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Different bottom trawl fisheries have a differential impact on the status of the North Sea seafloor habitats

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ABSTRACT

Fisheries using bottom-trawls are the most-widespread source of anthropogenic physical disturbance to seafloor habitats. To mitigate such disturbances, the development of fisheries-, conservation- and ecosystem-based management strategies requires the assessment of the impact of bottom trawling on the state of benthic biota. We explore a quantitative and mechanistic framework to assess trawling impact. Pressure and impact indicators that provide a continuous pressure – response curve are estimated at a spatial resolution of 1x1 minute latitude and longitude (~2 km^2) using three methods: L1 estimates the proportion of the community with a life span exceeding the time interval between trawling events; L2 estimates the decrease in median longevity in response to trawling; PD estimates the decrease in biomass in response to trawling and the recovery time. Although impact scores are correlated, PD has the best performance over a broad range of trawling intensities. Using the framework in a trawling impact assessment of ten métiers in the North Sea shows that muddy habitats are impacted the most and coarse habitats impacted the least. Otter trawling for crustaceans has the highest impact, followed by otter trawling for demersal fish, beam trawling for flatfish and flyshooting. Beam trawling for brown shrimps, otter trawling for industrial fish and dredging for molluscs have the lowest impact. Trawling is highly aggregated in core fishing grounds where the status of the seafloor is low but the CPUE per unit of impact is high, in contrast to peripheral grounds, where CPUE per unit of impact is low.

KEY WORDS

Trawling impact, method comparison, otter trawl, beam trawl, seine, dredge, footprint, soft sediment, seafloor habitats, recovery.

INTRODUCTION

With the adoption of the Convention on Biological Diversity and the Fish Stocks Agreement (Rice, 2014), and the subsequent development of Ecosystem-based Fisheries Management (EBFM, e.g. (Pikitch et al., 2004), sustainability has become an overarching principle across marine policy, both at the national and at the international level by numerous organizations (FAO, ICES, CBD, Arctic Council). Similarly, it is firmly embedded in European marine policy through the EU's Marine Strategy Framework Directive (MSFD) and Common Fisheries Policy. To ensure sustainability, marine scientists are increasingly being challenged to provide decision makers with ready-to-use tools to balance conservation and exploitation. These tools need to be able to demonstrate the consequences of likely trade-offs (central to EBFM) in fisheries management that maintains resilient and productive ecosystems, as well as human and ecosystem well-being and stewardship of marine ecosystems.

The EU’s MSFD (CEC, 2008) aims to maintain or achieve good environmental status (GES) for a number of ecosystem components including the benthic seafloor which is affected by a multitude of anthropogenic activities (Eastwood et al., 2007; Foden et al., 2011). While mining, dredging, disposal of dredged material and sand- and gravel extraction are localised activities and generally limited to coastal regions, bottom trawling (i.e. demersal trawls and seines, and dredges) occurs over large parts of the continental shelf (Halpern et al., 2008; Foden et al., 2011; Amoroso et al., 2018a). The footprint of bottom trawling on the European continental shelf varies between 28-85% per seafloor habitat type down to 200 m (Eigaard et al., 2017). This anthropogenic pressure exhibits a heterogeneous distribution in both space and time with some areas being trawled several times per year and other areas only trawled lightly or not trawled at all (Rijnsdorp et al., 1998; Lee et al., 2010; Gerritsen et al., 2013; van Denderen et al., 2015b).

Bottom trawling may disturb the seafloor, may damage biogenic structures and may kill benthic invertebrates, resulting in alterations to the structure and functioning of benthic ecosystems (Dayton et al., 1995; Thrush and Dayton, 2002; Kaiser, 1998). The impact of trawling is related to the footprint and trawling intensity, and differs between gear types due to variations in the penetration depth of the different gear components (Eigaard et al., 2016a; O 'Neill and Ivanović, 2016; Rijnsdorp et al., 2016; Hiddink et al., 2017). The impact is further governed by the sensitivity of the seafloor habitat which is related to resistance of the community to trawling, the recovery rate after trawling (Collie et al., 2000; Kaiser et al., 2006; Hiddink et al., 2019) and the degree of natural disturbance (Hall, 1994; Diesing et al., 2013; van Denderen et al., 2015a).

To support the MSFD, an assessment methodology is needed to estimate the impact of the different bottom trawling gears on the various seafloor habitats across the European shelf. The methodology to assess trawling impact has traditionally used expert judgement to derive sensitivity of different habitats for specific bottom trawl fisheries (Eno et al., 2013; Grabowski et al., 2014). Under such approaches, habitat sensitivity categories are assigned through an expert judgement-based resistance and resilience scoring of a selection of species and biogenic structures that are typical for the habitat. This approach is flexible and allows the incorporation of additional information the experts consider to be relevant. However, such categorical methods are less appropriate for impact comparisons across habitats because class boundaries are set arbitrarily for sensitivity and trawling pressure and are thus non-scalable. The arbitrary setting of class boundaries also means that different combinations of categories can yield similar impact scores, although the consequences of impact in each case will have different ecological implications. This precludes statistical assessments as a similar impact score can mean different things (ICES, 2016). In addition, the method lacks transparency as expert opinion is inherently subjective, and the assessment will be difficult to reproduce and compare between different studies or areas. As such, the approach is less appropriate to provide guidance on the regulation of bottom trawling in sedimentary habitats which both dominate the seafloor of the European shelf seas and are widely used by bottom trawlers (ICES, 2016).

To provide appropriate assessment of the intensively trawled sedimentary habitats that dominate the European continental shelf, and summarising these impacts at regional scales, an assessment methodology is needed that builds on the driver – response relationships on a continuous scale. In this paper we combine a number of quantitative methods that have recently been developed to estimate the impact of bottom trawling on the sea floor into a benthic impact assessment framework (Figure 1). The framework combines high resolution information about trawling pressure, gear characteristics (Eigaard et al., 2016; 2017; Hiddink et al., 2017), abiotic habitat characteristics (Davies et al., 2004; Wilson et al., 2018) and sensitivity of the benthic community (Rijnsdorp et al., 2018; Hiddink et al., 2019) to estimate benthic impact. The first method (L1) estimates the proportion of the benthic community with a life span exceeding the time interval between trawling events (Rijnsdorp et al., 2016; Eigaard et al., 2017). The second (L2) estimates the decrease in median longevity of the benthic community in response to trawling (Rijnsdorp et al., 2018) while the third (PD) estimates the decrease in biomass of the benthic community in response to trawling and the recovery time based on quantitative knowledge of the mortality imposed by a trawling event, the recovery rate of the benthos and the time interval between successive trawling events (Ellis et al., 2014; Pitcher et al., 2017).

The specific objectives of this paper are to (i) compare the performance of the three methods to estimate benthic impact based on their responsiveness to the observed range of trawling intensities; (ii) assess the benthic impacts of the ten dominant mobile bottom contacting gears (MBCG) in the North Sea; (iii) estimate which gear-habitat combinations provide the highest amount of fish landings for the lowest amount of benthic impact.

MATERIAL AND METHODS

Trawling pressure

Mean annual trawling intensities (swept area ratio, SAR) of vessels larger than 15 m were available for the period 2010-2012 at a grid cell resolution of 1 min latitude x 1 min longitude (~2 km^2 at 54°N) from Eigaard et al. (2017). Surface (0-2 cm) and sub-surface (>2 cm) trawling intensities were estimated for different métiers by combining VMS recordings of fishing activities with the information of the fishing gear obtained from EU-logbooks and information of gear dimensions (Eigaard et al., 2016a; Eigaard et al., 2016b). Total landed weight by trip was allocated to the trawled grid cells in proportion to fishing hours.

Data were available for 10 different métiers representing the major MBCG activities in European waters (Table 1): one fishery using a dredge to target molluscs, mainly scallops (DRB_MOL); five métiers using an otter trawl to target crustaceans *Nephrops* or *Pandalus* (OT_CRU), demersal fish species (OT_DMF), *Nephrops* and benthic fish (OT_MIX_1), bentho-pelagic species (OT_MIX_2) and small pelagic species (OT_SPF); two seine fisheries: Danish seiners (SDN) and fly shooters (SSC); and two beam trawl fisheries targeting brown shrimp (TBB_CRU) and flatfish (TBB_DMF).

The trawling footprint by métier was calculated as the sum of the surface area (km^2) of the grid cells with SAR >=1, plus the fractions of the grid cells trawled when SAR <1 assuming a uniform distribution of trawling activities within each grid cell (Eigaard et al., 2017; Amoroso et al., 2018). A second footprint indicator was calculated as the proportion of 1 minute latitude x 1 minute longitude grid cells with any trawling activity irrespective of the trawling intensity. This metric includes the untrawled part of grid cells trawled at an intensity of <1 yr^{-1} that may be trawled if longer time periods are assessed (Ellis et al., 2014; Eigaard et al., 2017; Amoroso et al., 2018a). A third indicator of the aggregation of trawling activities was estimated as the smallest proportion of grid cells where 90% of effort (swept area) is concentrated (Eigaard et al., 2017).

Habitat

Sand, mud and gravel content were obtained from Wilson et al. (2018) applying cubic interpolation to provide an estimate for each 1 minute latitude x 1 minute longitude grid cell. Tidal bed shear stress (N.m^{-2}) was obtained from a hydrodynamic model by John Aldridge (CEFAS) as used in Hiddink et al. (2006) and van Denderen et al. (2015a).

Impact assessment methods

Three methods, which assume that benthic community sensitivity to bottom trawling is related to longevity composition, were used to assess the impact of bottom trawling on the benthic ecosystem (Figure 1; Table 2). The longevity composition is related to the sediment composition, bed shear stress and trawling intensity and can be described by a logistic relationship between the cumulative biomass (B_i) of longevity class i, expressed as a proportion of the total biomass, and longevity based on a statistical fit to empirical data from the North Sea (equation [1]) (Rijnsdorp et al., 2018):

[1]
$$\ln\left(\frac{B_i}{1-B_i}\right) = \alpha + \beta_L \ln(L_i) + \beta_H H + \beta_T T + \beta_{HL} H{:}\, L_i + \beta_{HT} H{:}\, T$$

where α is the intercept, β_L is the coefficient of the log-longevity parameter L, β_H are the coefficients of the habitat parameters H (%gravel, %mud, log tidal shear stress), β_T is the regression coefficient for trawling intensity parameter T, β_{HL} is the regression coefficient for the interaction between habitat variable and longevity and β_{HT} is the regression coefficient for the interaction between habitat and trawling intensity.

Precautionary approach (L1)

This method assumes that a population is affected by trawling if animals are trawled during their life span. Only species in the community with a longevity less than the average interval between two successive trawling events will not be affected (Rijnsdorp et al., 2016). The method further assumes that all benthic species in the trawl path are affected. The impact I_{L1} can be estimated as the proportion of biomass of species with a longevity exceeding the reciprocal trawling intensity (L = 1/T), which was derived from equation [1] as:

[2]
$$I_{L1} = 1 - \frac{\exp\left(\alpha+\beta_L \ln\left(\frac{1}{T}\right)+\beta_H H+\beta_T \ln(T_0)+\beta_{HL} H \ln\left(\frac{1}{T}\right)+\beta_{HT}\, H \ln\,(T_0)\right)}{(1+\exp(\alpha+\beta_L \ln\left(\frac{1}{T}\right)+\beta_H H+\beta_T \ln(T_0)+\beta_{HL} H \ln\left(\frac{1}{T}\right)+\beta_{HT}\, H \ln\,(T_0)))}$$

Because the impact is estimated relative to the untrawled community, a value of T_0 = 0.01 was included to avoid taking the log of zero.

Statistical-impact approach (L2)

Trawling shifts the community composition towards shorter lived taxa. The median longevity of the community M_T in response to trawling is based on the statistical relationship between trawling intensity and longevity as found in Rijnsdorp et al. (2018).

By re-arranging equation [1], M_T is given by:

[3]
$$M_T = \exp\,(-\,(\alpha + \beta_H H + \beta_T T + \beta_{TH} T{:}\, H\,)/(\beta_L + \beta_{HL} H))$$

L2 estimates the relative change in median longevity in response to trawling by:

[4]
$$I_{L2} = 1 - M_T/M_0$$

where M_T is the median longevity at trawling intensity T and M_0 is the median longevity of the untrawled community.

Population dynamic approach (PD)

The population dynamic method estimates the impact of bottom trawling (I) in terms of the reduction in the benthic biomass (B) relative to the carrying capacity (K) of the habitat (Pitcher et al., 2017; Hiddink et al., 2019).

[5]
$$I_{pd} = 1 - B = 1 - \sum_{i=1}^{n} K_i * (1 - \sum_{m=1}^{10} T_m d_m / r_i)$$

Where r_i is the recovery rate, K_i is the biomass proportion of longevity class i in the total community, T_m is the trawling intensity and d_m is the depletion rate of métier *m*. The PD method assumes that there are no interactions between longevity classes and ignores differences in carrying capacity across grid cells.

Recovery time

Based on the population dynamic model, the recovery time t (years) from the impacted status (B0) to B_t=0.9K (Pitcher et al., 2017) is numerically estimated by simulating the community biomass in monthly steps for 50 yr and 100 longevity classes *i* of one year by [6].

$$B_t = \sum_i K_i \frac{B_0}{B_0+(K_i-B_0)\exp{(-r_i t)}} \qquad [6]$$

Model parameterisation

The parameters of the cumulative biomass – longevity relationship used in equations [1, 2, 3] are taken from Rijnsdorp et al. (2018) (Table SM1). The relationship was estimated from the longevity composition of the benthos in 790 box-core and grab samples collected at 401 stations in the North Sea and English Channel. A longevity class (<1, 1-3, 3-10, >10 yr) was assigned to each taxon, or the closest higher level, according information compiled by Bolam et al. (2014). The logistic regression was fitted through the observed cumulative biomasses B_1, B_3 and B_{10} and the observed habitat parameters measured at each station. Station and replicates nested within station were included as random effects to take account of the dependency of the cumulative biomass proportions within a sample.

Recovery rate is a function of longevity estimated from a meta-analysis of available literature (Hiddink et al. 2019): *r* x longevity = 5.31 (upper 95% cl = 11.43, lower 95% cl = 2.43).

Empirical estimates of depletion rates are available from a meta-analysis by Hiddink et al. (2017) for otter trawls (median: 0.06; 5%-95% range: 0.02 - 0.16), beam trawl (median: 0.14; 5%-95% range: 0.07 – 0.25) and dredge (median: 0.20; 5%-95% range: 0.13 – 0.30), but not for the different otter trawl métiers, seines and brown shrimp beam trawl. Because the depletion rate scales with the penetration depth of the gear (Hiddink et al., 2017) the depletion rate of the different otter trawl métiers and seines was estimated using the width of gear elements that penetrate into the seafloor relative to the total gear width (termed subsurface ratio SSR *sensu* Eigaard et al. (2016). The subsurface ratio of the standard otter trawl was set equal to the mean subsurface ratio of all otter trawl métiers weighted over their swept area (ratio = 0.18)(Table 1). The depletion rates of each otter metiers *m* were then estimated by 0.06* SSR_m / 0.18. The depletion rate of the SDN was set at the lowest depletion rate estimated of the otter trawls (OT_SPF = 0.009). Although the TBB_CRU is a beam trawl, the depletion rate was assumed to be similar to the reference otter trawl because it only has a light bobbin ground rope and no tickler chains.

Responsiveness of methods to trawling intensity.

The responsiveness of the impact assessment methods to trawling intensity is analysed by simulating the impact score for a random selection of grid cells by applying a range of trawling intensities between SAR = 0 to 50 yr^{-1}. The depletion rate was set at 0.06, typical for the otter trawl.

Trawling impact indicators

Impact. The trawling impact of all MBCG was assessed for each of the trawled grid cells and the mean impact was estimated for the total North Sea and for the main seafloor habitats. The trawling impact of métier *m* was estimated in two ways. First the impact was estimated against the untrawled reference: I_{ur} = Impact(T_m) with T_m representing the vector of trawling intensities by grid cell of métier *m*. Second, we estimated the impact of métier *m* against the trawled reference: I_{tr} = Impact(T_{MBCA}) - Impact(T_{MBCA}-T_m), with T_{MBCG} representing the vector of trawling intensities of all MBCG by grid cell.

Relative Benthic Status. The status of the sea floor is estimated as 1 –impact. Once a threshold value is set above which the impact is considered to threaten the good environmental status (GES) of the grid cell, the proportion of a region or habitat in GES can be calculated.

Recovery. Recovery is estimated as part of the PD method as the time (years) required for the benthic community biomass to increase from the impacted level (B_0) to 0.9K.

Trade-off impact and landings. The trade-off between impact and landings was analysed by comparing the landings per unit of effort (CPUE in kg.hour^{-1}) in each grid cell with the marginal impact due to an increase in trawling intensity of 1 year^{-1} assuming the catch rate will keep the same whatever the change in fishing intensity.

RESULTS

Responsiveness of indicators to trawling intensity.

Figure 2 shows that L1 is responsive to trawling intensities up to SAR=1 yr^{-1}. At a SAR = 0.5 yr^{-1}, the impact ranges between 0.85 and 1 with a median impact close to 1. L2 is responsive over a broader range of trawling intensities, but displays a wide variation across grid cells trawled that reflect the variation in bed shear stress. PD exhibits an almost linear response up to a trawling intensity of around 10 yr^{-1}. Beyond this level, the method's responsiveness reduces and eventually becomes insensitive for intensity above about 30 year^{-1}. In contrast to L1 and PD, the maximum impact estimated by L2 never reaches 1.

The impact scores estimated are strongly correlated across methods (Figure 3). This particularly applies to L1 and PD which has a Spearman rank correlation coefficient of r_{sp} = 0.97. The correlation between the L2 and the other methods is dependent on the level of shear stress. For grid cells exposed to a low level of shear stress (<0.1 N m^{-2}) the impact scores of PD and L2 are significantly correlated with a rank correlation coefficient of r_{sp} = 0.96. For grid cells exposed to a high shear stress (>0.5 N m^{-2}), the correlation breaks down to r_{sp} = 0.12.

Assessment of mobile bottom contacting gears

Trawling footprint

Activities of MBCG show a patchy distribution (Figure 4 top panels). Areas with trawling intensities exceeding 1 yr^{-1} are distributed all over the North Sea whereas low trawling areas mainly occur in the western part of the North Sea. The trawling footprint, representing the proportion of the available surface area trawled at least once in a year, is estimated at 60% of the sea floor between 0-1000 m and is trawled at an average intensity of 2.77 yr^{-1} (Table 3). Trawling is recorded in 90% of the 1x1 min grid cells. This percentage includes cells which are only partly trawled during a single year.

The trawling pressure differs across habitats (Table 3). Mud is the most intensively trawled habitat with both the highest proportion of the mud habitat surface area trawled (footprint = 0.87) and a high trawling intensity (SAR within the footprint = 3.05), while coarse sediments have the smallest footprint (0.50) and trawling intensity (SAR = 2.53). Sand, the dominant habitat type in the North Sea, has an intermediate footprint (0.64) and trawling intensity (SAR = 2.67). Mixed sediment has a relatively small footprint (0.59), but the highest trawling intensity (SAR = 4.20). Other habitats, mainly deep-sea muddy sand and mud, have an average trawling intensity (3.0) but a small footprint (0.37). The subsurface trawling intensities show relatively small differences between habitat types, with the exception of a low subsurface trawling intensity in other sediment (0.39). The level of trawling aggregation, as reflected by the percentage of the trawled grid cells where 90% effort occurs, does not differ much between habitat types (39-50%). However, trawling aggregation in mud is low with 90% of the trawling effort being deployed in 64% of the area, this means that mud habitat is not only impacted most heavily by trawling, but has also the longest recovery time to rebuild the biomass to 90% of its untrawled state (Table 3).

Trawling impact and status

Although the absolute impact scores differ between methods, they all show a relatively high impact along the Norwegian trench and parts in the central and northern North Sea where the longevity of fauna is high and natural disturbance low, and a low impact in the western North Sea (Figure 4 middle and bottom panels). Impact scores for the southern North Sea differ between methods. L1 and PD show relative high impact scores whereas L2 show a low impact.

The impact and areal extent of the impacted areas covary and differ between habitats (Table 3). Muddy sediments were impacted most with a habitat footprint of 87% that is trawled at an average rate of 3 year^{-1}. Mixed sediments was the second most impacted habitat. The habitat footprint of 59% was relatively low, although trawled at a high intensity of 4.2 yr^{-1}. Sandy sediments was the third most impacted habitat with a habitat footprint of 64% trawled 2.7 yr^{-1}, followed by coarse sediments with a habitat footprint of 50% trawled 2.5 year^{-1}.

The areal extent of the seafloor above or below a given status is shown in Figure 5. During the study period about 15% of the trawled grid cells were fished at an intensity that allows 95% of the benthic community to reach its life span without being disturbed by trawling (method L1). This was higher for coarse (20%) and mixed sediments (18%) but substantially lower for sand (10%) and mud (<2%). Trawling reduced the relative benthic status (RBS) in muddy sediments to <0.8 in 80% (L2) and 40% (PD) of the trawled grid cells. The RBS of mixed sediments was reduced to <0.8 in 55% (L2) and 20% (PD) of the trawled grid cells. The RBS of sandy sediments was reduced to <0.8 in 40% (L2) and 20% (PD) of the trawled grid cells. In coarse sediments RBS was reduced to <0.8 in 20% (L2) and 10% (B) of the trawled grid cells.

Recovery time

The estimated recovery time to 0.9K is less than one year in large parts of the North Sea (Figure 4). Recovery times between 1 and 5 years occur in discrete regions of high impact that are spread over the North Sea. Recovery times exceeding 5 yr occur in areas along the Norwegian trench.

Trade-off impact and landings

Bottom trawling is mostly aggregated in a relatively small part of the footprint (core fishing grounds), while the rest of the fishing effort is spread out over a large part of the sea floor (peripheral grounds). Figure 6a shows how trawling effort accumulates over the grid cells that are sorted from high to low trawling effort. The three vertical lines show examples of the distinction between core and peripheral fishing grounds based on an arbitrary criterion of effort aggregation of 50%, 75% and 90%. By plotting the corresponding status and recovery time of the grid cells in Figure 6b and Figure 6c, we can evaluate the differences in status and recovery time of core and peripheral grounds. For instance, if we arbitrarily define the core fishing grounds as those grid cells where 90% of the fishing effort occurs, core fishing grounds cover just over 40% of the grid cells (dashed line in Figure 6a). The corresponding RBS of the grid cells of the core fishing grounds ranges between 0 and 0.95 (Figure 6a,b) and the recovery time ranges between 0 and 10 years (Figure 6c). The peripheral fishing grounds, which receive 10% of the fishing effort, cover almost 60% of the trawled grid cells and have a RBS between 0.6-1 (L2) and 0.8-1 (PD). The recovery time of peripheral grid cells with a RBS < 0.9 is less than a few months.

The marginal impact, defined as the change in impact following an increase in trawling intensity of 1 yr^{-1}, in the intensively trawled grid cells is small compared to that in the less intensively trawled or untrawled grid cells. Figure 7a presents an example of the otter trawl métier targeting a mix of fish species (OT_MIX_1). The marginal impact increases with a RBS up to a level of 0.4 and thereafter levels off. The variability in marginal impact within a RBS bin reflects the differences in sensitivity of the benthos. The annual landings per swept area per grid cell (CPUE) is highly variable. Expressed per unit marginal impact, the CPUE –

marginal impact ratio is related to the status of the grid cell with highest values in low status grid cells (Figure 7b). Results of each métier are presented in the Supplementary Material.

Assessment by métier

Bottom trawling in the North Sea is dominated by otter trawl gears with a total area swept of 586 x 10^3 km^2, followed by seines (277 x 10^3 km^2), beam trawlers (94 x 10^3 km^2) and dredges (1.7 x 10^3 km^2) (Table 4). The fly shooters (SSC) and otter trawlers targeting demersal fish (OT_DMF) have the largest effort when expressed as area swept, whereas the otter trawlers targeting fish and crustaceans (OT_MIX_1) and the beam trawl fishery targeting flatfish (TBB_DMF) are the dominant gears in terms of fishing hours.

Métiers differ in their habitat association (Table 4). Scallop dredgers (DRB_MOL) operate in sediments characterised by a relatively high gravel content and high bed shear stress, while otter trawls targeting crustaceans (OT_CRU) operate in muddy sediments and a low bed shear stress in deeper waters. Seines are towed in sandy sediment at low (SDN) or intermediate (SSC) bed shear stress. Beam trawls targeting flatfish (TBB_DMF) or brown shrimps (TBB_CRU) operate in sandy sediments in relatively shallow waters and high bed shear stress.

An overview of the distribution and impact of each métier is given in the SM2-SM11. The trawling footprint varies across métiers and is largest for OT_DMF and OT_MIX_1. The trawling intensity within the footprint varies among métiers between 1.05 and 3.35 and is highest in the two seine métiers (SDN, SSC). The level of aggregation of effort ranges between 45% and 57% for most métiers, with the exception of the beam trawl fishery for brown shrimps, which have a high level of aggregation (29%), and the fly shooters, which have a low level of aggregation (78%).

The impact of each métier is assessed within its footprint (Table 4). Since the footprint of the métiers differ substantially, we also estimated the impact for a fixed reference area comprising of all grid cells trawled by MBCG, thus including grid cells that were not trawled by the considered métier (Figure 8). The results show that the impact estimated with L2 and PD methods are correlated. For both methods, the highest impact scores are estimated for OT_CRU and OT_MIX_1, followed by TBB_DMF and OT_DMF, OT_MIX_2 and SSC, TBB_CRU and by DRB_MOL, OT_SPF and SDN. The L2 impact scores of OT_DMF and OT_MIX_2 are relatively higher than their respective PD scores, due to their association with deeper waters and the higher sensitivity of the benthos, but only when assessed against the untrawled reference.

Expressed per unit of landings, OT_CRU and TBB_DMF have the highest impact, followed by SSC and OT_MIX_1 (Figure 9). The rank of the impact – landing ratio is not affected by the assessment method except for SDN, which has a zero impact score according to L2 because the gear does not disturb subsurface sediments.

DISCUSSION

Impact assessment framework

We used three complementary methods to assess the impact of bottom trawling on seafloor habitats. The methods are interrelated as they are based on the same macrofaunal longevity composition. The impact scores are, therefore, correlated, but differ in their responsiveness to trawling. L1 is most sensitive for low trawling intensities and gives information on the proportion of the sea floor that is unimpacted by trawling. Application of this method would result in a high level of benthic protection as it assumes that all species are sensitive to trawling, and that all individuals of a species need to live to their maximum longevity. L2 takes account of the effect of natural disturbance (bed shear stress) and is, therefore, less sensitive to trawling impact in habitats exposed to relatively high natural disturbance such as in the southern North

Sea. Finally, the PD method is a mechanistic model based on the logistic population growth equation that is commonly applied in ecology and fisheries.

The PD method has several advantages over the other methods. First, it is sensitive over a broader range of trawling intensities (L1 between 0 – 1 yr^{-1}; L2 between 0 - 5 yr^{-1}; PD between 0 to 10-30 yr^{-1}) which is more aligned with the range of trawling intensities observed (Eigaard et al., 2017; Amoroso et al., 2018a). Second, the method can differentiate between gears that differ in depletion rate in relation to the sediment penetration depth of the gear. The penetration depth can be estimated at lower cost and higher accuracy as compared to the estimation of the benthic depletion rates from biological sampling (Hiddink et al., 2017; Sciberras et al., 2018). Finally, the depletion and recovery parameters required for the PD method were derived from the globally available trawl impact studies (Hiddink et al., 2017; Sciberras et al., 2018). The method, along with its parameter estimates, are therefore applicable globally, although the recovery rates are still dependent on the longevity composition of the benthic community estimated for the North Sea that require further validation for a broader range of benthic biota and areas (Rijnsdorp et al., 2018; ICES, 2018).

A good indicator to assess good environmental status (GES) for the seafloor under D6 of the MSFD is one that tracks biodiversity, structure and function of the benthic community (ICES, 2016; ICES, 2017). While the three methods presented here have been demonstrated to identify functional responses to trawling across different habitats (from mud to coarse sediments), we did not set out to explicitly test whether biodiversity or assemblage structural changes respond. It is widely known, however, that macrofaunal assemblages vary depending on sediment type across the North Sea (Heip and Craeymeersch, 1995; Duineveld et al., 1991; Barrio-Frojan et al., 2012). Moreover, Bolam et al. (2014), based on a range of traits, ranked the dominant taxa across the North Sea according to their sensitivity to trawling, identifying a number of worm (e.g., Spintheridae, Aphroditae), mollusc (e.g., Llamellariidae) and echiurans to be the most sensitive. It is these inherent differences in trawling sensitivities, combined with the habitat-specificity of macrofaunal organisms, which leads to the different indicator responses we observe between mud and coarse sediments here. RBS, as estimated by the PD method, incorporates information on the total biomass which relates to functioning of ecosystems, and the relative abundance of different longevity classes, which relates to the structure and biodiversity. The L2 method, however, only incorporates information on structure and biodiversity and is therefore less likely to be a good indicator of function. The PD method, therefore, can be recommended as the most promising method to assess the trawling impact across soft sediment habitats. A slight variation of the PD method has recently been applied successfully to assess the RBS in 24 regions around the world (Pitcher et al. under review; Mazor et al., 2017). For the protection of highly valuable and sensitive species, such as VME’s or localised biogenic habitats, a more targeted, species-specific assessment is required such as the incorporation of species distribution modelling and the monitoring of important benthic habitats.

Impact of current fisheries on the status and functioning of the benthos

Our analysis shows that about 10% of the North Sea grid cells were not trawled during the study period, whereas about 15% of the trawled grid cells were trawled at an intensity that allows 95% of the benthic community to reach its life span (L1). In the remaining area, the proportion of the seafloor where trawling reduced the status of the benthos below 90% of the unimpacted state is estimated at about 60% (L2) and 40% (PD).

Differences in trait dominance between the habitats contribute to differences in sensitivity to trawling (Bolam et al., 2014, 2017; Foveau et al., 2017). Muddy habitats are impacted most because of a combination of high trawling intensity and large proportion of habitat affected, despite the relatively lower sensitivity of the benthos due to fewer long lived biota and deeper living species (Bolam et al., 2017; Rijnsdorp et al., 2018). Although a relatively large proportion of the mixed sediments habitat is unimpacted, the combination of a high trawling intensity and higher sensitivity of the benthos due the larger proportion of long-lived biota found within this habitat, is responsible for elevated impact levels. Coarse sediment is least impacted due to the combination of a relative low trawling intensity and the relatively low sensitivity of the benthos. Coarse sediments mainly occur in dynamic areas (high bed shear stress) that are dominated by mobile, shorter living species (Breine et al., 2018), which are less sensitive to trawling (van Denderen et al., 2015a; Foveau et al., 2017). The relatively high impact estimated for muddy and mixed habitats is in agreement with estimates for other areas of the world (Pitcher et al. under review).

Of the 10 métiers considered in the current assessment, those with the highest impact are the otter trawl fisheries for Nephrops and Pandalus (OT_CRU) and the otter trawl for mixed demersal fish and crustaceans (OT_MIX_1), followed by the otter trawl fisheries for mixed demersal fish (OT_DMF) and beam trawl fishery for flatfish (TBB_DMF). Lowest impact is estimated for DRB_MOL, OT_SPF, SDN and TBB_CRU, while SSC and OT_MIX_2 have an intermediate impact. The high impact métiers are characterised by a either a large footprint or a high depletion rate and high proportion of subsurface abrasion. The low impact of the DRB_MOL fishery, which may seem surprising given the high depletion rate (Hiddink et al., 2017), can be explained by the low trawling intensity and small footprint in areas with relative high shear stress. Lambert et al. (2017) indeed showed that the shallow waters in the Irish Sea to be resilient to scallop dredging.

Mitigating trawling impact

Because trawling is highly aggregated, the impact of trawling occurs mainly in the core fishing grounds where 90% of all effort occurs in less than 50% of the grid cells. In the peripheral areas, impact is generally low and the benthos can recover within one year.

Due to the non-linear relationship between trawling intensity and impact, the first trawling event has a larger impact than subsequent events (Duplisea et al., 2002; Hiddink et al., 2006). Indeed, the marginal impact in the core fishing grounds is lower than in the peripheral grounds or in untrawled areas, whereas the ratio of the median CPUE per unit of marginal impact was slightly higher. These results corroborate the findings of other studies (e.g., Jennings et al., 2012) which imply that a shift of fishing effort from the core to the peripheral grounds will result in a larger impact than a shift of effort from the peripheral to the core fishing ground.

Uncertainty and possible bias in trawling impact scores

Trawling pressure

With the exception of vessels below 12 m operating mainly in coastal waters for which VMS data were lacking, the trawling pressure estimates presented here are based on an adequate sampling of the gear dimensions, required to estimate the swept area, and high VMS coverage of the fishing fleets (Eigaard et al., 2016; 2017). Due to the heterogeneous distribution of bottom trawling, impact may be overestimated if assessed on a coarse spatial scale (Amoroso et al., 2018b; Kaiser, 2019). Even at the fine scale of 1 min longitude x 1 min latitude used in this study, we may slightly overestimate the footprint and impact as trawling was shown to be randomly distributed at this scale for most grid cells when assessed over a relatively short time period of a few years (Rijnsdorp et al., 1998). If the trawling events are randomly distributed within a grid cell, some parts will be trawled at a higher frequency and others at a lower frequency or not at all. Because the distribution is likely to become more uniform when assessed over longer time periods (Ellis et al., 2014; Amoroso et al. 2018) our impact estimates will likely reflect the impact that can be expected over longer time periods.

Depletion rates

The gear-specific depletion rates estimated by the meta-analyses of Hiddink et al. (2017) and Sciberras et al. (2018) are rather variable and do not take account of the possible influence of habitat. Both the vertical distribution of benthos in the sediment and the penetration depth of the gears will differ between sediment types (Snelgrove, 1999; Paschen et al., 2000). Indeed, Pitcher et al. (submitted), who re-analysed the relationship between gear-depletion rates and penetration depths of trawl gear into different sediments, demonstrated that depletion was less in sand than in gravel and mud.

Depletion rates of the benthic community are currently available for only a few of the major gear types (otter trawl, beam trawl, towed dredge and hydraulic dredge), but not for the seines and for the different versions of the main gear types (Hiddink et al., 2017; Sciberras et al., 2018). Here we estimated gear specific depletion rates of the dominant métiers operating in the North Sea based on the subsurface proportion of the footprint as a proxy of the relative penetration of the gear (Eigaard et al., 2017). Although these estimates are necessarily crude, we consider them to be an improvement to impact estimates using the depletion rate of the main gear type. Within the group of otter trawl métiers, there is a more than 10-fold difference in subsurface ratio of OT_CRU and the OT_SPF (Eigaard et al., 2016). The depletion estimates of the seines and crustacean beam trawl are uncertain because estimates of the depletion rates or penetration depth are presently unavailable. We assumed that the depletion rate of the seines was similar to the otter trawl after taking account of the subsurface ratio of the seines relative to the main otter trawl type. For the TBB_CRU we assumed the depletion rate to be similar to the main otter trawl type, which may be too high since the bobbin ground rope of the gear is relatively light (Tulp et al., 2020).

The uncertainties around the estimates of the subsurface ratio of the métiers, and the depletion rates inferred from these, affect the results of the L2 method. Here, the low impact estimated for the Danish seine (SDN) may be an underestimate since we used a subsurface ratio of zero. This implies that, according to L2, this métier will not have an impact on the benthic community. Future studies of the penetration profile of different type of bottom trawls, such as that conducted by Depestele et al. (2018), will provide important information to reduce uncertainty in impact estimates. Numerical models (O'Neill and Ivanović, 2016) may also be used to predict penetration depth and the gear-specific depletion rates based on the relationship with the penetration depth (Hiddink et al., 2017).

Habitat-specific longevity composition

Impact estimates of all three methods are affected by the uncertainty in the habitat-specific longevity composition of the benthic community which is estimated here using data from box core and grab samples taken in the English Channel and North Sea (Bolam and Eggleton, 2014; Rijnsdorp et al., 2018). Whether the model can be extrapolated to other European areas remains to be tested. In addition, box core and grabs effectively sample the macrofauna but under-represent the larger epi- and megafauna (Bergman and Van Santbrink, 1994; Bergman and van Santbrink, 2000). Since longevity scales with body size (although with a large variation around the relationship), the underrepresentation of larger animals within our assessments will underestimate the proportion of long-lived animals in the benthic community. Only a few samples were available for deeper areas in the northern and eastern North Sea which are characterised by low bed shear stresses. Although a recent analysis of the benthic community longevity composition in the neighbouring Kattegat corroborated the longevity composition estimated here for the North Sea (van Denderen et al., 2019), further studies are needed to validate the relationship and test it’s applicability in other sea areas.

Uncertainty in the recovery rate and gear-specific depletion rate also contribute to the uncertainty in estimates of the PD method (Pitcher et al., 2017; Hiddink et al., 2019). Because the recovery rate is estimated from the relationship with longevity, which showed substantial variation among taxa (Hiddink et al., 2019), the uncertainty in the recovery rate is determined by the uncertainty in the recovery – longevity relationship, as well as the uncertainty in the habitat specific longevity composition (Rijnsdorp et al., 2018).

As discussed above, further studies are needed to test the relationships for other sea areas and a broader range of seafloor habitats (ICES, 2018).

Future prospects

Although our impact estimates should be considered to be a first approximation, the methodology used to underpin them nevertheless provides important information that can be used to monitor changes in trawling impact in response to management, compare trawling impact across gears, compare trawling impact across habitats and assess the consequences of different management scenarios to mitigate the trawling impact. McConnaughey et al. (2020) reviewed various management scenarios to mitigate the impact of bottom trawling. Spatial management measures may be used to shift effort from peripheral to core fishing grounds, either through closed areas to fishing or a habitat credit system (Holland and Schnier, 2006; Batsleer et al., 2018). High impact gears may be excluded from more sensitive habitat types to lower impact, e.g. the removal of scallop dredges from mixed sediments with cobbles (Boulcott et al., 2014). Semi-pelagic otter boards, developed to reduce fuel cost, will also reduce the penetration profile and depletion rate of the gear. Replacing mechanical stimulation in beam trawl fisheries for flatfish by electrical stimulation reduce the trawling footprint and penetration profile taking account of the change in the distribution pattern over the seafloor habitats (Rijnsdorp et al., 2020). The assessment frameworks presented here can be used to quantify the contribution of different scenarios and technological innovations and guide management decisions to mitigate the trawling impact on the benthic ecosystem.

The methodologies build on mechanistic quantitative knowledge of how various bottom trawls affect the benthos (Eigaard et al., 2016a; Hiddink et al., 2017), including biological principles of mortality, reproduction and growth (Hiddink et al., 2017; Pitcher et al., 2017) and habitat specific patterns in the longevity composition of the benthic community and population growth rate (Rijnsdorp et al., 2018; Hiddink et al., 2019). The methods are parameterised based on empirical data which can be updated as additional information becomes available. As such, once the initial assessments are conducted for a region, experts working on the methods can contribute towards improving the parametrization of the assessment using regional-specific data sets.

The continuous driver – response relationship allows the setting of reference levels for GES to be used in an annual assessment of the status of the sea floor. Once a reference value for GES is set, the surface area of the seafloor with a good status can be estimated and monitored. Coupled to an analysis of the impact of trawling of different subsets of benthos representing different ecosystem functions (Rijnsdorp et al., 2016; Mazor et al., 2017), such as bioturbation or suspension feeding, an assessment of the trawling impact on ecological functions may be achieved. As such, the methods lend themselves to a quantitative exploration (i.e. that can be directly related to *in situ* gradient studies) of different options for setting thresholds to inform management to defining “adverse effects”. In so doing, the methods contribute towards evidence-based management of human activity that exert pressures on the seafloor and its respective habitats, a feature which epitomises the fundamental philosophy of EBFM. The exploration of different management options and their respective trade-offs can be empirically-based rather than based on the expert opinion of a specific stakeholder group. This can be a critical step to initiate the required dialogue of how (and why) human activity of a specific group could be managed in relation to ensuring seafloor integrity.

As the assessment of pressure and impact of fishing is done at a fine scale based on local environmental conditions (depth, bottom shear stress, grain size, etc.), individual scores can be aggregated up and reported for larger management units (e.g. EEZs, regional/subdivision scale, or MSFD broad habitat type). This flexibility across scales, coupled with the quantitative nature of the methods, ensures that they can provide an overarching regional approach that also allows benchmarking of other national assessments against regional assessment, thereby providing further consistency across assessments.

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Figure 1. Impact assessment framework showing how the information on the trawling pressure is combined with information on the habitat characteristics of the seafloor and information on the sensitivity of the benthic community to derive indicators of fishing pressure and benthic impact.

Figure 2. Pressure – response curves for the trawling impact assessment methods L1, L2, PD for a representative sample of habitat conditions in the North Sea. Hatched line shows the median impact scores. Coloured areas show the 1%-99% (light blue), 5%-95% (medium blue) and 25%-75% (dark blue) range of impact scores. Please note different scales on the x-axes.

Figure 3. Scatter plots of impact scores of grid cells estimated by methods L1, L2, PD and the spearman rank correlation coefficient. Only every 100th observation is plotted

Figure 4. Mean annual trawling intensity (swept area ratio) at the surface (SAR) and subsurface (SUBSAR) and its impact according to the methods L1, L2 and PD. For the PD approach the decrease in biomass relative to the untrawled state and the time (years) required to recover the biomass in absence of trawling to 0.9K (Recovery) is shown.

Figure 5. Relative benthic status as a function of the cumulative proportion of the grid cells trawled by mobile bottom contacting gears (MBCG), showing the proportion of the sea bed above or below any given status as determined by the methods L1, L2 and PD. Grid cells are sorted from low to high trawling effort. Results are shown for the main habitat types (coarse, sand, mud, mixed) and for all habitats together (all).

Figure 6. (a) Cumulative trawling effort (swept area); (b) grid cell status according method PD; (c) recovery time of status to 0.9K, in relation to the proportion of grid cells sorted from high to low fishing effort. Vertical lines separate the core parts of the trawled grid cells at 50% (-.-.-.), 75% (....) and 90% (----) of the fishing effort from the peripheral part of the trawled grid cells.

Figure 7. The marginal impact (left) and $\log_{10}$(cpue/marginal impact) ratio by grid cells (right) in relation to the biomass status for metier OT_MIX_1. The marginal impact was estimated with the PD method as the increase in trawling impact due to an increase in trawling intensity of 1 year^{-1}.

Figure 8. Scatter plot of L2 and PD impact scores by metier against the untrawled reference (a) and trawled reference (b). Impact scores are estimated for all grid cells trawled by mobile bottom contacting gears (MBCG) in the North Sea (0-1000 m).

Figure 9. Impact per unit of landings of the ten metiers according the L2 and PD method. Impact scores refer to the untrawled reference