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Original Article

Towards a framework for the quantitative assessment of trawling impact on the seabed and benthic ecosystem

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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 provides indicators for both trawling pressure and ecological impact. It builds on high-resolution maps of trawling intensity and considers the physical effects of trawl gears on the seabed, on marine taxa, and on the functioning of the benthic ecosystem. Within the framework, a reductionist approach is applied that breaks down a fishing gear into its components, and a number of biological traits are chosen to determine either the vulnerability of the benthos to the impact of that gear component, or to provide a proxy for their ecological role. The approach considers gear elements, such as otter boards, twin trawl clump, and groundrope, and sweeps that herd the fish. The physical impact of these elements on the seabed, comprising scraping of the seabed, sediment mobilization, and penetration, is a function of the mass, size, and speed of the individual component. The impact of the elements on the benthic community is 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, dispersal), and their 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 (EUNIS A5.3) is affected the most due to the combined effect of intensive fishing and large proportions of long-lived taxa.

Keywords: benthos, biological traits, good environmental status, indicators, method, mobile gear, physical impacts.

Introduction

Fishing is one of the important anthropogenic activities affecting marine ecosystems (Jennings and Kaiser, 1998; Halpern *et al.*, 2008), with continental shelf areas, in particular, being heavily exploited by bottom trawls towed over the seabed. Benthic ecosystems on the continental shelf provide important ecosystem goods and services, such as the provision of fisheries production and the food for bottom-dwelling fish species, which comprise about 23% of the global fisheries yield (FAO, 2009). They also play a vital role in the functioning of marine ecosystems and support a wide diversity of species. The bottom trawl fisheries typically use heavy otter boards or shoes to maintain contact with the seabed, and groundropes and chains to force fish into the net. Physical disturbance from such devices can cause significant changes to the seabed, cause mortality among the animals encountered, and affect the biogeochemical processes of the sediment—water interface (Dayton *et al.*, 1995; Auster *et al.*, 1996; Jennings and Kaiser, 1998; Watling and Norse, 1998; 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; Auster *et al.*, 1996; Jennings and Kaiser, 1998; Watling and Norse, 1998; 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 successfully ranks 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, is described by 11 qualitative descriptors; of which, the descriptor on seabed 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 affecting the seabed (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, therefore, cannot be tested solely using the data acquired through sampling programmes.

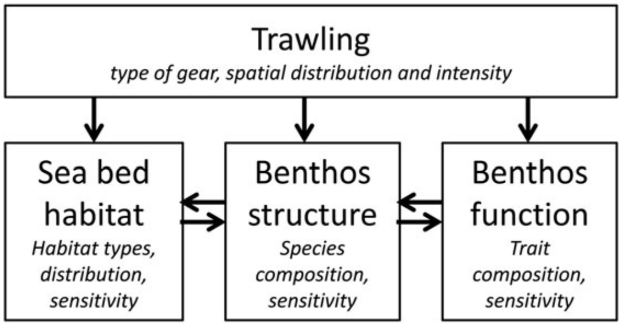


Figure 1. Components of the framework to assess the impact of trawling on the seabed and benthic ecosystem. Trawling effects are dependent on the type of gear and the distribution and intensity. Seabed habitats and benthic communities differ in their spatial distribution and sensitivity for trawling.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

The objective of this study was 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 on which the gear interacts with the seabed to the scale on which both the fisheries operate and are managed. Some simplifying assumptions need to be made to allow scaling up the assessments to these larger scales. The paper starts with a brief outline on the importance of seabed habitat and how bottom trawling affects seabed habitats, benthos community composition, and benthic ecosystem functioning (Figure 1). This highlights the processes that will need to be understood to allow an assessment of the large-scale effect of trawling on benthic ecosystems. Metrics for the physical impact of bottom trawls are developed that can be used in the estimation of indicators for the trawling pressure and the ecological impact of trawling. The framework, which can be applied to different benthic habitats and the various fishing gears, is explored in a preliminary assessment of the impact of bottom trawling in three dominant habitat types in the North Sea.

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 (Hiddink *et al.*, 2006; Gray and Elliott, 2009; 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 three-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; Miller *et al.*, 2012). Dense populations of epibenthic species may form mats or beds that structure the seabed (e.g. mussels), while infaunal species, such as spionid worms, create burrows or tubes (Bolam and Fernandes, 2003; Braeckman *et al.*, 2014). High densities of such species have been shown to affect sediment characteristics and faunal assemblage structure both directly and indirectly via alterations in near-bed hydrodynamic conditions (Dame *et al.* 2001; Rabaut *et al.*, 2007).

To develop an impact assessment framework, information on the distribution of seabed habitats is required. Seabed habitats can be classified according to a 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 European waters (http://www.emodnet-seabedhabitats.eu/), they provide a starting point for an impact assessment.

Trawling impact

Any gear that aims to catch demersal fish, crustaceans, or shellfish needs to be in contact with the seabed. Fishers have developed a variety of trawl gears to maximize 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 groundrope 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).

Physical impact on seabed habitat

The physical interaction of fishing gears with the seabed is extremely complex (O'Neill and Ivanović, 2016). 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 (He and Winger, 2010; Lucchetti and Sala, 2012; Buhl-Mortensen *et al.*, 2013). On soft sediments there can be compression, shearing, and associated displacement of the sediment (O'Neill and Ivanovic, 2016) and mobilization 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) (Lucchetti and Sala, 2012; Eigaard *et al.*, 2016).

Bottom trawls will scrape the seabed 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, while on harder substrates trawling may dislodge stones from the sediment by the action of tickler chains, rakes, or footrope, and these may subsequently be turned over, or end up in the net and be displaced or even removed (Auster *et al.*, 1996; Thrush and Dayton, 2002; Buhl-Mortensen *et al.*, 2013). Gear components may crush or break biogenic structures or material, such as dead shells, which may result in a reduction in the substrate for epibenthic species (Collie *et al.*, 2000; Kaiser *et al.*, 2006). Intensive trawling may cause sediment systems to become unstable (Kaiser *et al.*, 2002). Sediment disturbance may further affect the flux of nutrients from the sediment to the overlying water (Almroth-Rosell *et al.*, 2012). The physical impact of trawling gears on seabed habitat is based on the penetration of gear elements, the collision impact, and the sediment mobilization.

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.*, 2016; O'Neill and Ivanović, 2016). Rakes, or a series of tickler chains running in front of the groundrope, will penetrate and enhance the mixing in the impacted layer; this alters the sediment sorting and damages 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 (FGO, 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, for example, 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). The penetration depth of fishing gear components has been reviewed by Eigaard *et al.* (2016).

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 changes in 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 characterize and rank the potential effect that a gear component may have on the seabed may be used.

Sediment mobilization

Bottom trawls will mobilize sediment in the wake of the gear (De Madron *et al.*, 2005; Lucchetti and Sala, 2012). 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). A strong decrease in the mud fraction and an increase in the fine sand fraction have been, for example, observed over a period of 35 years in the sediments of the Bay of Biscay (Hily *et al.*, 2008). During sediment mobilization, pore water and its nutrients will be exchanged with the overlying water (De Madron *et al.*, 2005); this has resulted in enhanced total organic carbon concentrations in the water after the start of bottom trawling, likely due to the uplift from deeper sediments (Pusceddu *et al.*, 2005). In chronically trawled grounds, organic matter appears reduced, this has, for example, been shown along the continental slope of the northwestern Mediterranean Sea (Pusceddu *et al.*, 2014).

The amount of sediment that is mobilized is primarily determined by the particle size distribution of the sediment and the hydrodynamic drag of the gear (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 mobilization can be estimated from the towing speed and the size of the gear components (O'Neill and Ivanović, 2016).

Impact on benthic community composition and ecosystem function

Trawling may reduce benthic community biomass and biodiversity, and shift the assemblage composition towards short-lived, smaller species due to taxonomic differences in direct mortality and recovery rates (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 was reduced by ∼20% due to beam trawls and otter trawls and 40% by scallop dredges, whereas suspension-feeders declined by 70% due to 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 remineraliztion of nutrients (Thrush *et al.*, 2001; Olsgard *et al.*, 2008). Suspension-feeders transfer organic carbon from the pelagic system to the benthic foodweb, enhancing the rate of biodeposition (Graf and Rosenberg, 1997; Gray and Elliott, 2009). Benthic invertebrates may also play a role in the bioturbation of sediments (Aller, 1994; Reise, 2002). For example, species such as the heart urchin *Echinocardium cordatum* and the annelid worm *Scoloplos armiger* are diffusive mixers, physically mixing the sediment while moving (Lohrer *et al.*, 2005). Meanwhile, other species transport organic material downwards (e.g. the bivalve *Thyasira flexuosa* and echiuran worm *Echiurus echiurus*) as they feed on the surface and defaecate within the sediment matrix (downward conveyors), while species like the scaphopod *Antalis entalis* transport organic carbon upwards by subsurface feeding and defaecating on the surface (upward conveyors) (Queirós *et al.*, 2013). Others feed on dead organisms (scavengers), predate, or are parasitic on benthic organisms. Many provide food for other benthic invertebrates, fish, birds, or marine mammals (Bolam *et al.*, 2010).

Biological trait analysis (Bremner *et al.*, 2006; Bremner, 2008) has proved to be a useful approach to classify the relative vulnerability of benthic taxa to trawling disturbance as well as their relative recovery rate. Bolam *et al.* (2014), for example, indicated how differences in direct mortality among species groups are related to characteristics such as the position in the seabed profile, morphology (e.g. exoskeleton, crustose, soft bodied), and body size. Furthermore, differences in the recovery rate among species were related to life-history characteristics such as the longevity and larval development, and egg development modes. Morphological traits have been demonstrated to be important in determining the presence of a species 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). Furthermore, filter-feeders, attached and larger animals were relatively more abundant in lightly trawled areas, while areas with higher levels of trawling were characterized by a relatively high biomass of mobile animals and infaunal and scavenging organisms (e.g. Kaiser and Spencer, 1994; Tillin *et al.*, 2006). Biological trait analysis can also be used as a proxy to examine the changes in ecological function 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 the one dominated by subsurface deposit feeders (Rosenberg, 1995), while assemblages dominated by individuals that recruit via planktonic larvae are likely to recover more rapidly following large-scale physical disturbance than those reliant on benthic or lecithotrophic larvae (Savidge and Taghon, 1988; Thrush and Whitlatch, 2001).

Table 1. Overview of metrics for the physical impact of bottom trawling on the seabed and indicators for pressure of trawling and the ecological impact.

Metrics for the physical impact on the seabed	
I_p	penetration depth of the gear component
I_c	impulse momentum of the collision of the gear element
I_s	sediment mobilization
Pressure indicators	
P_1	Proportion of the habitat that is not trawled during a year
P_2	Proportion of the habitat that is trawled less than once in a year
P_3	Proportion of the habitat where 90% of the trawling effort is concentrated.
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

Sediment mobilization 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 in the food quality (Mayer *et al.*, 1991; Watling *et al.*, 2001). Sediment mobilization may also reduce the available light for primary producers and hence reduce primary production.

Assessment framework

Table 1 summarizes the metrics for the physical impact of trawling that is required to deal with the differences in impact between fishing gears, and the indicators for the trawling pressure and ecological impact.

Metrics for the physical impact on seabed habitat

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

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):

$$I_\mathrm{p} \sim f\,(MA^{-1})$$

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

$$I_\mathrm{c} \sim f\,(MU)$$

Sediment mobilization is a function of the hydrodynamic drag, which depends on the product of U^2 and the frontal surface area of the gear element S, which generates the turbulence. Hence, as a first approximation, sediment mobilization (I_s) 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 mobilized, 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, I_p and I_s will also be influenced by the particle size distribution of the sediment.

Trawling pressure indicators on the seabed

It is well established that bottom trawling is patchy, both in space and time, 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.*, 2010; Ellis *et al.*, 2014; van Denderen *et al.*, 2015). Figure 2a gives a hypothetical example of the spatial distribution of bottom-trawling frequencies. Intense trawling occurs in a relatively small proportion of the habitat when compared with the habitat that is trawled at a low frequency or that is not trawled.

The information contained in this graph can be condensed into 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 that 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.

Ecological impact indicators

The trawling frequency (f) determines the probability that an organism, which is within reach of the trawl gear, 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 taxon will fully recover is determined by their recovery time (R). If the recovery time is less or equal to the trawling interval, the taxon will be able to recover. For each taxon, a maximum trawling frequency ($f = R^{-1}$) can be defined where the taxon 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.

Following Thrush *et al.* (2005), 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 when trawling frequencies are <0.1 year^{-1} and this is true for about 30% of the habitat. Taxa with a recovery time of 1 year will be in a reference state when trawling frequencies are <1 year^{-1} and this is true for almost 60% of the habitat.

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 represent the proportion of the surface area of a habitat where recovery class t is in reference state, and b_t represent the biomass of the benthos with a recovery time of t. The impact (I) 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 combine the impact of different gears (f), a scaling term s_f can be included that expresses the relative impact rescaled to the gear with the largest impact as indicated by the metric for the collision impact described above:

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

The trawling impact indicator I estimates the status of the benthic community as the surface area of a particular habitat where different recovery classes are in reference states. A value of 1 reflects a situation

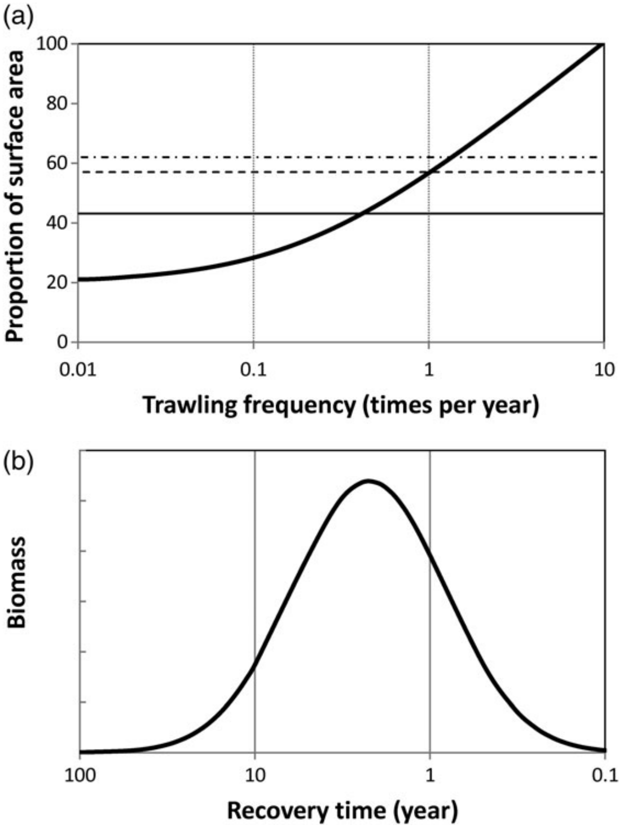


Figure 2. (a) Hypothetical relation of the heterogeneous distribution of bottom trawling showing the proportion of the surface area that is trawled less than a certain trawling frequency. Horizontal lines show the proportion of untrawled habitat (grey line), the surface area trawled less than one time per year (dashed line) and the surface area encompassing the lightly (heavily) trawled areas representing 10% (90%) of the total fishing effort (dash-dotted line). The untrawled area comprises 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 represents 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 of the benthic taxa and the trawling frequency are related via the reciprocal of the trawling frequency which gives the average interval between two trawling events.

where trawling has no impact on the benthos, while 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 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, taking account of the proportion of the community or functional group that is within reach of the trawl gear.

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 the EUNIS habitats 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, respectively. The assessment is a simplified example that is presented for illustration purposes only and assumes, for instance, that all benthos is within reach of the trawl gear and that there are no differences in trawling impact across fishing gears. This means that the preliminary assessment only determines trawling impact based on the trawling pressure indicators and the ecological indicators. It does not take into account the metrics related to the physical effects of the gear on the seabed (although we distinguish between surface and subsurface distribution of trawling effort).

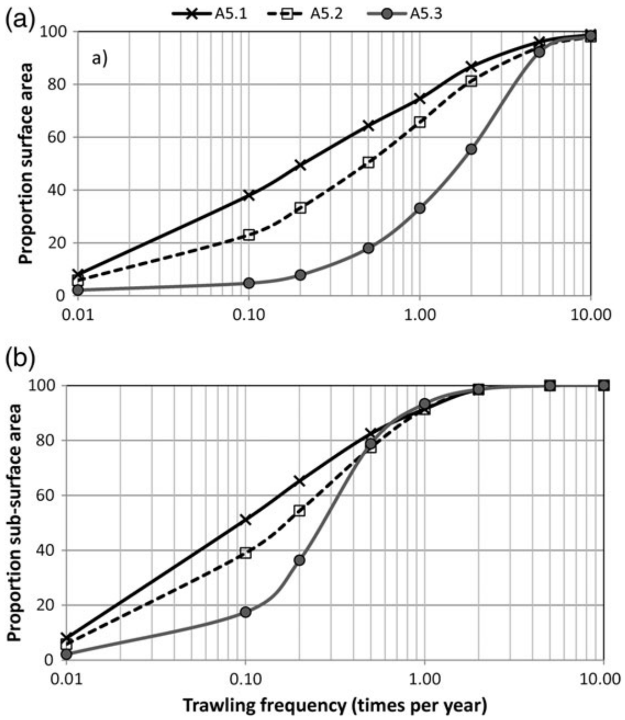


Figure 3. Surface area of three seabed habitats trawled less than the trawling frequency shown on the *x*-axis. A5.1, Sublittoral coarse sediment (crosses); A5.2, Sublittoral sand (squares); A5.3, Sublittoral mud (circles). (a) Surface pressure and (b) subsurface pressure.

Estimating trawling pressure indicators

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 min longitude × 1 min latitude (Eigaard *et al.*, 2015). This analysis took account of the differences in the footprint of the various métiers, distinguishing between surface and subsurface footprint (Eigaard *et al.*, 2016). 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 bottom trawl pressure increases from coarse sediments to mud. That is, the proportion of seabed trawled less than once a year is lowest (33%) for the Sublittoral mud habitat (A5.3) and increases to 66% for the Sublittoral sand (A5.2) and to 75% for the Sublittoral coarse sediment (A5.1). Meanwhile, the proportion of untrawled habitat (P1) is 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).

Estimating ecological impact indicators

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 boxcorer (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 grammes ash-free dry weight (Dutch CS, Dutch FS) or wet weight (other areas). Taxa were coupled with the infaunal trait dataset as first described by Bolam *et al.* (2014), which comprises 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 minimized, only those stations for which predicted fishing pressure was either low or zero (i.e. estimated total FP of $<0.5 \text{ year}^{-1}$) were used. We made the assumption that the data were representative for the benthic community that is within reach of bottom trawls.

Table 2. Data sources of boxcore samples used to estimate the biomass distribution over the longevity classes of the macrofauna (from van Denderen, 2015).

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, b, 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) and Tillin *et al.* (2006)
A5.3: Sublittoral mud	Fladen Ground	57.99	0.42	Tillin *et al.* (2006)

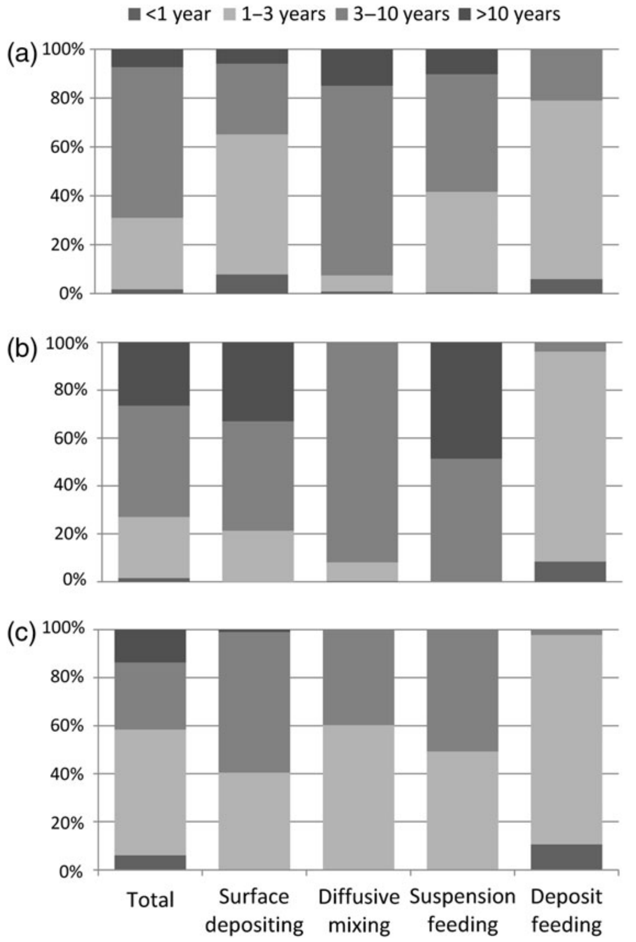
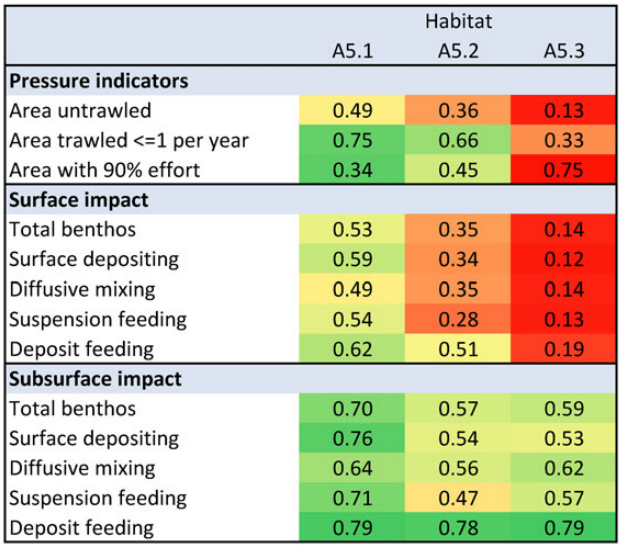


Figure 4. The proportion of biomass of longevity classes (<1, 1–3, 3–10, and >10 years) of the infaunal community (total) and two types of bioturbators (surface depositing, diffusive mixing) and two feeding types (suspension feeding, deposit feeding) in three habitat types: (a) A5.1, Sublittoral coarse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

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; Pitcher *et al.*, 2016). 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 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 Sublittoral coarse sediment (A5.1) and Sublittoral mud (A5.3). A similar difference in the biomass proportions of long-lived taxa is 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) that incorporated all species that had unequivocal affinity with these groups (see Bolam *et al.*, 2014). The selected species within these functional groups contribute 36% (surface depositing), 30% (diffusive mixing), 18% (suspension feeding), and 21% (subsurface 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 when compared with deposit feeders. For the bioturbation function, no clear difference was observed in the proportion of long-lived taxa.



	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 summarizing 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 seabed habitats: A5.1, Sublittoral coarse sediment; A5.2, Sublittoral sand; A5.3, Sublittoral mud.

Impact assessment of the three habitats

The indicators can be summarized 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 Sublittoral sand (A5.2) and least impact on Sublittoral coarse sediment (A5.1), with E 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 is reduced to values between 0.19 and 0.62 dependent on habitats. If we assume that bottom-trawling impact is related to subsurface effects only, the total benthos in Sublittoral mud (A5.3) and sand habitats (A5.2) are equally affected ($E = 0.57$ and 0.59), while the impact on coarse sediment (A5.1) is less ($E = 0.70$). Subsurface impacts are lowest for deposit feeders and this is similar to the surface impact estimates.

Discussion

Habitat–seabed risk assessment

The framework developed in the present paper provides a habitat–seabed risk assessment method that allows us to (i) quantify the pressure of bottom trawling on different ecosystem components, (ii) quantify the ecological impact of bottom trawling, and (iii) 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 (MSFD) 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). 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 our the traffic light system, arbitrary thresholds were used. Whether these thresholds represent GES, 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 (Knights *et al.*, 2013; Goodsir *et al.*, 2015).

The proposed framework can be applied widely because the data required will be generally available. The three pillars of the assessment framework are: (i) high-resolution data on the frequency of bottom trawling by fishing gear; (ii) information on the distribution of seabed habitats; and (iii) information on 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 (Deng *et al.*, 2005; Lee *et al.*, 2010; Hintzen *et al.*, 2012). Harmonized 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 can be found from various monitoring programmes (Rees *et al.*, 2007), which can be coupled with information on life history traits and functional traits (Brey, 2001; Bolam *et al.*, 2014).

Physical impact on seabed habitat

Although the mechanisms by which trawling affects the seabed are highly complex (O'Neill and Ivanović, 2016), 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 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. This reductionist approach can also be applied to assess passive gears. Passive gears have attracted special attention to reduce the ecological impact and fuel consumption of the fisheries (Suuronen *et al.*, 2012).

The methods to estimate penetration, collision, and sediment mobilization proposed in this paper should be seen as a first attempt that may guide future research and provide guidance towards an improved data collection of key variables for which empirical data are currently lacking. Some studies have already assessed the physical impact of trawl gears on the seabed, for example, using an empirical model of sediment mobilization (originally developed by O'Neill and Summerbell (2011) and reanalysed by O'Neill and Ivanović (2016)).

Pressure indicators on the seabed

The development of 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 indicative 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 equalize 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.

Pressure indicators take account of the differences in physical impact of different fishing gears. Based on the footprint estimates of 14 different European bottom trawl métiers (Eigaard *et al.*, 2016), the pressure indicators of the total fleet of bottom trawlers could be estimated at both the surface and the subsurface level. Further work is needed to refine the pressure indicators by taking account of the differences in towing speed among métiers that have a large effect on the physical impact.

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 increases with the level of resolution (Dinmore *et al.*, 2003; Mills *et al.*, 2007; Piet and Quirijns, 2009). A resolution of about 1 min latitude by 1 min longitude as used in this study is considered to be appropriate (Lee *et al.*, 2010; 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).

Ecological impact indicators

The ecological impact 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 principle of our approach 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 maximum longevity as a proxy for the recovery time. This choice is a conservative one, because the benthos will be able to sustain trawling intervals below their maximum 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. 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 closely 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 at first maturity. Because many life history traits are highly correlated, the choice will affect the estimated impact level although we expect that it is unlikely to affect the relative differences in trawling impact in a comparison of gears, habitats, or functional groups.

The application 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 (e.g. Tillin *et al.*, 2006; de Juan *et al.*, 2007).

It is emphasized that the application to real data in this study is a simplified example that is presented for illustration purposes only. It assumes, for instance, that all benthos are within the reach of the trawl gear and that there are no differences in trawling impact across fishing gears. Although the trawling intensity distributions represent the total international fleets (Eigaard *et al.*, 2015), the biomass distribution over the longevity classes is estimated from only one to four 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 Sublittoral coarse sediment (A5.1) is in line with the higher level of natural disturbance in these habitats (Hall, 1994). 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 characterized by coarse sediments.

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.* (2016) developed a spatially explicit model of the effect of trawling mortality and recovery dynamics of benthic biomass which was parameterized 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.

Conclusion

The impact assessment framework proposed in this paper is applicable to all benthic habitats and trawl fisheries and can be applied at different spatial scales (local, regional, management areas). The data requirement is modest and the framework can readily be applied if information exists regarding the distribution of the recovery rate of the benthos and the (preferably high resolution) distribution of trawling by habitat. Further work is needed to convert the footprint estimates of the different métiers into an estimate of the physical impact by taking account of the mass and towing speed of the gear components, and seabed characteristics that can be compared with the natural disturbance. Also, threshold levels for the pressure and impact indicators that relate to the GES of the habitat need to be derived.

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