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The footprint of bottom trawling in European waters: distribution, intensity, and seabed integrity

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Mapping trawling pressure on the benthic habitats is needed as background to support an ecosystem approach to fisheries management. The extent and intensity of bottom trawling on the European continental shelf (0–1000 m) was analysed from logbook statistics and vessel monitoring system data for 2010–2012 at a grid cell resolution of 1 × 1 min longitude and latitude. Trawling intensity profiles with seabed impact at the surface and subsurface level are presented for 14 management areas in the North-east Atlantic, Baltic Sea and Mediterranean Sea. The footprint of the management areas ranged between 53–99% and 6–94% for the depth zone from 0 to 200 m (Shallow) and from 201 to 1000 m (Deep), respectively. The footprint was estimated as the total area of all grid cells that were trawled fully or partially. Excluding the untrawled proportions reduced the footprint estimates to 28–85% and 2–77%. Largest footprints per unit landings were observed off Portugal and in the Mediterranean Sea. Mean trawling intensity ranged between 0.5 and 8.5 times per year, but was less in the Deep zone with a maximum intensity of 6.4. Highest intensities were recorded in the Skagerrak-Kattegat, Iberian Portuguese area, Tyrrhenian Sea and Adriatic Sea. Bottom trawling was highly aggregated. For the Shallow zone the seabed area where 90% of the effort occurred comprised between 17% and 63% (median 36%) of the management area. Footprints were high over a broad range of soft sediment habitats. Using the longevity distribution of the untrawled infaunal community, the seabed integrity was estimated as the proportion of the biomass of benthic taxa where the trawling interval at the subsurface level exceeds their life span. Seabed integrity was low (<0.1) in large parts of the European continental shelfs, although smaller pockets of seabed with higher integrity values occur. The methods developed here integrate official fishing effort statistics and industry-based gear information to provide high-resolution pressure maps and indicators, which greatly improve the basis for assessing and managing benthic pressure from bottom trawling. Further they provide quantitative estimates of trawling impact on a continuous scale by which managers can steer.

Keywords: benthic impact, bottom trawl, fishing pressure, indicators, Mediterranean Sea, Northeast Atlantic, seabed habitat, seabed integrity, trawling footprint, trawling intensity.

Introduction

Fishing is one of the dominant anthropogenic activities affecting marine ecosystems (Halpern *et al.*, 2008) and there is global concern about adverse effects of particularly bottom trawls on seabed habitats and the structure and functioning of benthic ecosystems (Dayton *et al.*, 1995; Jennings and Kaiser, 1998; Watling and Norse, 1998). These mobile, bottom-contacting gears have proven efficient for catching a range of fish and shellfish species and their use has increased globally since the 1950s (Valdemarsen, 2001; Watson *et al.*, 2006).

The continental shelf habitats along the European coasts are among the most productive fishing grounds for bottom-dwelling fish species and have already been trawled for centuries (Horwood, 1993; Kerby *et al.*, 2012; Bennema and Rijnsdorp, 2015). European bottom trawl fleets target a wide variety of species encompassing bottom-dwelling fish species, crustaceans and bivalves.

Bottom trawling will reduce the biomass and biodiversity of the benthic ecosystem, and may reduce the complexity of seabed habitats (Collie *et al.*, 2000b; Kaiser *et al.*, 2006; Buhl-Mortensen *et al.*, 2016) and affect the functioning and productivity of the benthic ecosystem (Jennings *et al.*, 2001; Hiddink *et al.*, 2011; van Denderen *et al.*, 2013; Pusceddu *et al.*, 2014) through a progression of state changes (Smith *et al.*, 2016). The ecosystem effects of bottom trawling will be determined by the type of gear deployed, the type of seabed, direct effects of the passage of a trawl, the footprint of the trawl and the trawling frequency and the sensitivity of the seabed and benthic ecosystem (Jennings *et al.*, 2005; Lucchetti and Sala, 2012; Rijnsdorp *et al.*, 2016).

In European waters, four main demersal towed gear groups can be distinguished: otter trawls, seines, beam trawls, dredges. These groups can be further broken up into métiers based on the target species (Eigaard *et al.*, 2016). The rigging of the gear used in these métiers (combinations of gear type and target species) is adapted to the specific target species and seabed habitats. For instance, to catch fish that show a herding response to the gear, fishers deploy long sweeps between the otter board and the net to increase the horizontal spread of the gear. Alternatively, twin otter trawls have been developed to increase the horizontal net opening without increasing the headline height and drag of the gear, which has proved to be an effective gear to target non-herded species like *Nephrops* and monkfish (Eigaard *et al.*, 2011). “Rock hopper” gears, where large rubber discs are fitted on the ground rope, have been introduced to trawl on rough grounds (Valdemarsen, 2001).

The differences in the gear characteristics between the métiers will lead to different benthic impacts. Otter trawls and seines mainly sweep the surface of the seabed, whereas shellfish or flatfish dredges and tickler chain beam trawls will penetrate deeper into the sediment (Buhl-Mortensen *et al.*, 2013; O’Neill and Ivanovic, 2016). For European fisheries, Eigaard *et al.* (2016) defined 14 different métiers and collected industry data on the characteristics and dimensions of individual gear-components to estimate whole-gear footprints of each métier on the seabed surface and subsurface level.

The mortality of benthic invertebrates imposed by the passage of a trawl is habitat specific and differs between benthic species groups and type of fishing gear. Collie *et al.* (2000a) and Kaiser *et al.* (2006) showed in their comprehensive reviews that the most severe impact occurred in response to scallop dredging in biogenic habitats, followed by beam trawls in sandy habitats and otter trawls in muddy habitats. In sandy sediments, deposit feeding macro-fauna were reduced by ~20% by beam trawls and otter trawls and 40% by scallop dredges, whereas suspension feeders were reduced by 70% by beam trawls, 45% by scallop dredges, and 5% by otter trawls. The recovery rate will depend on the life history characteristics, in particular the rate of reproduction and dispersal characteristics (Bolam *et al.*, 2014) and may be affected by environmental conditions such as temperature and hydrodynamics (Lambert *et al.*, 2014).

The continental shelf of European waters comprises a variety of seabed habitats. The European Nature Information System (EUNIS) has developed a generic and hierarchical habitat classification scheme (http://eunis.eea.europa.eu/index.jsp). Seabed habitat classifications are based on environmental variables that constrain biological communities, such as substrate type, energy level, depth, and light penetration. EUNIS habitat maps exist for several European Sea areas (http://www.emodnet-seabedhabitats.eu/default.aspx?page=1974), and therefore provide an appropriate starting point for the analysis of bottom trawling impacts on the benthic community. The EUNIS habitats classification reflects differences in sensitivities to trawling. In general, low energy habitats are rather stable and more vulnerable to trawling disturbances than habitats in high energy environments that are exposed to frequent natural perturbations (Hall, 1994). Poorly-sorted, gravelly or muddy sediments are more sensitive to bottom trawling, while well-sorted, sandy substrates are less sensitive (Bolam *et al.*, 2014).

The assessment of the impact of bottom trawling on the seabed and benthic ecosystem has been hampered by the lack of data on trawling effort at the appropriate resolution. It is well established that bottom trawling has a patchy distribution both in space (Rijnsdorp *et al.*, 1998; Pitcher *et al.*, 2000; Murawski *et al.*, 2005; Lee *et al.*, 2010) and time (Rijnsdorp *et al.*, 2011; Ellis *et al.*, 2014; van Denderen *et al.*, 2015a). Hence, for a proper assessment of the impact of bottom trawling on the seabed and benthic ecosystem, it is important to collect and analyse data at the appropriate scale (Piet and Quirijns, 2009). With the introduction of a satellite-based vessel monitoring system (VMS) as a surveillance and enforcement tool since the early 2000s, data have become available to study bottom-trawling effort at the appropriate spatial and temporal scale (Bastardie *et al.*, 2010; Lee *et al.*, 2010; Hintzen *et al.*, 2012; Gerritsen *et al.*, 2013).

The European Union adopted the Marine Strategy Framework Directive (MSFD) to more effectively protect the marine environment and aims to achieve good environmental status (GES) by 2020 (EC, 2008). Seabed trawling effects a wide range of habitats, environmental components and characteristics specifically defined in the MSFD (Smith *et al.*, 2016). The status of the marine environment, and the human pressures acting upon it, are described by eleven 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 (Rice *et al.*, 2012). In addition, indicators of fishing pressure have been proposed that are based on high resolution analysis of fishing effort to estimate the spatial extent of fishing and its impact on the seabed (Piet and Hintzen, 2012).

The objective of this article is to study the footprint of bottom trawling on the European continental shelf from the period 2010 to 2012 and compare it across management areas. Trawling distribution and intensity (calculated as swept area in a grid cell divided by surface area of a grid cell) is analysed at a resolution of 1 × 1 min longitude and latitude for different EUNIS habitat types and main gear groups, distinguishing between surface and subsurface footprints. Indicators of trawling pressure and seabed integrity are estimated and discussed in relation to the sensitivity of the seabed habitats.

Methods

Study area

The study area comprises the European continental shelf extending from the Barents Sea and Norwegian Sea in the north to the Mediterranean Sea in the south. Bottom trawling was summarized by ICES and FAO fisheries management areas (Figure 1).

Seabed habitat

EUNIS Level 3 seabed habitat information is available for a substantial part of the European continental shelf, but does not cover all the regions where bottom trawling takes place (http://www.emodnet-seabedhabitats.eu/default.aspx?page=1974). Therefore it was necessary to produce EUNIS-equivalent habitat maps, modelled from data of sediment and bathymetry, for the Barents Sea, the Norwegian Sea and the eastern Mediterranean, which, together with regional habitat maps of downloaded EUNIS data, form the basis of the further analyses (Figure 2). Habitat types with a small surface area were combined into larger classes with similar energy level or bathymetric condition and management areas were summarized separately within the Northeast Atlantic and the Mediterranean (Table 1). For the Norwegian Sea (IIa, IIb) and areas west and south of Ireland (VIIb–c, VIIj–k), habitat information was missing for a substantial part of the area.

Sublittoral sediments (A5), with sediment ranging from boulders and cobbles, through pebbles and shingle, coarse sands, sands, fine sands, muds, and mixed sediments, contribute 81.6% of the seabed in the Shallow zone in the Atlantic and 93.4% in the Mediterranean (Table 1). Infralittoral rock (A3) and circalittoral rock (A4), with a substrate of bedrock, clay, hard, non-mobile boulders or cobbles, contribute 4.5 and 1.1%, respectively, and the surface area of deep seabed (A6) contributes 1.9 and 3.0%. Within A5, sublittoral sandy (A5.2), or muddy sediments (A5.3) dominate the seabed in both the Atlantic and the Mediterranean. Coarse (A5.1) or mixed sediments (A5.4) are important in the Atlantic bathyal zone (12.7 and 11.4%) and sublittoral macrophyte-dominated sediment (A5.5) and sublittoral biogenic reefs (A5.6) in the Mediterranean (11.2 and 12.0%). In the Deep zone the seabed is largely dominated by deep sea mud (A6.5) in both the Atlantic [32.5% (53.4% unknown)] and the Mediterranean (96.3%) (Table 1).

Fishing effort and landings

The European fishing effort with mobile, bottom-contacting gears was analysed by the 14 métiers defined by Eigaard *et al.* (2016) for two depth zones (Shallow 0–200 m; Deep 201–1000 m). The gear-footprints of each métier are quite different and these differences are an integral part of the calculated fishing intensities at the surface and subsurface level, respectively. For presentation purposes, however, footprint results will be aggregated and only presented for the total bottom trawl fleet and for the four major gear groups: otter trawls, demersal seines, beam trawls and dredges.

Although VMS data were available for the period 2010–2012 for most of the European countries, some countries were missing, so that bottom trawling will be underestimated in the Bay of Biscay and the western Mediterranean Sea, and to a lesser extent in the Celtic Sea (Table 2), due to the lack of data from France and Spain. Also the absence of Polish and Finnish data leads to an underestimation in the eastern Baltic. In the Adriatic Sea, the lack of data from the former Yugoslavian countries will only have a small effect as bottom trawling outside their territorial waters is almost negligible (Scarcella *et al.*, 2014). To estimate the coverage of our data in the Atlantic (FAO area 27), a comparison was made between the total international fishing effort of demersal trawls, seines and dredges during 2010–2012 (measured in units of kWh of vessels of at least 12 m length as recorded in the STECF annual Evaluation of Fishing Effort Regimes in European Waters; https://stecf.jrc.ec.europa.eu/reports/effort) and the fishing effort of the bottom trawl métiers covered by our study (effort with vessels of at least 12 m length from countries having provided VMS and logbook data) (Supplementary Materials). For management areas I, IIa, IIb, Vb, and VIb1 information for total international effort was incomplete. Coverage was estimated using the ratio of the demersal landings of the sampled countries to the total demersal landings reported to ICES (http://www.ices.dk/marine-data/dataset-collections/Pages/Fish-catch-and-stock-as

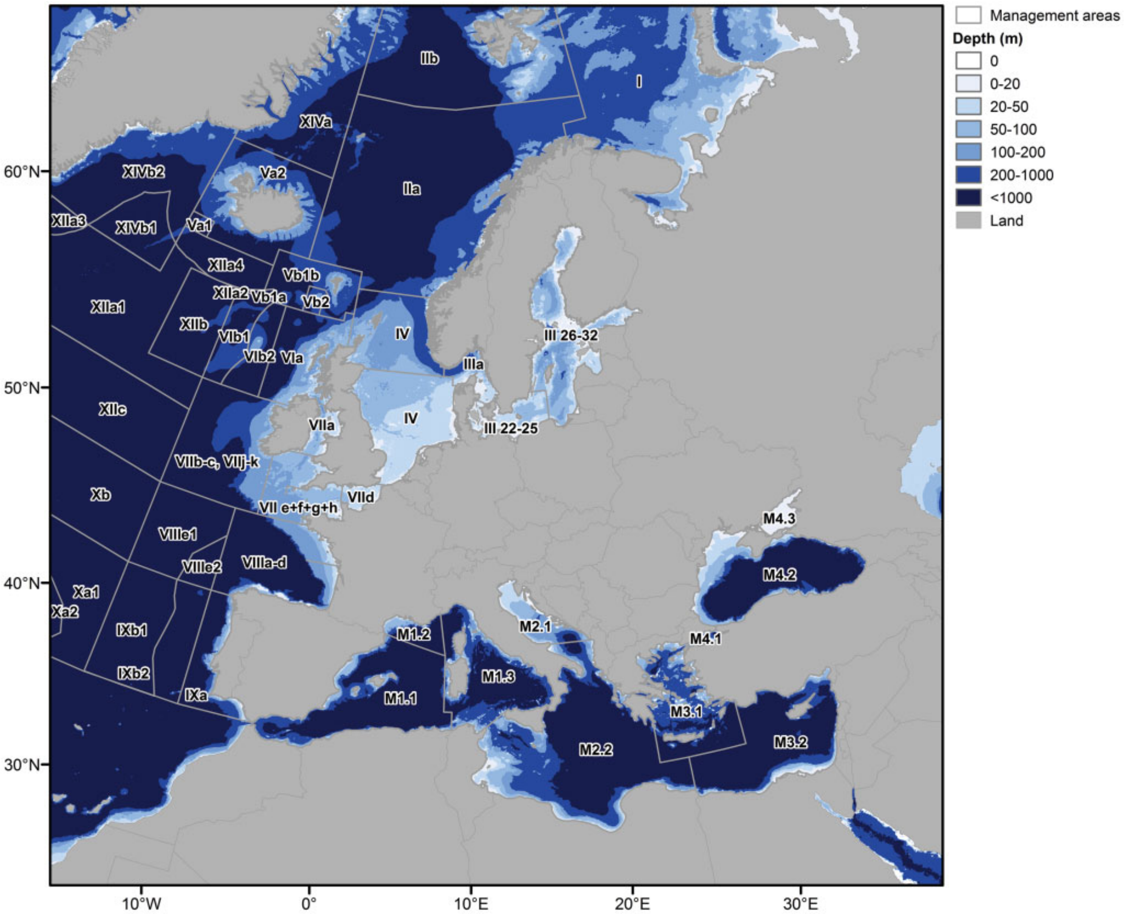

Figure 1. The ICES (www.ices.dk) and FAO (www.fao.org/gfcm) management units and bathymetry of the case study area. The bathymetry layer is obtained from the general bathymetry chart of the oceans (gebco.net; GEBCO one-minute grid, last updated in 2008) downloaded from the British Oceanographic Data Centre.

sessment.aspx). For the relevant Mediterranean areas (M1.3, M2.1, M2.2, and M2.3) information for total effort by country and vessel size was obtained from Sala and Damalas (2015) to provide estimates of the coverage in the analyses. Landings of bottom trawlers from Italy and Greece refer to the years 2013–2014, which were the only years where landings data from all Mediterranean member states were available (Sala and Damalas, 2015).

Bottom trawl effort was well-represented by the sampled fleets in most of the management areas (Table 2). Coverage in the Shallow zone was excellent (≥95%) in the Skagerrak-Kattegat (IIIa), the North Sea (IV), the Northwestern Shelf (VIa), VIb2, and the Irish Sea (VIIa). Good coverage (≥60%) was obtained in the Norwegian Sea (IIa), the western Baltic Sea (III 22–25), the Southwestern Shelf (VIIb,c,j,k), the Channel (VIId), the Celtic Sea (VIIe,f,g,h), the Iberian Portuguese area [IXa (Management area IXa was confined to the area south of 42^{o} N)], the Tyrrhenian Sea (M1.3), the Adriatic Sea (M2.1) and the Aegean Sea (M3.1). Coverage was reasonable (≥50%) for the Ionian Sea (M2.2), and poor in the Barents Sea (I), northern Norwegian Sea (IIb), eastern Baltic Sea (III 26–32), west of Faroes (Vb), VIb1, and Bay of Biscay (VIIIa,b,c,d).

In the following, results for the management areas with less than good coverage (<60%) are only briefly presented and are not included in general analyses and comparisons of fishing pressure.

Analysis of trawling intensity

VMS data were coupled to logbook data for the years 2010–2012, based on methodology developed by Bastardie *et al.* (2010), Hintzen *et al.* (2012), Russo *et al.* (2014), and Maina *et al.* (2016). Individual logbook observations from 13 countries were assigned to 14 different functional gear groups (métiers) based on target species and gear type information (Eigaard *et al.*, 2016).

Relationships between gear dimensions and vessel size (e.g. trawl door spread and vessel power) for each métier (Eigaard *et al.*, 2016) were used to assign the swept-width of gear to each logbook trip. In addition to the total width of the gear used to estimate the surface impact, the subsurface impact was estimated based on information on the dimensions of the gear components that penetrate into the seabed (Eigaard *et al.*, 2016).

The extended logbook data were combined with interpolated vessel tracks from VMS data (Hintzen *et al.*, 2010). In this way, the total seabed area swept by a given vessel and fishing gear over the 3-year period could be estimated taking into account the gear footprint of the métiers.

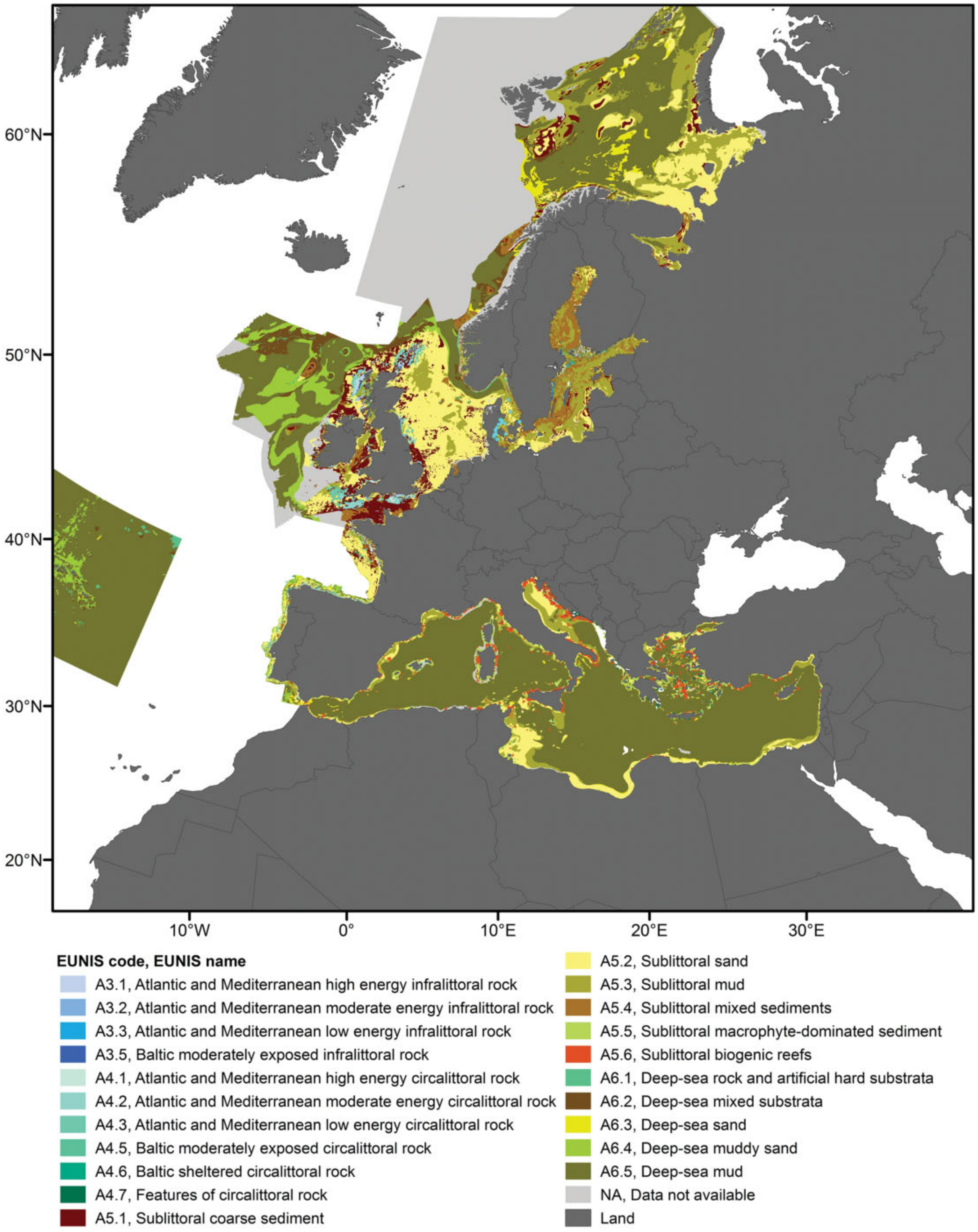

Figure 2. Habitat distribution of the case study area based on a) EUNIS Habitat level 3 and Baltic Habitat data downloaded from: http://www.emodnet-seabedhabitats.eu/default.aspx?page=1974) and b) habitat data information for Norwegian waters (provided by Institute of Marine Research, Bergen) and the eastern Mediterranean (provided by the Hellenic Centre for Marine Research) combined with bathymetric information to match EUNIS Habitats level 3 categories (data processing done by DTU Aqua).

Table 1. Percentage surface area of major EUNIS seabed habitats in the Northeastern Atlantic and the Mediterranean Sea.

Surface area (%)	**NE Atlantic**		**Mediterranean Sea**	
EUNIS habitat	0–200 m	201–1000 m	0–200 m	201–1000 m
A3, Infralittoral rock	0.91	0.00	0.00	0.00
A4, Circalittoral rock	3.56	0.02	1.10	0.11
A5.1, Sublittoral coarse sediment	12.68	0.09	0.00	0.00
A5.2, Sublittoral sand	36.36	0.19	36.05	0.09
A5.3, Sublittoral mud	21.12	0.25	34.07	0.40
A5.4, Sublittoral mixed sediments	11.43	0.14	0.02	0.00
A5.5, Sublittoral macrophyte-dominated sediments	0.00	0.00	11.22	0.82
A5.6, Sublittoral biogenic reefs	0.00	0.00	12.04	0.99
A6.1, Deep sea rock	0.01	0.26	0.00	0.00
A6.2, Deep sea mixed sediments	0.24	3.58	0.00	0.00
A6.3, Deep sea sand	0.32	2.63	0.72	0.69
A6.4, Deep sea muddy sand	0.18	6.94	0.00	0.00
A6.5, Deep sea mud	1.13	32.48	2.28	96.26
Unknown	12.05	53.42	2.49	0.65
Total (1000 km^2)	2215	3164	478	1990

Table 2. Total seabed area, yearly swept area, average trawling intensity, coverage (%) and landings of the fleets/countries included in this study by management area and depth zone. The landings were allocated in proportion to the effort by depth zone.

	Shallow zone (0–200 m)					**Deep zone (201–1000 m)**				
Management area	**Seabed area (1000 km^2)**	**Swept area (1000 km^2)**	**Intensity (year^{-1})**	**Coverage (%)**	**Landings sampled countries (1000 t)**	**Seabed area (1000 km^2)**	**Swept area (1000 km^2)**	**Intensity (year^{-1})**	**Coverage (%)**	**Landings sampled countries (1000 t)**
Barents Sea (I^1)	433	26	0.06	36^2	0.4	504	23	0.05	36^2	2.2
Norwegian Sea (IIa^1)	86	127	1.48	75^2	19.9	1304	119	0.09	75^2	20.1
North. Norwegian Sea (IIb^1)	201	50	0.25	40^2	3.0	648	22	0.03	40^2	3.6
West. Baltic Sea (III 22–25)	83	84	1.00	72	26.4					
East. Baltic Sea (III 26–32)	288	8	0.03	24	2.6	2	0	0.00		0.0
Skagerrak-Kattegat (IIIa)	41	147	3.63	100	24.5	14	36	2.56	100	7.1
North Sea (IV)	517	648	1.25	98	402.1	75	49	0.66	88	24.9
West of Faroes (Vb^1)	0	0		2^2	0.1	0	0	0.06	2^2	1.0
Northwestern Shelf (VIa)	105	55	0.52	100	17.5	124	9	0.07	56	9.3
West of Scotland (VIb1^1)	0	0	0.42	44^2	0.0	110	3	0.03	44^2	0.6
West of Scotland (VIb2^1)	6	6	1.04	99^2	0.0	100	3	0.03	99^2	4.1
Irish Sea (VIIa)	46	70	1.51	100	21.1	0	0	0.61		0.0
Southwestern Shelf (VIIbc, jk)	79	49	0.62	62	20.5	247	57	0.23	42	7.2
Channel (VIId)	32	57	1.78	60	12.4					
Celtic Sea (VIIefgh)	174	140	0.80	65	44.7	2	0	0.01	2	0.1
Bay of Biscay (VIIIa–d)	90	2	0.02	2	0.8	19	0	0.00	3	0.6
Iberian Portuguese area (IXa)	23	110	4.85	81^2	1.0	7	44	6.39	81^2	0.4
Tyrrhenian Sea (M1.3)	43	173	4.01	82^2	4.3	236	116	0.49	82^2	6.1
Adriatic Sea (M2.1)	36	303	8.50	72^2	26.6	2	6	3.12	72^2	0.9
Ionian Sea (M2.2)	41	141	3.45	53^2	5.5	318	70	0.22	53^2	19.5
Aegean Sea (M3.1)	52	87	1.65	75^2	1.5	205	51	0.25	75^2	3.8

1) Coverage estimated from contribution of the countries in the analysis to the total demersal landings reported in ICES data base; 2) Landings and percentage coverage were estimated for the depth zone 0–1000 m.

The area swept annually was estimated within grid cells of 1x1 minute longitude and latitude, which corresponds to ~1.9 km^2 at 56°N with cell size gradually increasing or decreasing the further south or north it is located. This grid cell size as a basis for the intensity calculations is consistent with results of previous studies showing that, at this resolution bottom trawling can be considered to be randomly distributed within a grid cell on an annual basis (Rijnsdorp *et al.*, 1998; Lee *et al.*, 2010) and become uniform at longer time scales (Ellis *et al.*, 2014).

The swept area estimations were performed at the national level using a standardized R workflow through a common web-based platform. Swept area estimates were subsequently combined across countries.

Indicators of trawling pressure

Four different indicators for trawling pressure, which relate to the EU Data Collection Framework indicators 5–7 (EC, 2008; Piet and

Hintzen, 2012; ICES, 2014), were estimated. The first indicator (I1; "Trawling footprint") shows the extent of bottom trawling, and reflects the proportion of the total seabed area (management area or habitat type) that is trawled annually during the three years of the analysis. Under the assumption of uniform distribution within grid cells the extent of bottom trawled was calculated in two ways: (i) percentage of the grid cells of a management area or habitat type (after standardization for differences in grid cell size) where any quantity of trawling has been recorded irrespective of its intensity; (ii) area of the seabed area trawled at least once a year. This first metric (i) includes the untrawled parts of grid cells where trawling intensity was less than once a year. The second metric (ii) was calculated as the sum of the surface area of the fully trawled grid cells (trawled $\geq$ 1 year^{-1}) plus the sum of the swept areas of partially trawled grid cells (trawled less than once a year). The first footprint calculation (i) acknowledges that our data (2010–2012) only covers a relatively short time-step. If a longer time step would be considered the untrawled parts of the grid cells would be increasingly likely to be trawled.

The second indicator (I2; "Trawling aggregation") reflects the seabed area where most of the trawling is concentrated. It is estimated as the smallest combined surface area of grid cells within which 90% of the trawling occurred in proportion to the total management area (Piet and Hintzen 2012). This area will also reflect the area where most of the catches will be taken.

The third indicator (I3; "Untrawled seabed") estimates the untrawled proportion of the seabed area as percentage of grid cells where no trawling was recorded.

A fourth indicator (I4; "Seabed integrity") evaluates the trawling intensity in the light of the sensitivity of the seabed to trawling impact. The indicator combines trawling intensity with the longevity distribution of the benthic community (Rijnsdorp *et al.*, 2016). The longevity distribution describes how the cumulative biomass (CB) of the community is distributed over the longevity classes, in other words what proportion of the benthic biomass is composed of taxa with a certain longevity. Assuming that the CB of the community has a log-linear relationship with the longevity of the taxa, we fitted a logistic regression CB $\sim\alpha+\beta$ ln(Longevity) through the CB proportions for longevity classes $<$1, $<$3, and $<$10 years observed in eight soft sediment study areas in the North Sea and Irish Sea using the data sets compiled by van Denderen *et al.* (2015b). The regression parameters were estimated as $\alpha = -2.9807$ and $\beta = 1.9695$ ($r^2 = 0.838$, $n = 24$). In this first exploration, we ignored the possible differences in the longevity distribution of the benthic community across habitats.

If the reciprocal of the trawling intensity, which reflects the average time interval between two successive trawling events, is less than the life span of an organism, the integrity of the seabed habitat to provide a place to live for the organism may be compromised (Thrush *et al.*, 2005; Rijnsdorp *et al.*, 2016). The seabed integrity in a grid cell can now be estimated as the biomass proportion of the benthic community where the reciprocal of the trawling intensity ($\frac{1}{t}$) is larger than the longevity of the taxa (Rijnsdorp *et al.*, 2016):

$$SBI = \exp\left(\alpha + \beta\left(\ln\frac{1}{t}\right)\right) \Big/ \left(1 + \exp\left(\alpha + \beta\left(\ln\frac{1}{t}\right)\right)\right)$$

where α and β are the coefficients of the logistic regression of the CB against the $\log_e$ of the life span of the taxa. The seabed integrity indicator (*SBI*) ranges between 0 (all taxa potentially impacted) and 1 (none of the taxa impacted). The seabed integrity of a habitat or management area is estimated as the average over its constituent grid cells, taking account of their different sizes. Because the longevity distribution refers to infaunal samples, seabed integrity values were estimated with the trawling intensity at the subsurface level.

Results

Distribution of bottom trawling

Bottom trawling is widely distributed over the continental shelf of Europe, although large parts are trawled at an intensity of less than once in every 2 years (Figure 3). Grid cell trawling intensities between 1 and 10 times per year occur in larger areas in the Norwegian Sea around Bjørnøya and along the coast off northern Norway, in large areas of the northern and southern North Sea, in Skagerrak-Kattegat, around Bornholm in the Baltic Sea, south and west of Ireland in the Celtic Sea and along the narrow continental shelf off Portugal. In the Mediterranean Sea, grid cell trawling intensities between 1 and 10 occur in larger areas in the Tyrrhenian Sea, the waters east of Tunisia, the Adriatic Sea and along the coasts of Greece. The trawling hot spots with significant areas of single cell intensities exceeding 10 times per year occur mostly in localized areas, along the coast of northern Norway, along the edge of the Norwegian deep in the northern North Sea and Skagerrak-Kattegat, in areas off the coasts of Ireland and United Kingdom, south and west of Portugal, along the coasts of Italy and in larger parts of the Adriatic Sea.

At the subsurface level, bottom trawling intensities are generally much lower (Figure 4). The lower subsurface intensities are due to the lower subsurface penetration of most of the bottom trawl métiers (Eigaard *et al.*, 2016). The relatively high subsurface footprint in the southern North Sea, Irish Sea, Celtic Sea and the Channel are largely due to the trawling activities of the beam trawl and dredge fisheries, which have similar surface and subsurface contact areas, but also some of the otter trawl métiers contribute significantly in some areas. In the Northern North Sea, Skagerrak-Kattegat, Irish Sea, Iberian Portuguese area, and Adriatic Sea the high subsurface footprint is mainly a result of high fishing intensities with bottom trawls targeting crustaceans and mixed fish, which have a significant subsurface contact area (Eigaard *et al.*, 2016).

The intensity of bottom trawling largely follows the bathymetry of the European waters, where the majority of fishing effort and seabed impact (area swept) takes place at depths $<$200 m (Figure 5). For the Skagerrak-Kattegat and the Iberian Portuguese area in the Atlantic, and the Tyrrhenian and Adriatic Seas in the Mediterranean, the depth zone from 200 to 500m is also fished rather intensively (from two to five times annually when averaged across the full management area), whereas the intensity below 500 m is limited for all management areas (Figure 5).

The gear types deployed also relate to the bathymetry (Figure 6); where beam trawls and dredges are deployed in shallower waters (almost exclusively at depths from 20 to 100 m) the demersal otter trawls and seines are universal gears that are deployed at all depths. The otter trawl has by far the largest distribution area in both the Atlantic and Mediterranean shelf areas (Figure 6). Demersal seines have a wide distribution in the Norwegian Sea, North Sea, waters around the United Kingdom and the Baltic Sea, beam trawls are mostly deployed in the southern North Sea, the Celtic Sea, the Channel, the Bay of Biscay and the Adriatic Sea, while dredging is restricted to coastal waters around the

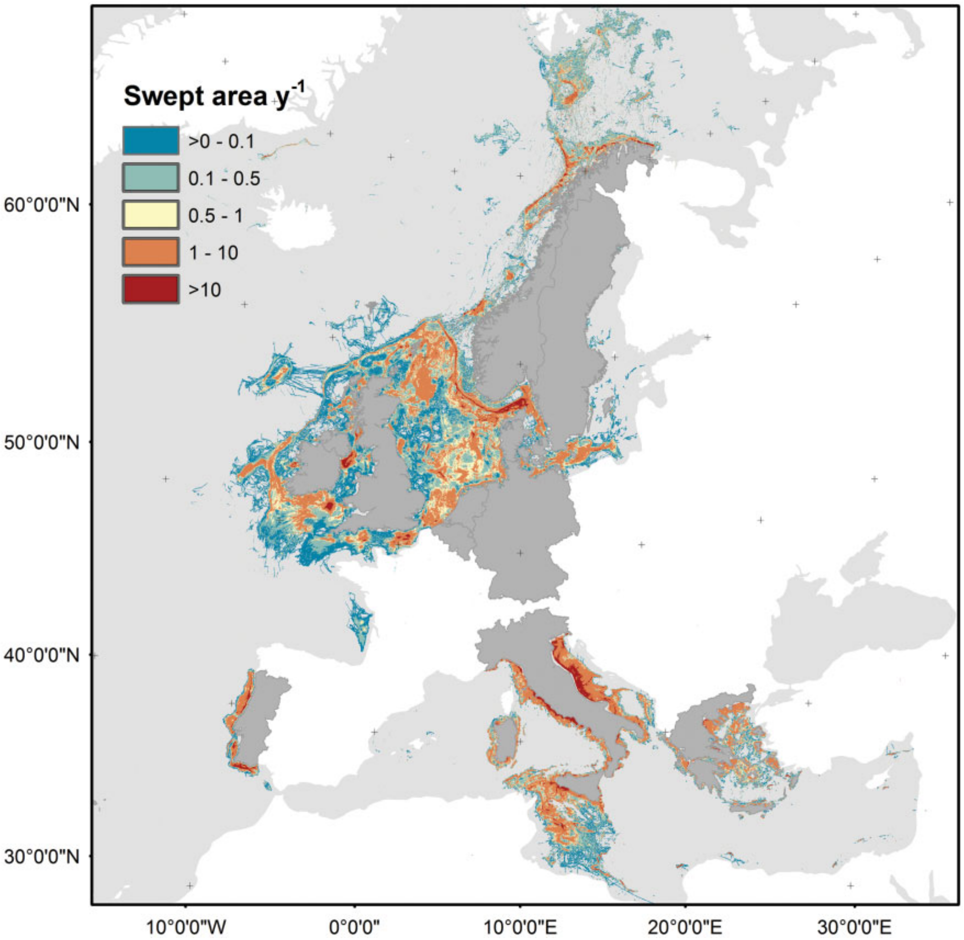

Figure 3. Mean annual trawling intensity in the period 2010–2012 at the surface level (sediment abrasion < 2 cm). The intensity is estimated from VMS and logbook data of bottom trawl fleets as the total area swept yearly in grid cells of 1×1 min divided by grid cell size. Countries marked dark grey provided data.

United Kingdom and France, and to a lesser extent the Belgian, Dutch and Danish coasts.

Indicators of trawling footprint and seabed integrity

Bottom trawling pressure on the seabed can be summarized in a trawling intensity profile, which shows the relationship between the annual trawling intensity and cumulative area of the grid cells in decreasing order of their trawling intensity. Trawling intensity profiles at the surface and subsurface level were estimated for each management area by depth zone.

A comparison of the Shallow zone profiles across the fourteen management areas with good coverage ($\geq$60%) shows that the proportion of the seabed with trawling intensities > 0.1 per year ranges between 50–95% and 25–85% for the surface and subsurface intensity, respectively (Figure 7). Management areas not only differ in the extent of trawling but also in the relative importance of the subsurface intensity. In the most intensively fished area Adriatic (M2.1), surface and subsurface intensities are high in large parts of the management area. Also in the Skagerrak-Kattegat (IIIa), Celtic Sea (VIIefgh), and Irish Sea (VIIa), the surface and subsurface intensity profiles are relatively close. In contrast, surface and subsurface profiles are far apart in western Baltic Sea (III 22–25), West of Scotland (VIb2), and Aegean Sea (M3.1), reflecting subsurface intensity in only a small part of the management area. In the other management areas surface and subsurface profiles are at intermediate distance.

For the Deep zone only four management areas have trawling intensities > 0.1 per year over a substantial proportion of the seabed; the Skagerrak-Kattegat (IIIa), North Sea (IV), Iberian Portuguese area (IXa), and Adriatic Sea (M2.1) have between 40 and 90% of the seabed trawled at the surface level, and between 25 and 80% at the subsurface level (Figure 8).

Table 3 gives an overview of the indicators by management area and depth zone. The trawling footprint estimated by metric (i) (the percentage of all the grid cells trawled, irrespective of intensity), varied between 53% (IIa) and 99% (VIb2) for the Shallow zone, and between 6% (IIa) and 94% (IXa) for the Deep zone (Table 3, Figure 9). These estimates include the untrawled parts of the seabed of those grid cells that were trawled less than once a year. Excluding the untrawled parts of these grid cells (metric ii), the trawling footprint is considerably less, ranging between 28% (VIa) and 85% (M2.1) for the Shallow zone, and between 2% (VIIefgh) and 77% (IXa) for the Deep zone.

The indicator for the aggregation of bottom trawling shows that 90% of the fishing effort occurs in 17–63% (median 36%) of the total management area for the Shallow zone (Table 3, Figure 9). For the Deep zone 90% of the effort is

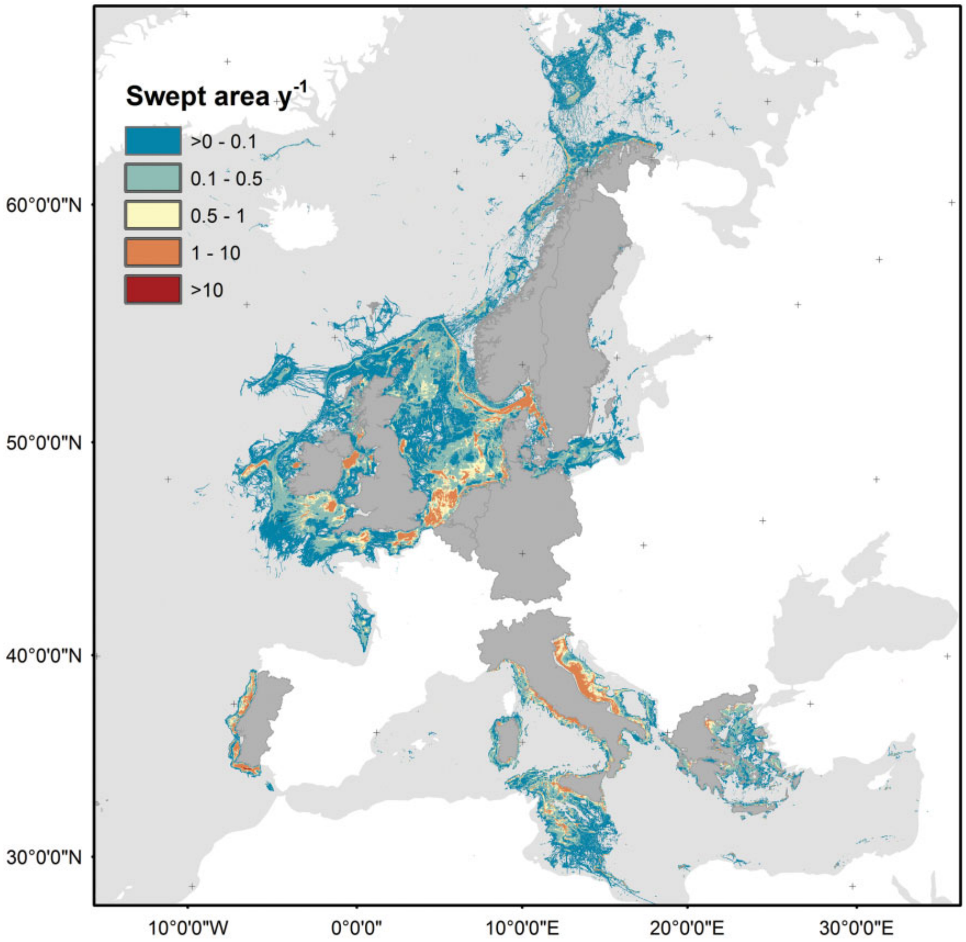

Figure 4. Mean annual trawling intensity in the period 2010–2012 at the subsurface level (sediment abrasion ≥ 2 cm). The intensity is estimated from VMS and logbook data of bottom trawl fleets as the total area swept yearly in grid cells of 1 × 1 min divided by grid cell size. Countries marked dark grey provided data.

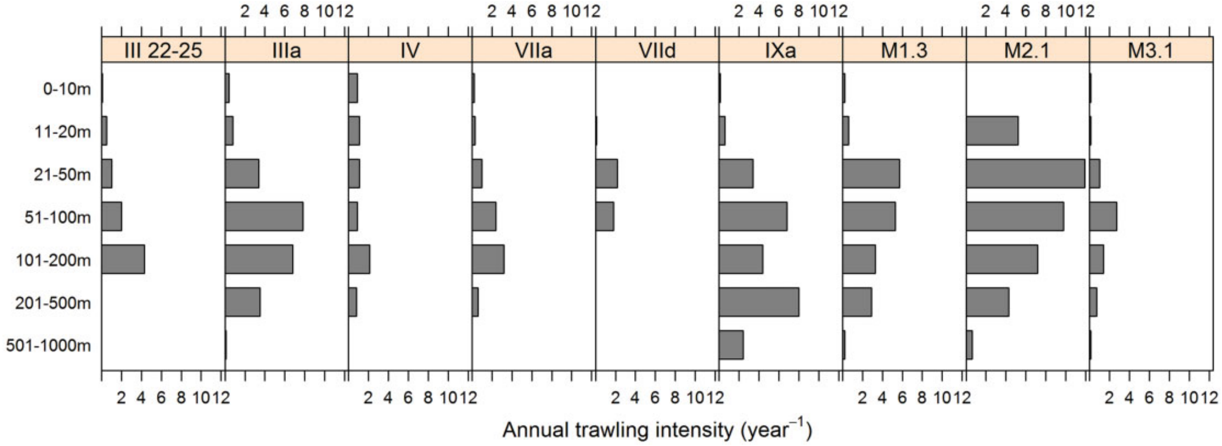

Figure 5. Trawling intensity by depth zone for the nine management areas with the highest observed trawling intensities (intensity > 2 year^{-1} in at least one depth zone).

concentrated in 2–46% (median 9%) of the total management area.

Per unit of landings, the median footprint of bottom trawling was 1.39 km^2 t^{-1} (mean = 3.36, $SD = 4.45$) across all depths and management areas, when calculated using metric ii. Highest footprints were observed in the Iberian Portuguese area (IXa) and Aegean Sea (M3.1) in the Mediterranean (Table 3). For the management areas for which both landings and effort data were

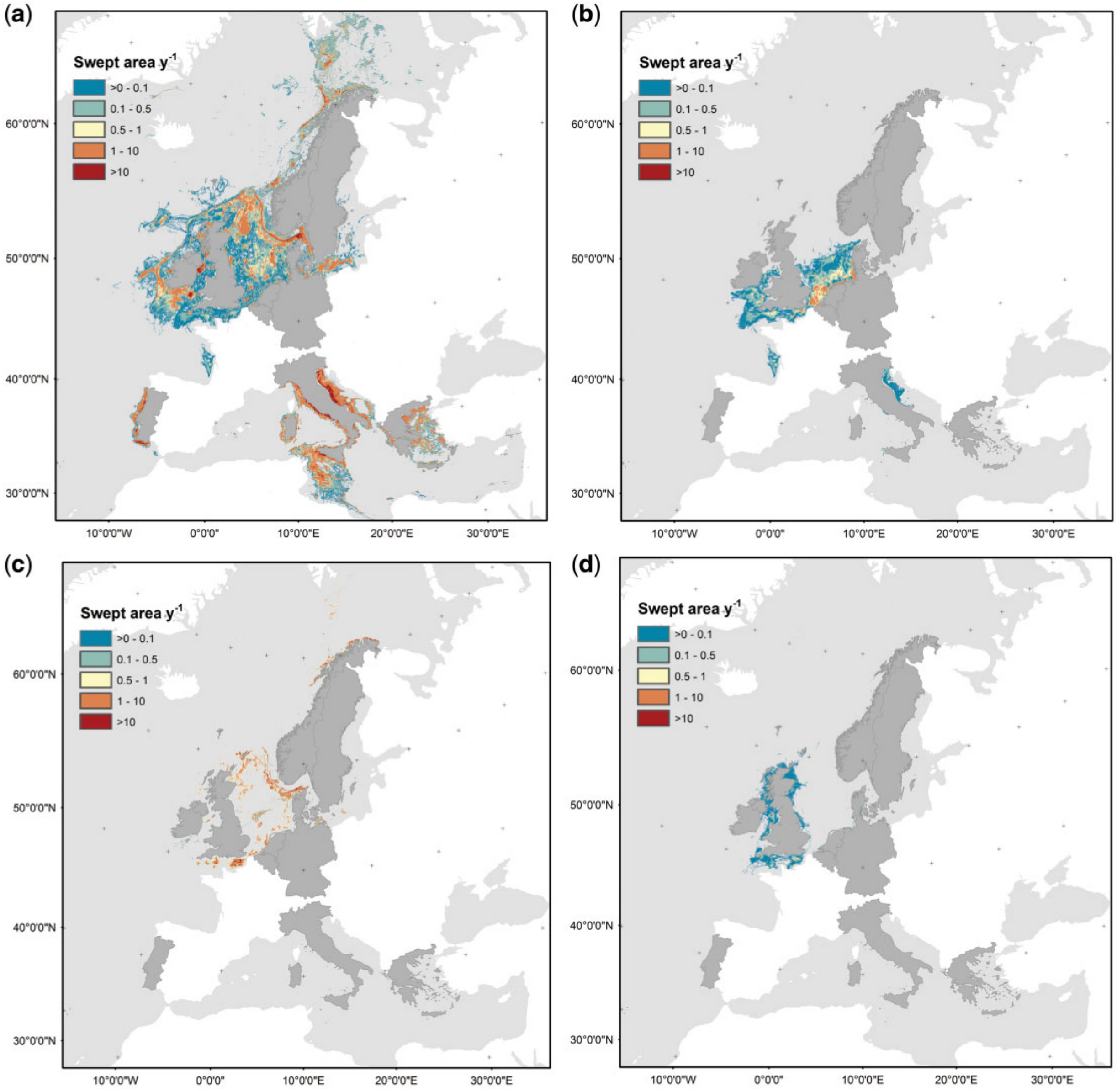

Figure 6. Fishing intensity at the surface level by main gear groups (a: demersal otter trawls, b: beam trawls, c: demersal seines, and d: dredges) for the areas analysed.

available by depth zone, the median footprint was 1.43 km^2 t^{-1} (mean = 4.26, *SD* = 6.33) and 1.47 km^2 t^{-1} (mean = 3.33, *SD* = 3.81) for the Shallow and Deep zone, respectively.

The proportion of the seabed that is untrawled (as the complement of the trawl footprint calculated by metric (i), varied between 1% and 47%, and between 6% and 94%, for the Shallow and Deep zone, respectively (Table 3). For the Shallow zone, the management areas west of Scotland (VIb2)—1% and the North Sea (IV)—7% had very little untrawled seabed. In the Mediterranean Sea, the untrawled areas ranged between 14 and 25% for M1.3, M2.1, and M3.1. For the Deep zone, the untrawled areas were generally larger: areas west of Scotland (VIb2)—87%, North Sea (IV)—49% and in the Mediterranean Sea from 24 to 81%. If the untrawled seabed is calculated as the complement of metric ii (the actual seabed swept, rather than grid cells with any effort), the proportion of untrawled seabed increases to a value between 15 and 72%, and between 23 and 98% for the Shallow and Deep zone, respectively.

Seabed integrity estimated at the subsurface level for the well covered management areas revealed that grid cells either have a low (<0.17) or a high (>0.82) integrity (Figure 10). Within the extensive areas of low seabed integrity, small islands with high integrity values are visible. The mean seabed integrity varied between management areas (Table 3); at the subsurface level, seabed integrity ranged between 0.16 (M2.1) and 0.77 (III 22–25) for the Shallow zone. For the Deep zone, the seabed integrity values ranged between 0.29 (IXa) and 0.98 (IIa). Evaluated at the surface level, where trawling intensities are higher, seabed integrity estimates were lower and ranged between 0.15–0.57 and 0.16–0.95 in the Shallow and Deep zones, respectively.

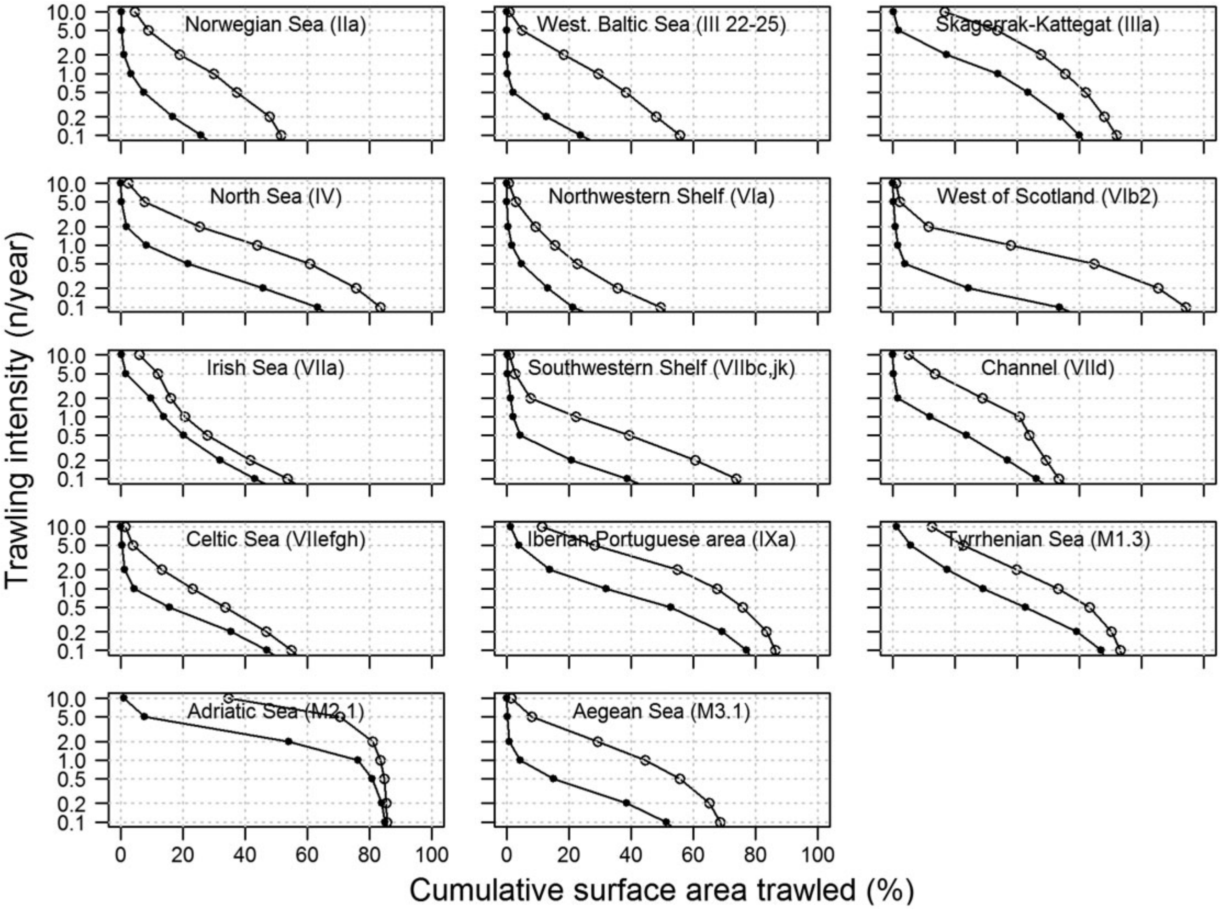

Figure 7. Trawling intensity profiles at the surface (open circles) and subsurface level (dots) for all well-represented management areas (inclusion of $\geq$ 60% of total effort) for the depth range 0–200 m.

Trawling footprint by habitat

The footprint of bottom trawling by seabed habitats was assessed for the Northeast Atlantic and the Mediterranean Sea separately. Figure 11 shows the footprints estimated by metric i (the percentage of all the grid cells trawled, irrespective of intensity) and metric ii (area of the seabed trawled at least once a year) alongside the surface area of the habitat. The analysis shows that bottom trawling is not restricted to a particular habitat. All soft sediment habitats in both the Northeast Atlantic and Mediterranean Sea are trawled extensively with the proportion of the grid cells trawled ranging between 50 and 90%. Lower footprints are observed in infralittoral rock and other hard substrata (A3), unknown habitat in the shallow Atlantic (0–200 m) and unknown and deep Sea habitat (A6) in the deep Atlantic (201–1000 m). Assessed by metric ii, the habitats trawled most extensively are sublittoral sand (A5.2) and sublittoral mud (A5.3) followed by sublittoral mixed sediments (A5.4) and sublittoral coarse sediment (A5.1). In the Mediterranean, Sublittoral biogenic reefs (A5.6), sublittoral macrophyte-dominated sediments (A5.5) and deep sea sediments (A6) are trawled extensively with a footprint of around 50%.

Discussion

We discuss bottom trawling in light of the four indicators analysed: I1) Trawling footprint, I2) Trawling aggregation, I3) Untrawled seabed, and I4) Seabed integrity.

Trawling footprint

Large parts of the continental shelf and the slope of the continental shelf of Europe are trawled by bottom gears. The Trawling footprint in the Shallow zone ranged between 28 and 99% in the management areas of the Northeastern Atlantic and between 57 and 86% in the Mediterranean Sea. In the Deep zone the Trawling footprint was lower with a maximum of 94% in the Atlantic and 76% in the Mediterranean Sea.

The ratio of the Trawling footprint over the landings shows that highest ratios occurred in the management areas in the Iberian Portuguese area and in the Mediterranean Sea, reflecting the higher level of exploitation in the latter as compared with some of the Atlantic management areas where fishing effort has been reduced since the mid-2000s (Vasilakopoulos *et al.*, 2014; STECF, 2014). The larger degree of oligotrophy in many parts of the Mediterranean Sea may also be part of the explanation why much more seabed has to be covered to exploit one ton of fish. The relatively low ratio observed in the North Sea may be related to the substantial contribution of industrial fisheries in this area, which target low value species [e.g. sandeel (*Ammodytes marinus*) and Norway Pout (*Trisopterus Esmarkii*)] and high catch volumes. The results do not suggest that bottom trawling in the Deep zone may have a higher footprint-to-landings ratio. A more detailed analysis is needed to investigate how the ratio of the bottom-trawling footprint over the landings and revenue is

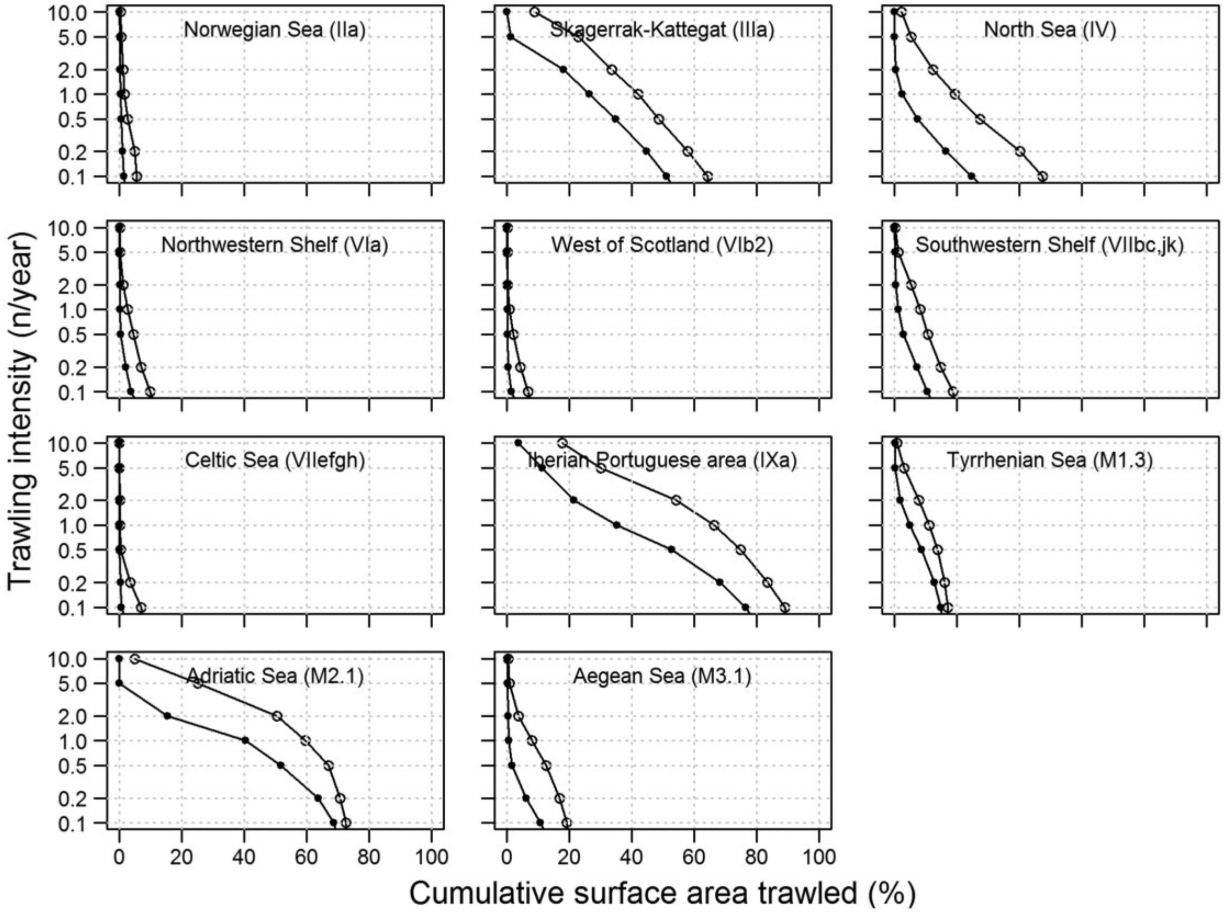

Figure 8. Trawling intensity profiles at the surface (open circles) and subsurface level (dots) for all well-represented management areas (inclusion of $\geq 60\%$ of total effort) for the depth range 201–1000 m.

Table 3. Indicators of trawling pressure in management areas, as percentage area of: grid cells with effort (I1, metric i), seabed trawled 1 or more times yearly (I1, metric ii), grid cells with 90% of effort (I2), untrawled grid cells (I3), seabed integrity (I4) and seabed trawled per unit of landings for the depth zones 0–200 m and 201–1000 m.

	Depth zone 0–200 m						**Depth zone 201–1000 m**					
area	**Footprint grid cells (%)**	**Footprint seabed (%)**	**90% effort (%)**	**Untrawled grid cells (%)**	**SBI subsurface**	**Seabed trawled per unit landing (km^2t^{-1})**	**Footprint grid cells (%)**	**Footprint seabed (%)**	**90% effort (%)**	**Untrawled grid cells (%)**	**SBI subsurface**	**Seabed trawled per unit landing (km^2t^{-1})**
Norwegian Sea (IIa)	52.6	39.4	23.0	47.4	0.76	1.7	5.6	3.1	1.7	94.4	0.98	1.9
West. Baltic Sea (III 22–25)	62.7	40.7	29.9	37.3	0.77	1.3						
Skagerrak-Kattegat (IIIa)	75.8	63.1	37.6	24.2	0.43	1.0	67.8	51.0	30.1	32.2	0.52	1.0
North Sea (IV)	93.0	63.1	45.4	7.0	0.46	0.8	51.4	30.7	20.5	48.6	0.77	0.8
Northwestern Shelf (VIa)	70.1	27.8	21.5	29.9	0.76	1.7	17.6	5.6	4.7	82.4	0.95	1.3
West of Scotland (VIb2)	99.2	66.2	54.2	0.8	0.58		13.0	3.0	2.6	87.0	0.97	1.7
Irish Sea (VIIa)	84.7	33.0	17.4	15.3	0.58	0.7						
Southwestern Shelf (VIIbcjk)	83.7	44.4	36.2	16.3	0.66	1.7	23.2	12.2	9.2	76.8	0.90	2.4
Channel (VIId)	76.1	46.0	30.1	23.9	0.57	1.2						
Celtic Sea (VIIefgh)	75.3	36.9	27.3	24.7	0.58	1.4	11.3	2.0	1.8	88.7	0.98	1.4
Iberian Portuguese area (IXa)	88.5	76.8	46.1	11.5	0.29	16.8	93.6	76.6	40.7	6.4	0.29	12.6
Tyrrhenian Sea (M1.3)	76.9	63.8	35.1	23.1	0.39	6.5	18.8	14.1	9.4	81.2	0.86	5.9
Adriatic Sea (M2.1)	86.0	84.8	63.1	14.0	0.16	1.1	76.2	66.8	46.0	23.8	0.36	1.2
Aegean Sea (M3.1)	74.8	56.8	40.7	25.2	0.56	19.4	24.3	13.3	10.5	75.7	0.90	10.8

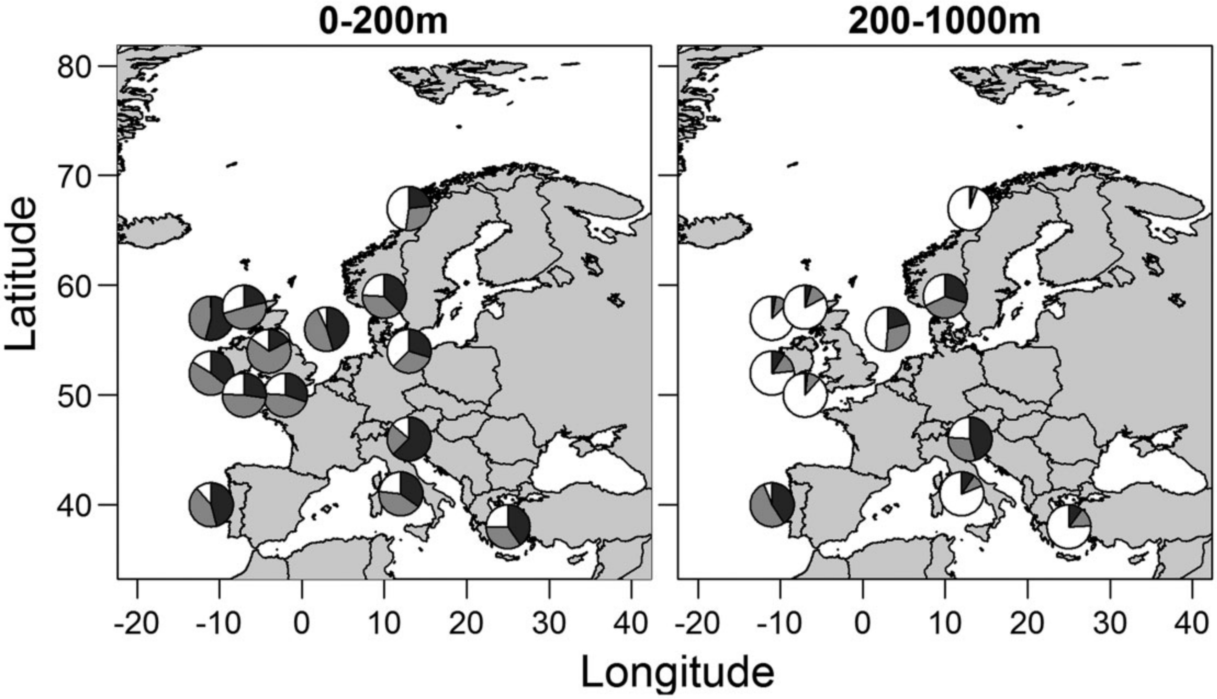

Figure 9. Indicators of trawling pressure: I1, trawling Footprint (grey + black); I2, trawling aggregation (black) and I3, untrawled Seabed (white) by management area in the Northeastern Atlantic and the Mediterranean Sea for two depth zones: 0–200 m (left panel) and 201–1000 m (right panel). The trawling footprint is expressed as the percentage of grid cells that are trawled in the management area (metric i). Management areas with coverage below 60% are not shown.

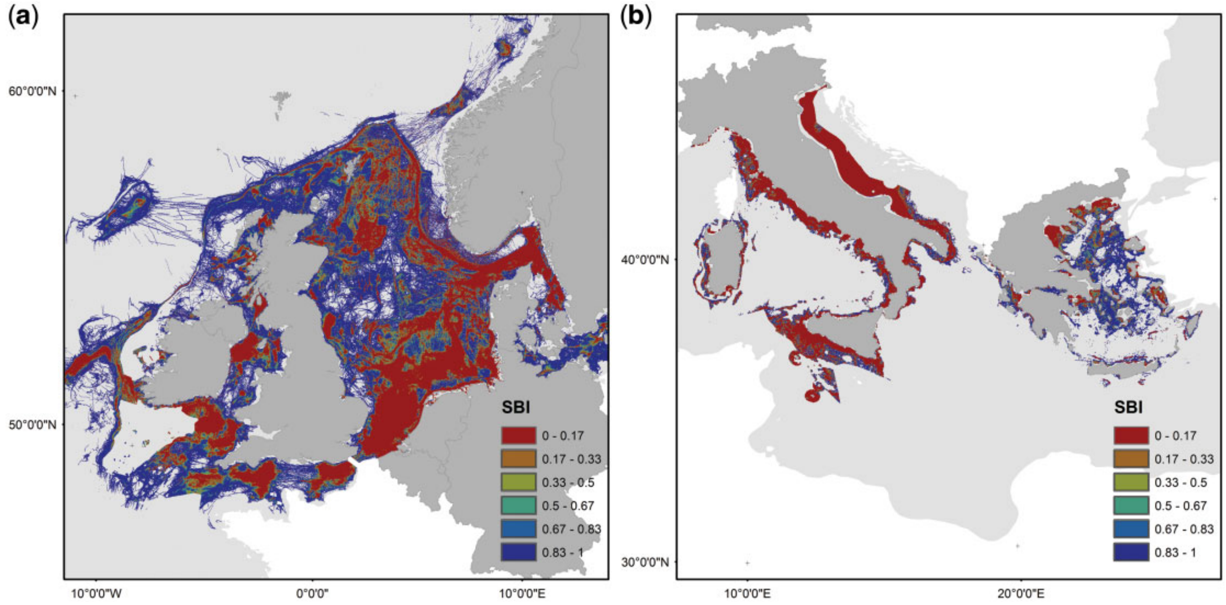

Figure 10. SBI values corresponding to the subsurface trawling intensities (sediment abrasion ≥ 2 cm) in the Atlantic and Mediterranean Sea (Italian and Greek exclusive economic zones). For the SBI, 0 = all taxa impacted and 1 = no taxa impacted. The white areas show grid cells that were untrawled.

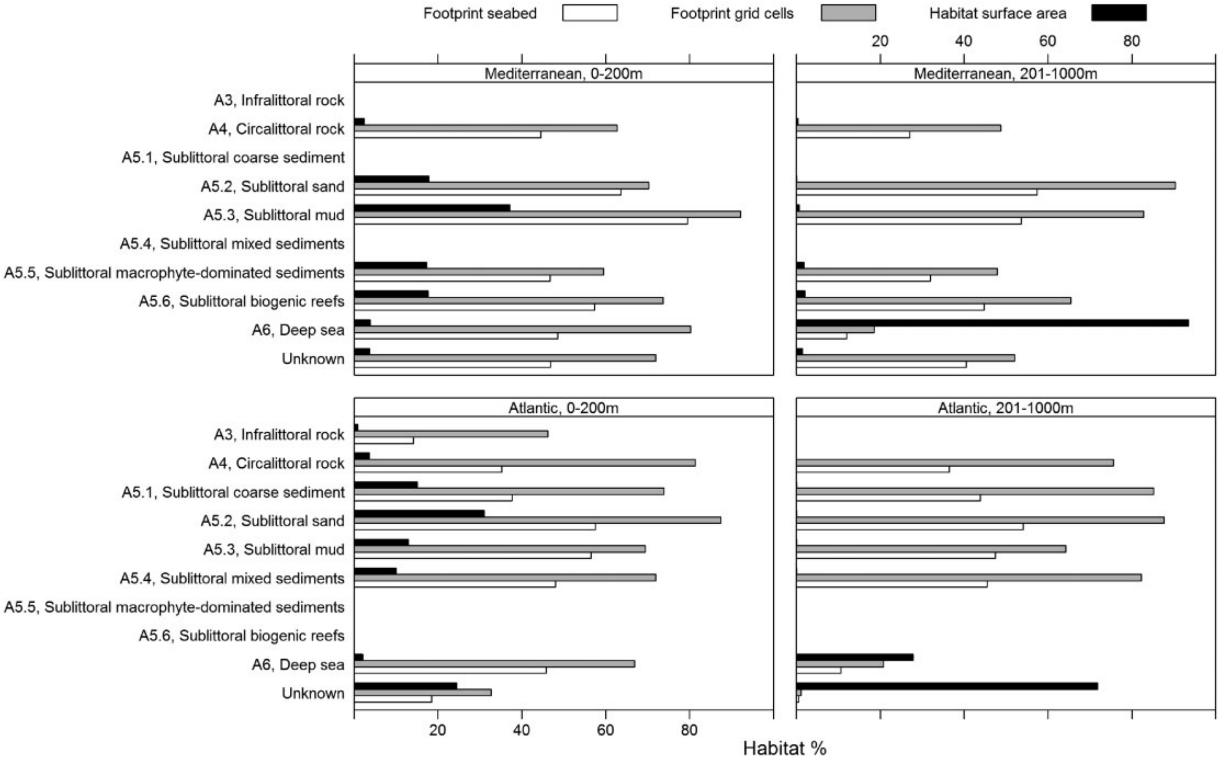

Figure 11. Indicators of trawling pressure per EUNIS habitat and depth zone in the Northeast Atlantic and the Mediterranean Sea. The trawling footprint (I1) is estimated by metric i (the percentage of all the grid cells trawled, irrespective of intensity, grey bars) and metric ii (area of the seabed trawled at least once a year, white bars) and plotted alongside the relative surface area of each habitat type (black bars).

related to depth. Clark *et al.* (2016) showed that the bycatch of sensitive fish species increased in deep-sea trawl fisheries of the Northeast Atlantic around 800 m depth, so adding to the concern about the impacts of deep water trawling.

No clear differences occurred in the trawling footprints of the different seabed habitats. The broad diversity of habitats trawled, ranging from muddy or sandy sediments, via coarse and mixed sediments to gravel and other hard substrata, is related to the wide range of bottom trawls and technology that has evolved over time and that allowed fishers to move into formerly untrawlable habitats (Valdemarsen, 2001; Rijnsdorp *et al.*, 2008; Eigaard *et al.*, 2014).

Aggregation of bottom trawling

The maps of trawling intensity show a heterogeneous distribution pattern with intensive bottom trawling in localized areas, and low-intensity trawling elsewhere. The heterogeneity is observed in all management areas, for all four gear types and for all habitats. It is likely that the trawling hotspots may reflect certain morphological features, such as gradients in bathymetry, changes in bottom type or the occurrence of un-trawlable grounds. Some of the fine grained patterns shown in the maps in the north-eastern North Sea reflect steep depth gradients along the Norwegian trench. Similar patterns exist along all the continental shelf in the NE Atlantic and along the Italian and Greek coasts in the Mediterranean. In the Celtic Sea and Irish Sea, much of the fishing effort is concentrated on mud patches and muddy gullies (Gerritsen and Lordan, 2014). A second mechanism generating trawling hotspots is related to the patchiness in the distribution patterns of the target fish and their prey (Rijnsdorp *et al.*, 2011; Ellis *et al.*, 2014). Flatfish beam trawls aggregate on local fishing grounds of around ∼25 nautical miles^2 with an above average catch rate. These hot spots are transient, lasting from a few days up to 1–2 weeks (Poos and Rijnsdorp, 2007. If the trawling hot spots are related to morphological features, it is likely that these patterns will be stable; if they are transient, the trawling pattern will become homogenized when evaluated over longer time periods.

As a result of the heterogeneity in bottom trawling, the area where 90% of the fishing effort is concentrated ranges between 17% for the Irish Sea and 63% for the Adriatic Sea, with the remaining areas evenly distributed in between. This 90% effort area also represents the area where most of the landings are taken. The heterogeneity in the distribution of bottom trawling implies that a substantial part of the footprint is inflicted by a minor part of the effort and landings. A reduction in footprint may be achieved by restricting the bottom trawling to the seabed where most bottom trawling takes place (Jennings *et al.*, 2012).

Untrawled seabed

In all management areas between 15 and 72% of the seabed in the most intensively fished depth zone (0–200 m) was untrawled during the 3-year study period. On this short time scale, the proportion untrawled seabed will be higher since bottom trawling is randomly distributed within grid cells (Rijnsdorp *et al.*, 1998; Pitcher *et al.*, 2000; Lee *et al.*, 2010) and even in a grid cell with an average trawling intensity of 1 year^{-1}, part of the grid cell will be untrawled.

When assessed on a longer time scale, the proportion of untrawled seabed will be lower. Based on the footprint including the surface area of the grid cells trawled less than once a year (metric i), the untrawled proportions were estimated to between 1 and 47%. We expect that these parts of the grid cells will be trawled when studied over longer time periods since random distribution on the annual time scale will become a uniform distribution at a time scale of multiple years (Ellis *et al.*, 2014). In addition it is possible that grid cells without any trawling activity during the study period may be trawled in future.

Whether the grid cells that were not trawled during the study period will remain untrawled when studied over longer time periods will depend on the stability of the spatial distribution of the fisheries. There is some support for the stability in the effort distribution patterns assessed at the scale of ICES rectangles (30 × 30 nautical miles) (Jennings *et al.*, 1998; Piet and Quirijns, 2009). However, can we expect that the distribution of bottom trawling at the spatial resolution required for assessing the impact on the seabed and benthic communities will be stable on a decadal time scale? Piet and Quirijns (2009) showed that over a period of 11 years the effort distribution patterns of the Dutch beam trawl fleet was stable at the scale of the ICES rectangle. However, when analysed at smaller grid cells sizes, the correlation between annual patterns reduced, to around 0.20–0.30 when the time interval increased from 2 to 5 years. The Dutch beam trawl fishery operates in rather homogeneous soft-sediment habitats and when assessed over longer time periods the heterogeneity will gradually reduce over time. For fisheries where the distribution is determined by morphological features of the seabed, the heterogeneous distribution pattern may be more stable. Comparison of the observed distribution of bottom trawling of the Norwegian fleet in our study, which shows zones of intensive trawling related to specific morphological features such as steep depth gradients near the shelf break, the flanks of banks and more level areas of certain banks, shows close similarity to the distribution between 2003 and 2007 (Buhl-Mortensen *et al.*, 2016). Overall, we expect that the estimates of proportion of seabed that is untrawled will decrease when a longer time period is considered, particularly in areas with a homogeneous seabed habitat.

Seabed integrity

The average seabed integrity of the management areas and habitats varied substantially. Lowest seabed integrity was observed in the Adriatic (M2.1) and the Iberian Portuguese area (IXa) in the Shallow zone. For the Deep zone, seabed integrity values were higher. The estimated seabed integrity is closely related to the proportion of the management area trawled at the subsurface level <0.1 year^{-1}, that relates to a longevity of $\geq$ 10 years. Our study showed that more than 30% of the soft-sediment habitats in the Northeastern Atlantic and Mediterranean Sea were untrawled or trawled at an intensity of <0.1 year^{-1}, which may not compromise the integrity of the habitat. This conclusion applies to all management areas, except for the Adriatic Sea (M2.1) and the Iberian Portuguese area (IXa) where smaller proportions of the seabed (15 and 23%, respectively) were trawled <0.1 year^{-1}at the subsurface level.

In the well covered management areas, the seabed integrity of grid cells was either high (>0.82) or low (<0.17). Areas with intermediate seabed integrity were sparse (Figure 10). This dichotomy relates to the trawling intensity profile and the longevity distribution of the benthic community. High seabed integrity will be restricted to grid cells with a trawling intensity of <0.1 year^{-1}, because taxa with a life span of >10 years comprise 17% of the biomass of the benthic community. It is only a narrow range of intensity (0.1–0.5 year^{-1}) for which SBI takes middling/moderate values. Most cells have either high or low intensity and so the SBI is either high (>0.82) or low (<0.17), respectively.

Within the areas of low seabed integrity islands of high integrity can be observed. Areas with a high seabed integrity value occur in the western and northern North Sea, as well as in localized areas in the coastal zone. In addition to these, small pockets of untrawled seabed will occur that are not shown in our analysis. These pockets will be related to the safety zone around oil or natural gas platforms, and the untrawlable seabed around wrecks and other physical obstacles that can obstruct the safe deployment of bottom trawls. Duineveld *et al.* (2007) showed that the benthic community in the safety zone of a platform showed a higher density of mud shrimps and fragile bivalves. These areas are too small to be detected at the resolution used in this study and we can expect that at a higher resolution more islands of high integrity will appear.

For the German Bight, where similar impact assessments of seabed integrity have been conducted before, results for SBI at the 0.9 level resemble patterns for Fock *et al.*'s (2011) disturbance indicator I at the 90% probability level representative of self-sustaining communities taking into account inter-annual variability in trawling intensity.

Biogenic habitats are known to be particularly vulnerable to bottom trawling (Watling and Norse, 1998; Collie *et al.*, 2000a,b; Kaiser *et al.*, 2006). With the exception of Sublittoral macrophyte-dominated sediments (A5.5) and sublittoral biogenic reefs (A5.6) in the Mediterranean, biogenic habitats were not represented in the EUNIS level 3 habitat maps available to this study. Most biogenic habitats are classified in EUNIS level 4 or 5 (Davies *et al.*, 2004) and are an integrative part of the broader EUNIS level 3 habitat classes used in this study. Examples are mearl beds (A5.1), eel grass beds (A5.5332), Seagrass meadows (A5.535), sublittoral polychaete worm reefs on sediment (A5.61), mussel beds (A5.62), cold water coral reefs (A6.61), and sponge beds (A6.62). This also refers to reef habitats (type 1170) protected under the EU Habitats Directive (92/43/EEC). In the Mediterranean, our analyses indicated that ∼40% of the macrophyte-dominated sediments and biogenic habitats (A5.5 and A5.6) are trawled. Although these two habitat types contribute 11% and 12% of the seabed, it is likely that the smaller level 4 and 5 habitats will be patchily distributed (and impacted) within these two lower-level habitat types. Some specific habitat types such as seagrass or coralligenous habitats are protected by regulation (EC, 1967/2006). In the Atlantic, cold water coral habitats have been mapped in recent years and management measures have been put in place to protect them from bottom trawling (Ardron *et al.*, 2014).

As biogenic habitats and macrophyte-dominated sediments are only partly reflected in the currently available EUNIS maps, our study focussed on assessing the trawling impact on the soft sediment habitats (A5.1–A5.4) that dominate the continental shelf areas of Europe, and the SBI is for infauna only in any case. For these habitats we expect that the subsurface level contact will be most relevant for assessing the impact on the seabed habitat and the benthic community. The subsurface level contact represents the heavier gear components that penetrate into the seabed

(Eigaard *et al.* 2016) and will be more closely related to the physical disturbance of the seabed as well as to the mortality imposed on benthos (Collie *et al.*, 2000a; Kaiser *et al.*, 2006).

Critical trawling intensity

We considered an annual trawling intensity of 0.1 year^{-1} to be a critical intensity beyond which bottom trawling may start compromising the integrity of the seabed and associated benthic community. This critical intensity was based on the data from van Denderen *et al.* (2015b) showing that about 17% of the infaunal biomass comprised of taxa with longevity of 10 years or more. For biogenic habitats, the critical intensity will be (much) lower, as the longevity of biogenic habitats may be in the order of decades or even centuries (Clark *et al.*, 2016; Pitcher *et al.*, 2016).

The critical trawling intensity based on the longevity composition can be considered to be a low risk reference. It does not mean that taxa that are trawled at least once during their lifespan will no longer be able to maintain themselves. Since the typical mortality imposed by bottom trawling range between a few % to >50% (Collie *et al.*, 2000a; Kaiser *et al.*, 2006), one trawling event will only temporarily reduce the biomass but will not wipe out the population. Less cautious threshold values for trawling intensity can be derived by taking account of the direct mortality imposed by bottom trawling and the recovery rate of the biota (Pitcher *et al.*, 2016), or can take the distribution of the onset of reproduction as a reference.

Methodological improvements

In our analysis, effort data from a few countries could not be included and, although we restricted our estimations of the SBI to the well-covered management areas, there is still some effort missing. The coverage by rectangle shows underestimates in the Bay of Biscay, the southern parts of the Channel and Celtic Sea as well as along the edge of the continental shelf west of Ireland (Supplementary Figure S1–S3). If the fisheries that were not covered occurred in the already heavily trawled areas, our estimates of seabed integrity would not be affected. If the fisheries, however, are operating in areas where we observed little or no fishing, even light trawling may have already compromised seabed integrity. This could also apply in the high integrity areas observed in some of the coastal waters because we have not included data of vessels <12 m length in our analysis, but in general trawlers and seiners <12 m are not common. Most likely, coverage is over-estimated from the assumption that all STECF registered effort with vessels >12 m are included in our analyses (which is only true for 2012, as the threshold was 15 m in 2010 and 2011), but the bias due to the 12–15 m vessel group is likely to be small.

The seabed integrity estimated in this paper should be considered as a first attempt. The same longevity distribution, suggesting a critical trawling intensity of 0.1 year^{-1}, was applied to all EUNIS habitats. It is likely that the longevity distribution of the benthic community will differ across habitats. Hence, the critical trawling intensity of 0.1 year^{-1} will not be appropriate for biogenic habitats which are characterized by taxa with much longer life spans (Clark *et al.*, 2016). On the other hand, in habitats exposed to high natural variations, taxa with relatively short life spans may dominate. Hence, the critical trawling intensity may be refined when information on the longevity distribution of the benthic community becomes available for different habitat types. Further improvements can be expected when more refined EUNIS level 4 or 5 habitat maps can be used in combination with the longevity distribution of the untrawled community. Also the use of trawling intensities with impact at the subsurface level for estimating seabed integrity (based on the soft-sediment focus of this study) may alternate with the use of surface intensities (e.g. in habitats dominated by emergent fauna) according to improved information of habitat types and community composition.

We assumed that the gear components that only contact the surface of the seabed have a negligible impact. Although this may be a reasonable assumption for the soft-sediment habitats, it may not apply to hard bottoms (A3 and A4) and mixed sediments (A5.4) which are inhabited by emergent sessile epifauna that may be sensitive to sweeps or other gear components only contacting the surface of the seabed (Collie *et al.*, 2000a,b; Davies *et al.*, 2004; Gage *et al.*, 2005). As the trawling intensity at the surface level is higher than at the sub-surface level, seabed integrity of these habitats may be overestimated.

In estimating seabed integrity, we assumed that all taxa are equally vulnerable to the gear. The seabed integrity estimate, therefore, is a minimum estimate because taxa that are robust or live in the sediment beyond the reach of the gear are unlikely to be affected. A more refined indicator of the seabed integrity can be calculated by restricting the analysis to the taxa which are vulnerable to the fishing gear. Selection criteria can be based on a biological traits analysis (Bolam *et al.*, 2014).

Seabed integrity was assessed herein for the impact of bottom trawling on the benthic community composition. Bottom trawling will affect the functioning of the benthic ecosystem as it will reduce benthic biomass and shift the species composition from long-lived, suspension-feeding taxa to opportunistic detritus feeders and predators (Kaiser *et al.*, 2006; van Denderen *et al.*, 2015b). By linking the trawling intensity profile with the longevity distribution of a functional group, the SBI can also be estimated for different functional groups (Rijnsdorp *et al.*, 2016).

Bottom trawling remobilizes sediment through the turbulence generated in the wake of the gear (O'Neill and Summerbell, 2011). This resuspension may reduce the organic material in the sediment and may enhance the transport of fine sediment (Pusceddu *et al.*, 2014). The detailed maps of the footprint and intensity of trawling presented in this article, in combination with the métier-specific towing speed (Eigaard *et al.*, 2016), will provide a solid basis to estimate the amount of sediment that will be remobilized by bottom trawling (Oberle *et al.*, 2016).

Management implications

The use of the longevity distribution of the benthic community that is typical for a seabed habitat offers a simple and transparent quantitative alternative to the sensitivity and resistance/resilience matrix approaches described by e.g. Eno *et al* (2013), Grabowski *et al.* (2014), Knights *et al.* (2015) that are based on expert judgement. These matrix approaches are mostly broad threat/impact assessments that consider a range of human activities, pressures and ecological components (species or habitats), or focus on a single impacting activity, e.g. fishing, comparing various types and gears. These qualitative approaches are very useful as screening tools for risk assessment and management action prioritization, where categorical data are used as proxies in the absence of spatial extent or frequency data. Assumptions (made for example on the extent of a habitat trawled and how often) based on expert knowledge and backed up by extensive stakeholder consultations are used to reach a consensus on the habitat sensitivity matrices (Eno *et al*., 2013; Knights *et al*., 2015). These assumptions incorporate several relevant concepts such as the degree of impact (acute mortality, chronic with detrimental effects), susceptibility (percentage feature removal or damage) and recovery, but scales and scores would vary greatly between studies depending on fisheries examined and habitats/components included (e.g. to <2 years to +100 years to recovery) and on levels of expertise. Although based on scientific knowledge about the impact of fishing on seabed habitats and benthic ecosystems, such approaches are difficult to reproduce and apply directly to other systems. They require very complex matrices and their strength is in demonstrating the range and order of magnitude of effects.

The longevity distribution approach presented here focuses on the taxa longevity concept coupled with accurate spatial trawling intensity data, gear component information and fishery-relevant habitat maps. The approach and outputs are easy to visualize and to communicate to managers and stakeholders by, for example, showing hotspots of trawling intensity or areas of compromised seabed integrity (where subsurface levels of trawling intensity exceeds benthic life span). It provides managers a tool to demonstrate distance to conservation targets or high-level objectives and monitor the evolution of trawling impact over time. For example, recommended protection levels for certain European marine sites under the Natura 2000 ranges between 20 and 60% of total habitat area, and NGOs advocate even higher levels for rare habitats such as seagrass beds and maerl (Anon, 2014). In many cases such protection would require as a first step the identification (as shown here) of the overlap of the pressure with the habitat in question, to be followed by footprint reduction. The method proposed here should not be interpreted as a metric of the reduction in benthic biomass due to bottom trawling, but does allow, as a first step, to define maximum local fishing pressure by which managers can steer towards biodiversity targets. Furthermore, the approach provides a useful way to investigate whether fishing on previously untrawled or trawled areas is more beneficial in reaching biodiversity targets, thereby facilitating the discussion on the usability of marine protected areas (MPAs). Insights to this discussion are both timely and relevant, especially as EU Member States are preparing their Programme of Measures to fulfil the aims of the MSFD, in which further inclusion of spatial protection measures and MPAs is expected to be an important step towards fulfilling the commitments undertaken at the World Summit on Sustainable Development and in the Convention on Biological Diversity.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the article.

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References

Anon. 2014. Priorities for MSFD programmes of measures. Joint NGO Paper. http://www.seas-at-risk.org/images/pdf/archive/2014/NGO_priorities_for_PoM_-__with_additional_chapters_-_FINAL_17_October_2014.pdf

Ardron, J. A., Clark, M. R., Penney, A. J., Hourigan, T. F., Rowden, A. A., Dunstan, P. K., Watling, L. *et al*. 2014. A systematic approach towards the identification and protection of vulnerable marine ecosystems. Marine Policy, 49: 146–154.

Bastardie, F., Nielsen, J. R., Ulrich, C., Egekvist, J., and Degel, H. 2010. Detailed mapping of fishing effort and landings by coupling fishing logbooks with satellite-recorded vessel geo-location. Fisheries Research, 106: 41–53.

Bennema, F. P., and Rijnsdorp, A. D. 2015. Fish abundance, fisheries, fish trade and consumption in sixteenth-century Netherlands as described by Adriaen Coenen. Fisheries Research, 161: 384–399.

Bolam, S. G., Coggan, R. C., Eggleton, J. E., Diesing, M., and Stephens, D. 2014. Sensitivity of macrobenthic secondary production to trawling in the English sector of the Greater North Sea: a biological traits approach. Journal of Sea Research, 85: 162–177.

Buhl-Mortensen, L., Aglen, A., Breen, M., Buhl-Mortensen, P., Ervik, A., Husa, V., Løkkeborg, S., Røttingen, I., and Stockhausen, H. H. 2013. Impacts of fisheries and aquaculture on sediments and benthic fauna: suggestions for new management approaches, Fisken og Havet 2, 69pp

Buhl-Mortensen, L., Ellingsen, K. E., Buhl-Mortensen, P., Skaar, K. L., and Gonzalez-Mirelis, G. 2016. Trawling disturbance on megabenthos and sediment in the Barents Sea: chronic effects on density, diversity, and composition. ICES Journal of Marine Science, 73(Suppl. 1): i98–i114.

Clark, M., Althaus, F., Schlacher, T., Williams, A., Bowden, D., and Rowden, A. 2016. The impacts of deep-sea fisheries on benthic communities: a review. ICES Journal of Marine Science, 73(Suppl. 1): i51–i69.

Collie, J. S., Hall, S. J., Kaiser, M. J., and Poiner, I. R. 2000a. A quantitative analysis of fishing impacts on shelf-sea benthos. Journal of Animal Ecology, 69: 785–798.

Collie, J. S., Escanero, G. A., and Valentine, P. C. 2000b. Photographic evaluation of the impacts of bottom fishing on benthic epifauna. ICES Journal of Marine Science, 57: 987–1001.

Davies, C. E., Moss, D., and O Hill, M. 2004. EUNIS Habitat Classification Revised 2004. Report to the European Topic Centre on Nature Protection and Biodiversity. European Environment Agency. 307 p.

Dayton, P. K., Thrush, S. F., Agardy, M. T., and Hofman, R. J. 1995. Environmental-effects of marine fishing. Aquatic Conservation-Marine and Freshwater Ecosystems, 5: 205–232.

Duineveld, G. C. A., Bergman, M. J. N., and Lavaleye, M. S. S. 2007. Effects of an area closed to fisheries on the composition of the benthic fauna in the southern North Sea. ICES Journal of Marine Science, 64: 899–908.

EC. 1967/2006. Council Regulation (EC) No 1967/2006 of 21 December 2006 concerning management measures for the sustainable exploitation of fishery resources in the Mediterranean Sea, amending Regulation (EEC) No 2847/93 and repealing Regulation (EC) No 1626/94. OJ L 409, 30.12.2006, p. 11.

EC. 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environment policy (Marine Strategy Framework Directive). Journal of European Union, 164: 19–40.

Eigaard, O. R., Rihan, D., Graham, N., Sala, A., and Zachariassen, K. 2011. Improving fishing effort descriptors: modelling engine power and gear-size relations of five European trawl fleets. Fisheries Research, 110: 39–46.

Eigaard, O. R., Marchal, P., Gislason, H., and Rijnsdorp, A. D. 2014. Technological Development and Fisheries Management. Reviews in Fisheries Science and Aquaculture 22: 156–174.

Eigaard, O., Bastardie, F., Breen, M., Dinesen, G., Hintzen, N., Laffargue, P., Nielsen, J. *et al.* 2016. Estimating seabed pressure from demersal trawls, seines, and dredges based on gear design and dimensions. ICES Journal of Marine Science 73(Supplement 1): i27–i43.

Ellis, N., Pantus, F., and Pitcher, C. R. 2014. Scaling up experimental trawl impact results to fishery management scales — a modelling approach for a “hot time”. Canadian Journal of Fisheries and Aquatic Sciences, 71: 733–746.

Eno, N. C., Frid, C. L. J., Hall, K., Ramsay, K., Sharp, R. A. M., Brazier, D. P., Hearn, S. *et al.* 2013. Assessing the sensitivity of habitats to fishing: from seabed maps to sensitivity maps. Journal of Fish Biology, 83: 826–846.

EUNIS. http://www.eea.europa.eu/themes/biodiversity/eunis/eunis-habitat-classification (downloaded 12 July 2015).

Fock, H. O., Kloppmann, M., and Stelzenmüller, V. 2011. Linking marine fisheries to environmental objectives: A case study on seafloor integrity under European maritime policies. Environment Science Policy, 14: 289–300.

Gage, J. D., Roberts, J. M., Hartley, J. R., and Humphery, J. D. 2005. Potential impacts of deep-sea trawling on the benthic ecosystem along the Northern European continental margin: a review. *In* Benthic Habitats and the Effects of Fishing, vol. 41, pp. 503–517. Ed. by B. W. Barnes, and J. P. Thomas. American Fisheries Society Symposium, Bethesda, Maryland, USA.

Gerritsen, H. D., Minto, C., and Lordan, C. 2013. How much of the seabed is impacted by mobile fishing gear? Absolute estimates from vessel monitoring system (VMS) point data. ICES Journal of Marine Science, 70: 523–531.

Gerritsen, H. D., and Lordan, C. 2014. “Atlas of commercial fisheries around Ireland”. Marine Institute, Ireland. ISBN 978-1-902895-56-7. 59 pp.

Grabowski, J. H., Bachman, M., Demarest, C., Eayrs, S., Harris, B. P., Malkoski, V., Packer, D. *et al.* 2014. Assessing the vulnerability of marine benthos to fishing gear impacts. Reviews in Fisheries Science and Aquaculture, 22: 142–155.

Hall, S. J. 1994. Physical disturbance and marine benthic communities: life in unconsolidated sediments. Oceanography and Marine Biology Annual Review, 32: 179–239.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D’Agrosa, C., Bruno, J. F. *et al.* 2008. A global map of human impact on marine ecosystems. Science, 319: 948–952.

Hiddink, J. G., Johnson, A. F., Kingham, R., and Hinz, H. 2011. Could our fisheries be more productive? Indirect negative effects of bottom trawl fisheries on fish condition. Journal of Applied Ecology, 48: 1441–1449.

Hintzen, N. T., Piet, G. J., and Brunel, T. 2010. Improved estimation of trawling tracks using cubic Hermite spline interpolation of position registration data. Fish Research, 101: 108–115.

Hintzen, N. T., Bastardie, F., Beare, D., Piet, G. J., Ulrich, C., Deporte, N., Egekvist, J. *et al.* 2012. VMStools: Open-source software for the processing, analysis and visualisation of fisheries logbook and VMS data. Fisheries Research, 115–116: 31–43.

Horwood, J. 1993. The Bristol Channel Sole (*Solea solea* (L)) - a Fisheries Case-Study. Advances in Marine Biology, 29: 215–367.

ICES. 2014. Second Interim Report of theWorking Group on Spatial Fisheries Data (WGSFD), 10–13 June 2014, ICES Headquarters, Copenhagen, Denmark. ICES CM 2014/SSGSUE:05. 102 pp.

Jennings, S., and Kaiser, M. J. 1998. The effects of fishing on marine ecosystems. Advances in Marine Biology, 34: 201–352.

Jennings, S., Dinmore, T. A., Duplisea, D. E., Warr, K. J., and Lancaster, J. E. 2001. Trawling disturbance can modify benthic production processes. Journal of Animal Ecology, 70: 459–475.

Jennings, S., Freeman, S., Parker, R., Duplisea, D. E., and Dinmore, T. A. 2005. Ecosystem consequences of bottom fishing disturbance. American Fisheries Society Symposium, 41: 73–90.

Jennings, S., Lee, J., and Hiddink, J. G. 2012. Assessing fishery footprints and the trade-offs between landings value, habitat sensitivity, and fishing impacts to inform marine spatial planning and an ecosystem approach. ICES Journal of Marine Science, 69: 1053–1063.

Kaiser, M. J., Clarke, K. R., Hinz, H., Austen, M. C. V., Somerfield, P. J., and Karakassis, I. 2006. Global analysis of response and recovery of benthic biota to fishing. Marine Ecology-Progress Series, 311: 1–14.

Kerby, K., Cheung, W. L., and Engelhard, G. H. 2012. The United Kingdom’s role in North Sea demersal fisheries: a hundred year perspective. Reviews in Fish Biology and Fisheries, 22: 621–634.

Knights, A. M., Piet, G. J., Jongbloed, R. H., Tamis, J. E., White, L., Akoglu, E., Boicenco, L. *et al.* 2015. An exposure-effect approach for evaluating ecosystem-wide risks from human activities. ICES Journal of Marine Science, 72: 1105–1115.

Lambert, G. I., Jennings, S., Kaiser, M. J., Davies, T. W., and Hiddink, J. G. 2014. Quantifying recovery rates and resilience of seabed habitats impacted by bottom fishing. Journal of Applied Ecology, 51: 1326–1336.

Lee, J., South, A. B., and Jennings, S. 2010. Developing reliable, repeatable, and accessible methods to provide high-resolution estimates of fishing-effort distributions from vessel monitoring system (VMS) data. ICES Journal of Marine Science, 67: 1260–1271.

Lucchetti, A., and Sala, A. 2012. Impact and performance of Mediterranean fishing gear by side-scan sonar technology. Canadian journal of fisheries and aquatic sciences, 69: 1806–1816.

Maina, I., Kavadas, S., Katsanevakis, S., Somarakis, S., Tserpes, G., Georgakarakos S. 2016. A methodological approach to identify fishing grounds: A case study on Greek trawlers. Fisheries Research, 183, 326–339.

Murawski, S. A., Wigley, S. E., Fogarty, M. J., Rago, P. J., and Mountain, D. G. 2005. Effort distribution and catch patterns adjacent to temperate MPAs. ICES Journal of Marine Science, 62: 1150–1167.

Oberle, F. K. J., Storlazzi, C. D., and Hanebuth, T. J. J. 2016. What a drag: Quantifying the global impact of chronic bottom trawling on continental shelf sediment. Journal of Marine Systems

O’Neill, F. G., and Ivanovic, A. 2016. The physical impact of towed demersal fishing gears on soft sediments. ICES Journal of Marine Science, 73(Supplement 1): i5–i14.

O’Neill, F. G., and Summerbell, K. 2011. The mobilisation of sediment by demersal otter trawls. Marine Pollution Bulletin, 62: 1088–1097.

Piet, G. J., and Hintzen, N. T. 2012. Indicators of fishing pressure and seabed integrity. ICES Journal of Marine Science, 69: 1850–1858.

Piet, G. J., and Quirijns, F. J. 2009. The importance of scale for fishing impact estimations. Canadian Journal of Fisheries and Aquatic Sciences, 66: 829–835.

Pitcher, C. R., Poiner, I. R., Hill, B. J., and Burridge, C. Y. 2000. Implications of the effects of trawling on sessile megazoobenthos on a tropical shelf in northeastern Australia. ICES Journal of Marine Science, 57: 1359–1368.

Pitcher, C. R., Ellis, N., Venables, B., Wassenberg, T. J., Burridge, C. Y., Smith, G. P., Browne, M. *et al.* 2016. Effects of trawling on sessile megabenthos in the Great Barrier Reef and evaluation of the efficacy of management strategies. ICES Journal of Marine Science, 73(Suppl. 1): i115–i126.

Poos, J. J., and Rijnsdorp, A. D. 2007. The dynamics of small-scale patchiness of plaice and sole as reflected in the catch rates of the

Dutch beam trawl fleet and its implications for the fleet dynamics. Journal of Sea Research, 58: 100–112.

Pusceddu, A., Bianchelli, S., Martin, J., Puig, P., Palanques, A., Masque, P., and Danovaro, R. 2014. Chronic and intensive bottom trawling impairs deep-sea biodiversity and ecosystem functioning. Proceedings of the National Academy of Sciences of the United States of America, 111: 8861–8866.

Rice, J., Arvanitidis, C., Borja, A., Frid, C., Hiddink, J. G., Krause, J., Lorance, P. *et al.* 2012. Indicators for sea-floor integrity under the European Marine Strategy Framework Directive. Ecological Indicators, 12: 174–184.

Rijnsdorp, A. D., Buys, A. M., Storbeck, F., and Visser, E. G. 1998. Micro-scale distribution of beam trawl effort in the southern North Sea between 1993 and 1996 in relation to the trawling frequency of the seabed and the impact on benthic organisms. ICES Journal of Marine Science, 55: 403–419.

Rijnsdorp, A. D., Poos, J. J., Quirijns, F. J., HilleRisLambers, R., de Wilde, J. W., and Den Heijer, W. M. 2008. The arms race between fishers. Journal of Sea Research 60: 126–138.

Rijnsdorp, A. D., Poos, J. J., and Quirijns, F. J. 2011. Spatial dimension and exploitation dynamics of local fishing grounds by fishers targeting several flatfish species. Canadian Journal of Fisheries and Aquatic Sciences 68: 1064–1076.

Rijnsdorp, A. D., Bastardie, F., Bolam, S. G., Buhl-Mortensen, L., Eigaard, O. R., Hamon, K. G., Hiddink, J. G. *et al.* 2016. Towards a framework for the quantitative assessment of trawling impacts on the seabed and benthic ecosystem. ICES Journal of Marine Science (2016) 73(Supplement 1), i127–i138. doi:10.1093/icesjms/fsv207

Russo, T., D'Andrea, L., Parisi, A., and Cataudella, S. 2014. VMSbase: an R-package for VMS and logbook data management and analysis in fisheries ecology. PLoS One, 9: e100195.

Sala, A., and Damalas, D. 2015. Scientific, Technical and Economic Committee for Fisheries (STECF) – Landing Obligation - Part 6 (Fisheries targeting demersal species in the Mediterranean Sea) (STECF-15-19), 2015. Publications Office of the European Union, Luxembourg, ISSN 1831-9424, ISBN 978-92-79-54006-6, doi:10.2788/65549, EUR 27600 EN, JRC 98678, 268 pp.

Scarcella, G., Grati, F., Raicevich, S., Russo, T., Gramolini, R., Scott, R. D., Polidori, P. *et al.* 2014. Common sole in the northern and central Adriatic Sea: Spatial management scenarios to rebuild the stock. Journal of Sea Research 89: 12–22.

Scientific, Technical and Economic Committee for Fisheries (STECF) – Evaluation of Fishing Effort Regimes in European Waters - Part 2 (STECF-14-20). 2014. Publications Office of the European Union, Luxembourg, EUR 27027 EN, JRC 93183, 844 pp.

Smith, C. J., Papadopoulou, K. -N., Barnard, S., Mazik, K., Elliott, M., Patrício, J., Solaun, O., Little, S., Bhatia, N., and Borja, A. 2016. Managing the marine environment, conceptual models and assessment considerations for the european marine strategy framework directive. Frontiers in Marine Science, 3: 19.

Thrush, S. F., Lundquist, C. J., and Hewitt, J. E. 2005. Spatial and temporal scales of disturbance to the seafloor: a generalized framework for active habitat management. American Fisheries Society Symposium, 41: 639–649.

Valdemarsen, J. W. 2001. Technological trends in capture fisheries. Ocean and Coastal Management, 44: 635–651.

van Denderen, P. D., van Kooten, T., and Rijnsdorp, A. D. 2013. When does fishing lead to more fish? Community consequences of bottom trawl fisheries in demersal food webs. Proceedings of the Royal Society B: Biological Sciences, 280: 20131883.

van Denderen, P. D., Hintzen, N. T., Van Kooten, T., and Rijnsdorp, A. D. 2015a. Temporal aggregation of bottom trawling and its implication for the impact on the benthic ecosystem. ICES Journal of Marine Science, 72: 952–961.

van Denderen, P. D., Bolam, S. G., Hiddink, J. G., Jennings, S., Kenny, A., Rijnsdorp, A. D., and van Kooten, T. 2015b. Similar effects of bottom trawling and natural disturbance on composition and function of benthic communities across habitats. Marine Ecology Progress Series, 541: 31–43.

Vasilakopoulos, P., Maravelias, C. D., and Tserpes, G. 2014. The Alarming Decline of Mediterranean Fish Stocks. Current Biology, 24: 1643–1648.

Watling, L., and Norse, E. A. 1998. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. Conservation Biology, 12: 1180–1197.

Watson, R., Revenga, C., and Kura, Y. 2006. Fishing gear associated with global marine catches: II. Trends in trawling and dredging. Fisheries Research, 79: 103–111.

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