dutch CS, Dutch FS, Silver Pit). In all areas, samples were sieved over a 1 mm mesh sieve and biota were identified to the lowest taxonomic level possible. Biomass per taxonomic group was estimated in grams ash free dry weight (Dutch CS, Dutch FS) or wet weight (other areas). Species were coupled to the BENTHIS infaunal trait dataset as first described by Bolam et al (2014), which comprise information on the longevity class, feeding mode and bioturbation mode. For the purposes of the current study, and to help ensure that the effects of trawling on benthic biomass distribution between habitats were minimised, only those stations for which predicted fishing pressure was either low or zero (i.e., estimated total FP of < 0.5 $year^{-1}$) were used.

***Table 2**. Data sources of boxcore samples used to estimate the biomass distribution over the longevity classes of the macrofauna (from van Denderen et al. submitted)*

Habitat	Study site	Latitude degrees	Longitude degrees	Source
A5.1: Sublittoral coarse sediment	Dutch CS	53.19	4.44	van Denderen et al., (2014)
A5.2: Sublittoral sand	Silver Pit	54.04	1.93	Jennings et al., (2001a, 2001b, 2002)
	Dutch FS	54.55	2.93	van Denderen et al., (2014)
	Long Forties	57.40	-0.17	Tillin et al., (2006)
	Dogger Bank	55.05	1.93	Queirós et al., (2006) Tillin et al., (2006)
A5.3: Sublittoral mud	Fladen Ground	57.99	0.42	Tillin et al., (2006)

We used longevity as proxy for the recovery time of taxa. It is an intuitively simple metric and supported by field studies showing that short-lived species will tolerate higher trawling intensities than long-lived species (Kaiser et al., 2006; Tillin et al., 2006). Longevity shows a strong correlation with other life-history traits that affects recovery time, such as age at maturation (Charnov, 1993; Brey, 2001; Bolam and Eggleton, 2014; Pitcher et al., 2015). It should be noted that for taxa forming biogenic structures, the recovery time of the biogenic structures will almost certainly exceed the longevity of the individual organism.

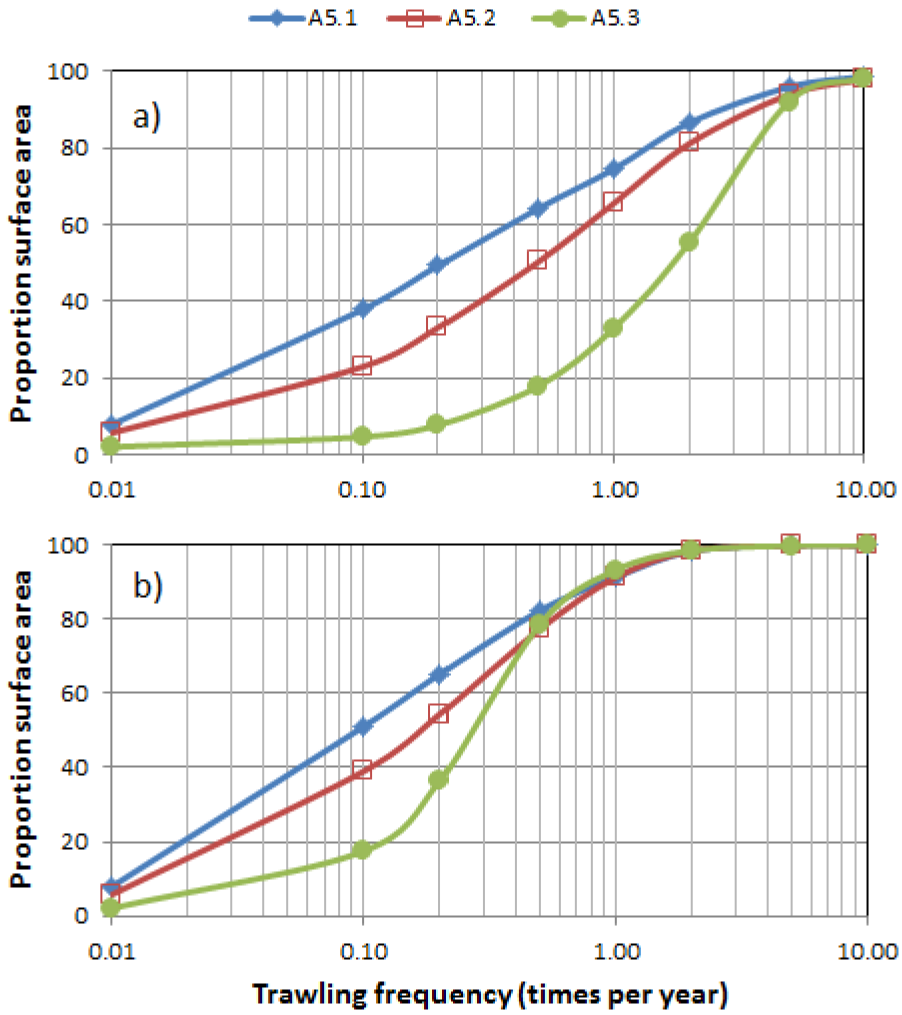

Figure 3. *Surface area of three sea bed habitats trawled less than the trawling frequency shown on the X-axis. A5.1 – sublittoral coarse sediment (♦), A.5.2 – sublittoral sand (□), A5.3 – sublittoral mud (•). Upper panel: surface pressure; Lower panel: sub-surface pressure.*

Figure 4 shows the average biomass distribution over longevity classes estimated for three habitat types. The biomass proportion of long lived taxa is largest in the sublittoral sand (A5.2). Lower proportions of long lived taxa are found in the coarse sediment (A5.1) and sublittoral mud (A5.3). A similar difference in the biomass proportions of long lived taxa was noticeable within functional groups (Figure 4). For illustration purposes, we analysed two feeding groups (suspension feeders and deposit feeders) and two bioturbating groups (diffusive mixing, surface depositing). These functional groups contribute 36% (surface depositing), 30% (diffusive mixing), 18% (suspension feeding) and 21% (deposit feeding) of the biomass of the infaunal community. Functional groups also differ in their longevity distribution. Suspension feeders comprise a larger proportion of long-lived taxa as compared to deposit feeders. For the bioturbation function, no clear difference was observed in the proportion of long-lived taxa.

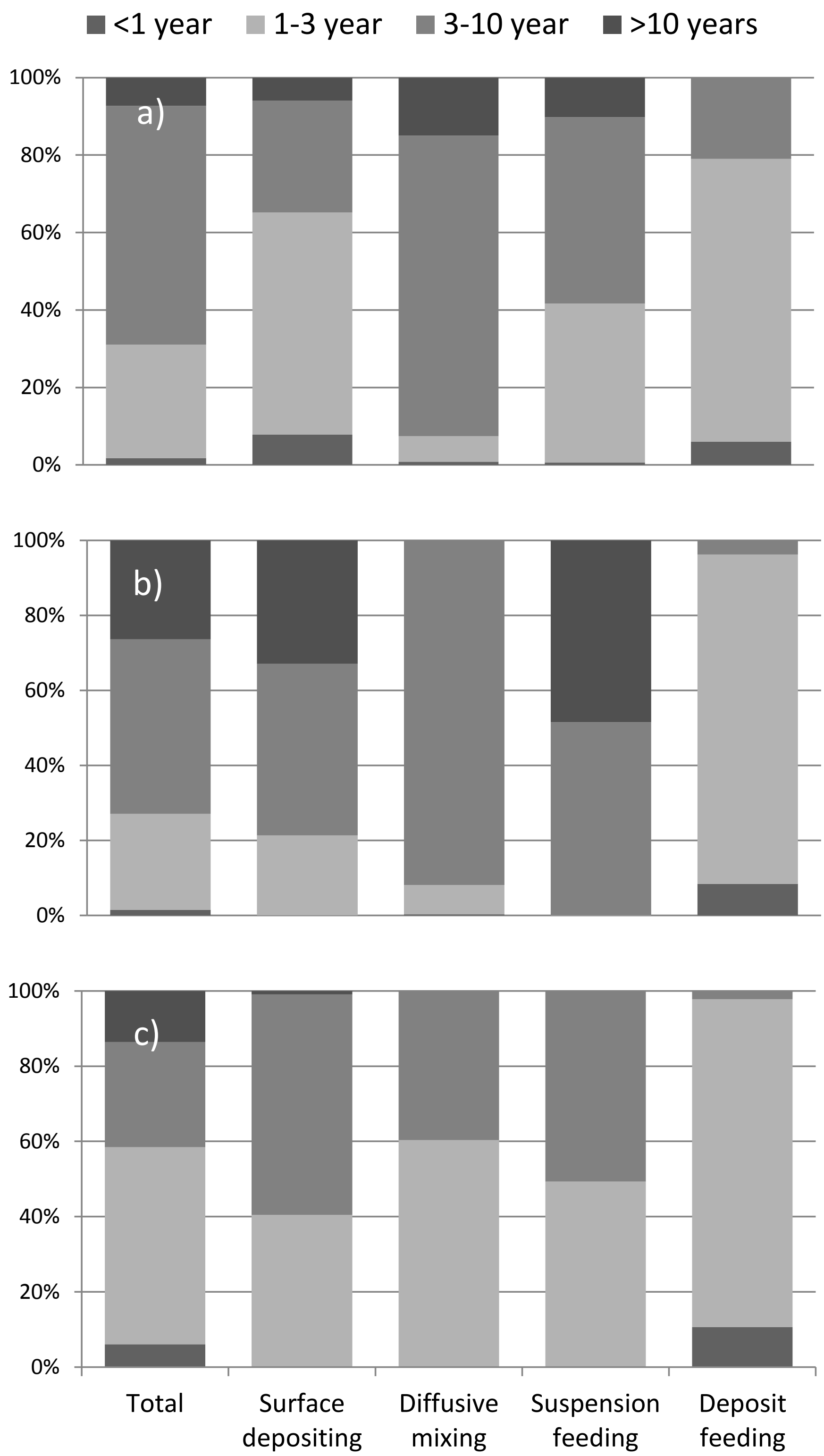

Figure 4. *Proportion of biomass of longevity classes (<1 year, 1-3 year, 3-10 year and >10 years) of the infaunal community (total) and two types of bioturbators (surface depositing, diffusive mixing) and two feeding types (suspension feeding, deposit feeding) in three habitat types: (a) A5.1 sublittoral coarse sediment; (b) A5.2 sublittoral sand; (c) A5.3 sublittoral mud.*

6.3 Impact assessment of three habitats

The indicators can be summarised in a 'traffic light' diagram that informs managers about both the pressure and the environmental status of the three habitats (Figure 5). The average annual trawling intensities recorded in the period 2010-2012 substantially reduce the surface area where the benthos is in their reference state. For the total community, bottom trawling has the largest impact on sublittoral mud (A5.3), followed by sandy habitat (A5.2) and least impact on coarse sediment (A5.1) with E_{sur} reduced to 0.14, 0.35 and 0.53, respectively. Within each habitat, the trawling impact differs between functional groups. The impact of bottom trawling on deposit feeders is smaller than for the other functional groups as they comprise shorter-lived taxa and E_{sur} is reduced to values between 0.19 and 0.62 dependent on habitat. If we assume that bottom trawling impact is related to subsurface effects only, the total benthos in sublittoral mud and sand habitats are equaly impacted (E_{sub}= 0.57 and 0.59), while the impact on coarse sediment is less (E_{sub}=0.70). Similar to the surface impact estimates, subsurface impacts are lowest for deposit feeders.

	Habitat		
	A5.1	A5.2	A5.3
Pressure indicators			
Area untrawled	0.49	0.36	0.13
Area trawled <=1 per year	0.75	0.66	0.33
Area with 90% effort	0.34	0.45	0.75
Surface impact			
Total benthos	0.53	0.35	0.14
Surface depositing	0.59	0.34	0.12
Diffusive mixing	0.49	0.35	0.14
Suspension feeding	0.54	0.28	0.13
Deposit feeding	0.62	0.51	0.19
Subsurface impact			
Total benthos	0.70	0.57	0.59
Surface depositing	0.76	0.54	0.53
Diffusive mixing	0.64	0.56	0.62
Suspension feeding	0.71	0.47	0.57
Deposit feeding	0.79	0.78	0.79

Figure 5. *Traffic light diagram summarising the pressure indicators and the surface and subsurface impact of bottom trawling on the total benthic community (total benthos), two bioturbating types (surface depositing, diffusive mixing) and two feeding types (suspension feeding, deposit feeding) in three different sea bed habitats: A5.1 coarse sediment, A5.2 sandy sediment, A5.3 muddy sediment.*

7 DISCUSSION

7.1 habitat – seabed risk assessment

The framework developed in the present paper provides a habitat – seabed risk assessment method that allows us to (1) quantify the pressure of bottom trawling on different ecosystem components, (2) quantify the ecological impact of bottom trawling, (3) evaluate the effect of alternative management scenarios (Cormier et al. 2013; Stelzenmüller et al., 2015). The proposed framework is consistent with the DPSIR (Driver-Pressure-State-Impact-Response) framework applied for ecosystem based management (Knights et al., 2013), and with the Marine Strategy Framework Directive that requires indicators for the pressure of human activities on the seabed, as well as indicators for the condition and integrity of its ecological function (Rice et al., 2012; ICES, 2014). In order to assess the risk of the trawling impact on the integrity of the seabed habitat and benthic ecosystem, reference levels for pressure and environmental status are required. In the traffic light diagram arbitrary thresholds were used. Whether these thresholds represents Good Environmental Status, as required under the MSFD, is a question that needs further research and stakeholder consultation. Because the assessment method is built on spatially explicit information, the implications for GES can be evaluated at different spatial scales. The indicators can be combined with indicators of other anthropogenic activities affecting the integrity of the seabed, such as dredging activities, construction of windfarms or oil rigs, or the occurrence of hypoxia due to eutrophication allowing an integrated ecosystem-based management of all relevant human pressures (Goodsir et al., 2015; Knights et al., 2013).

The proposed framework can be applied widely because the data required will be generally available. The three pillars of the assessment framework are (1) high resolution data on the frequency of bottom trawling by fishing gear; (2) information on the distribution of seabed habitats; (3) information of the composition of the benthic community with regard to biological traits that are related to their sensitivity and resilience to bottom trawling impacts. Trawling frequency information can be obtained from Vessel Monitoring by Satellite (VMS) data that are routinely collected (Hintzen et al., 2012; Lee et al., 2010b; Deng et al., 2005). Harmonised seabed habitat maps are becoming increasingly available and now cover major parts of the European seas (Populus et al., 2015; Tempera, 2015). Data on the benthic community composition will be available from various monitoring programmes (Rees et al., 2007), that can be coupled to information on life history traits and functional traits (Brey, 2001; Bolam et al., 2014).

7.2 Pressure indicators

The pressure indicators builds on the work of Piet and Hintzen (2012). The area not trawled is estimated from the surface area of the grid cells where no trawling is observed plus the untrawled surface area of the grid cells where the area swept was less than the surface area of the grid cell. The extent of trawling is given by 100% - %untrawled area. The proportion of the area trawled less than once per year is informative of the proportion of the habitat that is lightly trawled. The area where 90% of the trawling occurs indicates the size of the intensively trawled area. Because catch rates tend to equalise across fishing grounds (Gillis and Peterman, 1998; Rijnsdorp et al., 2000), this area represents the area where the bulk of the landings is being taken.

The pressure indicators will be sensitive to the resolution at which the analysis is carried out. At a low resolution, the patchy distribution will be averaged out with areas trawled less intensively. Hence, the estimate of the untrawled area increase with the level of resolution (Dinmore et al., 2003; Mills et al., 2007; Piet and Quirijns, 2009). A resolution of about 1 minute latitude by 1minute longitude as used in this study is considered to be appropriate (Lee et al., 2010b; Gerritsen et al., 2013) as trawling is shown to be randomly distributed at this level of resolution (Rijnsdorp et al., 1998; Ellis et al., 2014). Beyond this resolution, the rounding of GPS position in VMS may cause a bias in the analyses.

7.3 Physical impact indicators

Although the mechanisms by which trawling affects the seabed are highly complex (O 'Neill and Ivanović, 2015), simplified rules were derived based on first principles of physics. Key parameters are the mass and size of the gear components, and the speed at which the gear is towed over the seabed. In combination with information on the trawling frequencies, this information can be used to map the physical impact of bottom trawling and to quantify the differences in physical impact across fisheries. Eigaard et al (this volume) collected data on the gear dimensions and towing speeds and estimated the footprint of 14 different European bottom trawl metiers at the surface and subsurface level. The reductionist approach can be applied to assess passive gears. Passive gears have attracted special attention to reduction the ecological impact and fuel consumption of the fisheries (Suuronen et al., 2012).

The next step is to convert the footprint estimates into an estimate of the physical impact by taking account of the differences in mass and towing speed of the gear components, and seabed characteristics such as grain size and texture. The method to estimate penetration, collision and sediment mobilisation proposed in this paper should be seen as a first attempt. It may guide future research and provide guidance toward an improved data collection of key variables for which empirical data are currently lacking. An empirical model on sediment mobilisation originally developed by O’Neill and Summerbell (2011) was reanalysed and presented by O’Neill and Ivanovic (2015).

7.4 Ecological impact indicators

The third group of indicators were developed to assess the impact of trawling on the benthos and the benthic ecosystem. The objective, again, was to provide a relatively simple but generic approach that is based on first principles and that can be applied to a wide variety of habitats and a broad range of spatial scales. The key of the method is to couple the average trawling interval to the recovery time of the various components of the benthic community. In the example given, we used longevity as a proxy for the recovery time. This choice is a conservative one, because benthos will be able to sustain trawling intervals below their longevity, although at reduced levels of biomass. It should be noted, however, that for taxa forming biogenic structures, the recovery time of the biogenic structures will almost certainly exceed the longevity of the individual organism. The trait longevity was classified into four classes and did not distinguish between taxa with a longevity over 10 years. Also, for many taxa longevity data were unavailable and had to be estimated from the longevity of related taxa (Bolam et al., 2014). From a conservation perspective, more refined data would improve the responsiveness of the indicator. Other recovery metrics could be used, such as the age of first maturity. Because the life history traits are highly correlated, the choice will affect the estimated impact level but is unlikely to affect the relative difference in trawling impact in a comparison of gears, habitats or functional groups.

The use of this framework on real data shows that different types of habitats have communities with a different longevity composition and as such they score differently when assessing trawl impact. The results furthermore show that functional groups may differ in their longevity compositions; suspension feeders, likely to be predominantly bivalves, are longer living and hence more vulnerable to trawl impact than deposit feeders. Such findings indicate how trawling can change ecological function of an area, as is found by Tillin et al. (2006) and de Juan et al. (2007).

It is emphasized that the application to real data is presented for illustration purposes only. Although the trawling intensity distributions represent the total international fleets (Eigaard et al., in prep), the biomass distribution over the longevity classes is estimated from only 1 to 4 sampling sites in each habitat. Hence, these data cannot be considered to give an accurate representation of the habitats. Nevertheless, the smaller proportion of long lived taxa in the coarse sediment habitat (A5.1) is in line with the higher level of natural disturbance in these habitats. Diesing et al., (2013) estimated the frequency of natural disturbance events and compared these with the trawling frequency of the seabed. Under the assumption of a fixed penetration depth for all gears and habitats, they showed that trawling disturbance was greatest in muddy substrates and deep circalittoral habitats, and less in high energy habitats characterised by coarse sediments. Their findings support the results found in this study.

Other studies have used more sophisticated approaches. Duplisea et al. (2002) studied the effect of bottom trawling with a size-structured model of the benthic community comprising meiofauna and two types of macrofauna. Hiddink et al. (2006) extended the model and included spatial differences in habitat. They showed that trawling reduced biomass, production, and species richness and that the impacts of trawling were greatest in areas with low levels of natural disturbance. Ellis et al. (2014) and Pitcher et al. (2015) developed a spatially explicit model of the effect of trawling mortality and recovery dynamics of benthos biomass which was parameterised based on empirical studies. These more sophisticated models, describing the population dynamics of the benthos, have a greater data requirement and may not be applicable to large spatial scales.

The framework proposed in this paper is less demanding in its data needs and can already be applied if information exist about the recovery distribution of the benthos that is typical for the habitat and the high resolution distribution of trawling. It is applicable to all benthic habitats and trawl fisheries and can be applied at different spatial scales (local, regional, and management areas). The approach is a first step and further work needs to be done, amongst other to estimate the physical impact of bottom trawling of different fishing gears and to define threshold levels for the pressure and impact indicators that relate to the Good Environmental Status of the habitat.

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