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Benthic impact of fisheries in European waters: the distribution and intensity of bottom trawling

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SUMMARY

Mapping and monitoring of pressure from fishery on the marine benthic environment is necessary to support an ecosystem approach to fisheries management (EAFM). In many cases this need is not reflected in official fisheries statistics and logbooks, where focus typically is on catch rather than effort. Consequently, most logbook information is not well suited for quantitative estimation of seafloor impact (swept area and impact severity) of the different gears and trips. We developed a method to overcome this information deficiency of official statistics and produced European wide high-resolution fishing intensity maps (total yearly swept area within grid cells of 1*1 minutes longitude and latitude) for 2010, 2011 and 2012. The annual distribution and intensity of bottom trawling on the European continental shelf was analyzed for different management areas and gear groups, distinguishing between surface and sub-surface effects. Fishing pressure indicators were calculated and compared for each management area; i) proportion of area untrawled, ii) proportion of area with an annual swept area intensity ≥ 1, and iii) proportion of area where 90% of the effort is concentrated).

The management area with the largest proportion of surface area being trawled ≥ 1 time a year was the Adriatic Sea (64%) and the management area with the lowest proportion of surface area being trawled ≥ 1 time a year was the Northwestern Shelf (15%). Also the Tyrrhenian Sea (45%), the Channel (41%) and the North Sea (36%) have a substantial part the seabed trawled at intensities above 1, indicating a high level of fishing pressure on the benthic habitats. The results of the analysis also showed that in all European seas, between 33% and 72% of the sea bed down to 200 m was not trawled during the study period.

When considering all three fishing pressure indicators jointly (proportion of area untrawled, proportion with an annual intensity ≥ 1, and with 90% of the effort) four management areas draw attention; the North Sea, the Channel, the Tyrrhenian Sea and Adriatic Sea. These four areas all score relatively high on all three pressure indicators, and also have a substantial part (> 50%) of the total area impacted at the sub-surface level. Within the soft sediment habitats that dominate the continental shelf areas of Europe, mud habitats appear to be trawled most intensively while at the same time they likely have a higher sensitivity to bottom trawling as compared to the sandy and coarser sediments. Consequently, current fishing practices in parts of these four management areas could potentially compromise seafloor integrity.

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1. 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 sea bed habitats and the structure and functioning of benthic ecosystems (Dayton et al., 1995; Watling and Norse, 1998; Jennings and Kaiser, 1998). These mobile, bottom contacting gears have proven efficient for catching a number of fish and shellfish species and their use has increased globally since the 1950s (Watson et al., 2006; Valdemarsen, 2001).

The continental shelf habitats along the European coasts are among the most productive fishing grounds for bottom dwelling fish species and has 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 sea bed habitats (Watling et al., 1998; Thrush and Dayton, 2002) 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). The ecosystem effects of bottom trawling will be determined by the type of gear deployed, the type of sea bed, direct effects of the passage of a trawl, the foot print of the trawl and the trawling frequency and the sensitivity of the sea bed and benthic ecosystem (Jennings et al. 2005; Rijnsdorp et al., 2015).

In European waters, four main demersal gear groups can be distinguished based on their characteristics (otter trawl, seine, beam trawl, dredge). The groups can be further broken up into métiers based on the target species (Eigaard et al. 2011; Eigaard et al., 2015). The rigging of the gear used in these métiers is adapted to the specific target species and sea bed 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 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 that apply large rubber discs to 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 into the sediment. In a pan-European study, Eigaard et al (2015) collected data on the gear characteristics and dimensions of the gear used in 14 different métiers to estimate the foot print on the surface and sub-surface level. The surface area affected during one hour of fishing differed widely across the métiers. Scottish seining has the largest overall gear footprint of ~1.6 $km^2\ h^{-1}$ of which 0.08 km^2 has an impact at the subsurface level (sediment penetration ≥ 2 cm). Otter trawling for Nephrops and demersal fish covers 1.2 $km^2\ h^{-1}$ and has the highest impact at the subsurface level of ~0.28 $km^2\ h^{-1}$. Beam trawling for flatfish ranks low when comparing overall footprint size/hour but ranks substantially higher when comparing the impact at the subsurface level (0.19 $km^2\ h^{-1}$).

The mortality imposed by the passage of a trawl is habitat specific and differs between benthic species groups and type of fishing gear. Collie et al. (2000) and Kaiser et al. (2006) showed in their comprehensive reviews that the most severe impact occurred in biogenic habitats (sessile epifaunal species) in response to scallop-dredging, followed by the effect of beam trawls in sandy habitats and otter trawls in muddy habitats. In sandy sediments, deposit feeding macrofauna were reduced by approximately 20% by beam trawls and otter trawls and 40% by scallop dredges, whereas suspension feeders declined by 70% by beam trawls, 45% by scallop dredges and 5% by otter trawls. 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 of a variety of sea bed habitats. The European Nature Information System (EUNIS) has developed a generic and hierarchical habitat classification scheme (http://eunis.eea.europa.eu/index.jsp). Sea bed habitats are classified based on environmental variables that constrain biological communities such as substrate types, 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 will reflect differences in sensitivities to trawling. Low energy habitats will be rather stable and will be 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 will be more sensitive to bottom trawling, while well-sorted, sandy substrates will be less sensitive (Bolam et al., 2014).

The assessment of the impact of bottom trawling on the sea bed and benthic ecosystem has been hampered by the lack of data of 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 (van Denderen et al., 2015). Hence, for a proper assessment of the impact of bottom trawling on the sea bed and benthic ecosystem, it is important to collect and analyze data on 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 (Hintzen et al., 2012; Lee et al., 2010; Gerritsen et al., 2013).

The European Union adopted the Marine Strategy Framework Directive (MSFD) to protect more effectively the marine environment and aims to achieve good environmental status (GES) by 2020 (EC, 2008). The status of the marine environment, and the human pressures acting upon it, are described by eleven qualitative descriptors of which the descriptor on seafloor integrity (or D6) states that “the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected”. Quantitative indicators and reference levels are required to assess progress towards GES (Rice et al., 2012). In addition, indicators of fishing pressure that are based on high resolution analysis of fishing effort have been proposed that estimate the spatial extent of fishing and its impact on the seafloor (Piet and Hintzen, 2012).

The objective of this paper is to study the distribution and intensity of bottom trawling on the European continental shelf for the period 2010-2012 and compare it across management areas. Trawling intensity will be analysed for different sea bed habitat types and the main gear groups, distinguishing between surface and sub-surface effects. Trawling intensity will be expressed as the proportion of the sea bed habitat trawled at certain intensities (untrawled, trawled ≤1 time per year and trawled >5 time per year) and discussed in relation to the sensitivity of the sea bed habitats.

2 METHODS

2.1 Study area

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

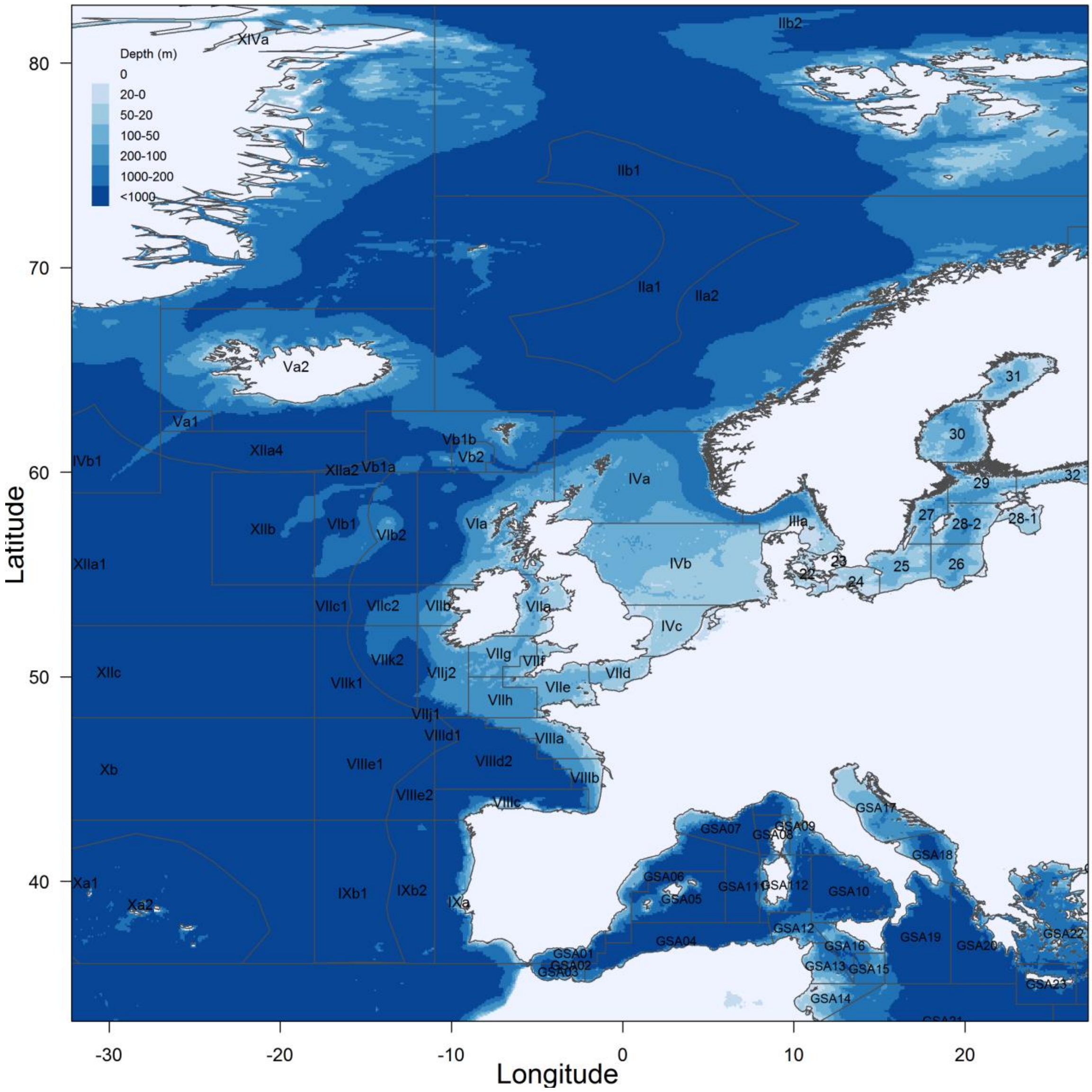

Figure 1. The management units and bathymetry of the case study area.

Sea bed habitat

EUNIS Level 3 sea bed habitat information was available for a substantial part of the European continental shelf, but do 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 Mediterranean (Figure 2) as well as for the Barents Sea and Norwegian Sea (Figure 1, supplementary data), which together with regional habitat maps of downloaded EUNIS data (two examples in Figure 3) form the basis of the further analyses.

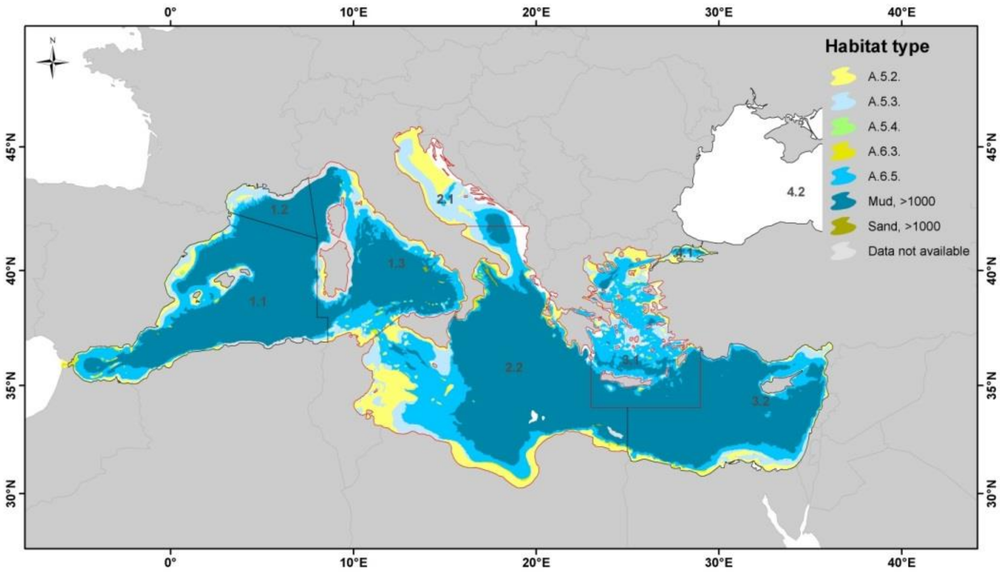

Figure 2. Habitat distribution of the Mediterranean according to the EUNIS categorization. Modelled from sediment and bathymetry data provided by HCMR.

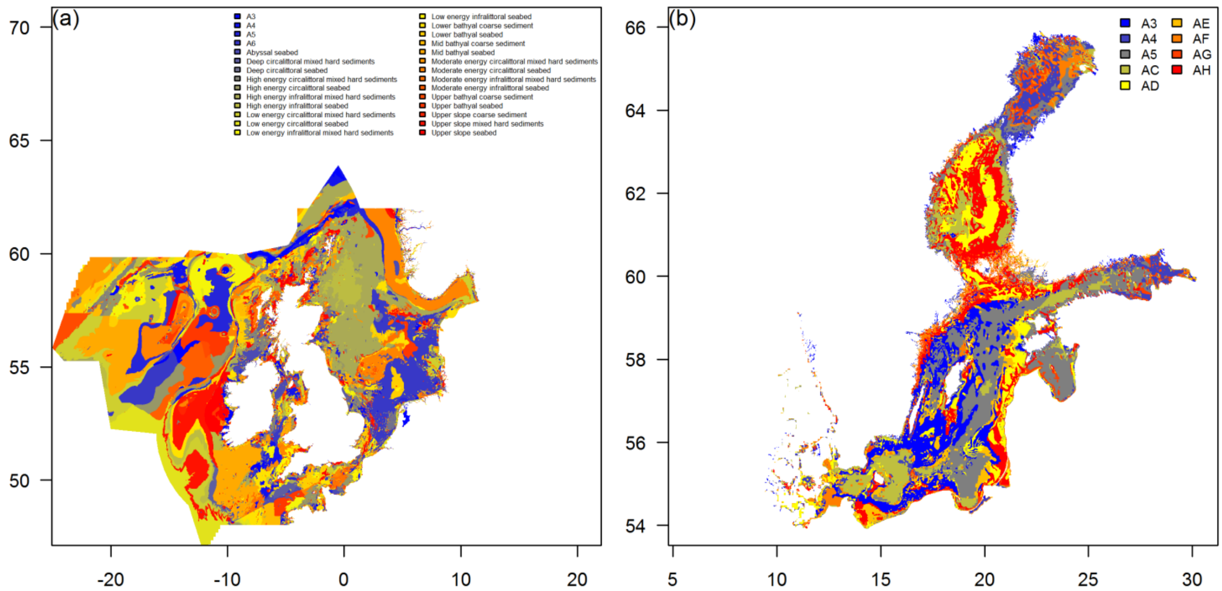

Figure 3. a) habitat distribution of Atlantic management units based on EUNIS data from (http://www.emodnet-seabedhabitats.eu/default.aspx?page=1974). b) same for the Baltic Sea.

Table 1. Surface area of sea bed habitats (%) between 0-200 meters depth for the management areas with good fishing effort coverage.

	Western Baltic	Skagerrak	North Sea	Channel	Celtic Sea	Irish Sea	Northern Shelf	Western Shelf	Tyrrhenian Sea
	22-25	IIIa	IVa, b, c	VIId	VIIIe, f, g,h	VIIa	VIa	VIIb, c, j, k	1.3
A3.1: Atlantic and Mediterranean high energy infralittoral rock		0.5	0.2	2.6	0.8	0.7	3.9	0.2	
A3.2: Atlantic and Mediterranean moderate energy infralittoral rock	0.0		0.3	1.2	0.5	0.3	1.4	0.0	0.7
A3.3: Atlantic and Mediterranean low energy infralittoral rock	0.0		0.0		0.0	0.1	0.4		
A4.1: Atlantic and Mediterranean high energy circalittoral rock			0.1	4.7	0.5	0.6	0.8	0.1	
A4.2: Atlantic and Mediterranean moderate energy circalittoral rock			2.0	16.5	6.4	2.2	6.1	1.5	
A4.3: Atlantic and Mediterranean low energy circalittoral rock			1.5		5.4	0.3	2.9	0.6	
A5.1: Sublittoral coarse sediment			12.1	47.8	31.3	38.1	39.5	2.1	0.7
A5.2: Sublittoral sand	0.0	4.1	69.5	10.4	20.3	22.3	30.4	17.0	6.9
A5.3: Sublittoral mud	0.1	0.3	10.1	0.5	6.1	16.1	8.8	0.9	23.7
A5.4: Sublittoral mixed sediments			0.5	16.3	9.5	19.0	2.6	0.1	58.6
Sublittoral macrophyte-dominated sediment									4.6
A6.1: Deep-sea rock and artificial hard substrata			0.0			0.1	0.0		
A6.2: Deep-sea mixed substrata			0.0			0.0	0.0	0.0	0.0
A6.3: Deep-sea sand or A6.4: Deep-sea muddy sand			0.2		0.0	0.0	0.2	0.5	2.4
A6.5: Deep-sea mud			0.1		0.0	0.1	0.1	0.6	2.5
Deep circalittoral mixed hard sediments			1.0						
Deep circalittoral seabed			0.5		18.6		2.0	67.2	
High energy circalittoral mixed hard sediments			0.0						
High energy circalittoral seabed			0.0	0.0	0.0	0.0	0.0	0.3	
High energy infralittoral mixed hard sediments			0.0						
High energy infralittoral seabed			0.4		0.1	0.1	0.3	1.8	
Low energy circalittoral mixed hard sediments			0.1			0.0			
Low energy circalittoral seabed			0.1		0.1	0.0	0.0	0.6	
Low energy infralittoral mixed hard sediments						0.1			
Low energy infralittoral seabed			0.0				0.0	0.0	
Moderate energy circalittoral mixed hard sediments			0.6					0.0	
Moderate energy circalittoral seabed			0.2	0.0	0.3	0.0	0.0	5.7	
Moderate energy infralittoral mixed hard sediments			0.1						
Moderate energy infralittoral seabed			0.1		0.0	0.0	0.1	0.2	
Upper bathyal seabed			0.0						
Upper slope coarse sediment			0.0		0.0	0.1	0.2	0.1	
Upper slope mixed hard sediments			0.0		0.1				
Upper slope seabed			0.2				0.2	0.5	
Baltic circalittoral coarse sediment	2.7	0.1							
Baltic circalittoral mixed sediment	16.1	0.8							
Baltic circalittoral mixed substrata	3.2								
Baltic circalittoral mud	7.3	5.7							
Baltic circalittoral rock and boulders	0.1	1.1							
Baltic circalittoral sand	16.4	1.0							
Baltic coarse sediment below the halocline	0.0								
Baltic coarse sediment below the halocline ??	0.6								
Baltic infralittoral coarse sediment	1.8	10.3							
Baltic infralittoral mixed sediment	1.1	20.8							
Baltic infralittoral mixed substrata	7.6	3.5							
Baltic infralittoral mud	2.8	19.1							
Baltic infralittoral rock and boulders	0.7	2.2							
Baltic infralittoral sand	15.0	30.5							
Baltic mixed sediment below the halocline	2.8								
Baltic mixed substrata below the halocline	0.0								
Baltic mud below the halocline	20.4								
Baltic sand below the halocline	1.2								

The management areas are different with respect to dominating habitat types within the 200 meters depth zone. In particular the North Sea sticks out with one very dominating habitat type, 69.5% sublittoral sand, and with few habitats of coarser sediments. Also the Western Baltic and the Skagerrak-Kattegat are dominated by soft sediment (mud and sand) habitat-types with only few areas of mixed, coarse or rocky sediments. These latter types of sediments (and habitat types) are more dominating in the Northern Shelf (Via) all area VII (Channel, Celtic Sea, Irish Sea and Western shelf) with the Channel having the highest proportion of coarse and rocky sediments. The Tyrrhenian Sea habitats at depths less than 200 m are dominated by mixed sediments (58.6%).

2.2 Fishing effort data

The European fishing effort with mobile, bottom contacting gears was analyzed by the 14 métiers defined by Eigaard et al (2015) (Table 2). The total footprints of an average vessel of each métier are quite different and these differences are an integrative part of the calculated fishing intensities at the surface and subsurface level, respectively. For presentation purposes, however, results will be aggregated and presented for the total bottom trawl fleets and for the four major gear groups; otter trawls, demersal seines, beam trawls and dredges.

Although VMS data were available for most of the European countries, some of the important bottom trawling countries was missing, in particular the absence of French and Spanish VMS-based fishing effort information was visible in the coverage assessment of our effort data. To estimate the coverage of our data, a comparison was made between the total international fishing effort as recorded in the STECF data base (https://datacollection.jrc.ec.europa.eu/data-dissemination) and the fishing effort of the bottom trawl métiers covered by our study (Table 3).

Bottom trawl effort was well covered by the sampled fleets in most of the management areas (Table 3). Coverage was excellent (>95%) in Skagerrak (IIIa), North Sea (IVa,b, c), Northwestern Shelf (VIa) and Irish Sea (VIIa). Good coverage (>70%) was obtained in the Norwegian Sea (IIa), Baltic Sea (22-25), Celtic Sea (VIIe,f,g,h), off the Portuguese coast (IXa) and in the Ionian Sea (2.2). Coverage was less good in the Channel (VIId), Western Shelf (VIIb,c,j,k), Bay of Biscay (VIIIa-d), Tyrrhenian Sea (1.3), Northern Adriatic (2.1) and Agean Sea (3.1).

Table 2. Métiers of the European bottom trawl fleet and the foot print of an average vessel at the surface and sub-surface level per hour of fishing (from Eigaard et al. 2015).

Main gear type	BENTHIS metier	Typical target species	Foot print ($km^2 . hr^{-1}$)		Towing speed ($nm. h^{-1}$)
			Surface	Sub-surface	
Otter trawls	OT_CRU	Nephrops or shrimps	0.12	0.25	2.5
	OT_DMF	Cod or plaice or Norway pout	0.06	0.71	3.1
	OT_MIX	Individual species not informed	0.05	0.27	2.8
	OT_MIX_DMF_BEN	Mixed benthic fish	0.06	0.63	3.0
	OT_MIX_DMF_PEL	Mixed bentho-pelagic fish	0.09	0.33	2.6
	OT_MIX_CRU	Mixed shrimp	0.16	0.39	2.9
	OT_MIX_CRU_DMF	Nephrops and mixed fish	0.28	0.94	3.4
	OT_SPF	Sprat or sandeel	0.03	1.06	2.9
Beam trawls	TBB_CRU	Crangon	0.05	0.05	2.9
	TBB_DMF	Sole and plaice	0.19	0.00	5.2
	TBB_MOL	Thomas' Rapa whelk	0.02	0.00	2.4
Dredges	DRB_MOL	Scallops, mussels	0.08	0.00	2.5
Demersal seines	SDN_DEM	Plaice, cod	0.00	0.99	0-2.5
	SSC_DEM	Cod, Haddock, flatfish	0.08	1.50	0-3.0

Table 3. Annual mean number of fishing effort of the Atlantic fleets/countries and Mediterranean fleets/countries covered in this study by management area and the % of the total EU effort. Effort data are based on the STECF data base and represent bottom trawl fleets.

Management Area	Days at sea ($x 10^3$)	kW-days (x 1000)	% of total EU effort
Norwegian Sea (IIa)	7		75%
Baltic Sea (22, 23, 24, 25)	1475		94%
Skagerrak / Kattegat (IIIa)	958		99%
North Sea (IVa,b,c)	4864		99%
Channel (VIId)	1844		52%
Celtic Sea (VII e, f, g, h)	3896		80%
Irish Sea (VIIa)	1606		100%
Northwestern Shelf (VIa)	2165		95%
Western Shelf (VIIb-c, VIIj-k)	2538		60%
Biscay (VIIIa-d)	2197		20%
Portuguese shelf (IXa)	613		73%
Tyrrhenian Sea (1.3)		26 672*	59%
Northern Adriatic (2.1)		26 360*	28%
Ionian Sea (2.2)		931*	76%
Agean Sea Sea (3.1)		45 177*	46%

* No effort data was reported to the EU from Greece In the period 2010-2012. This was, however, done in 2013 and since Greek effort constitutes a large part of the data behind the Mediterranean effort maps above, it was decided to assume that annual mean coverage in 2010-2012 is similar to the 2013 coverage estimated as the proportion of total effort, which is conducted with Italian and Greek vessels of at least 12 meters

VMS data were coupled to logbook data and combined per métier, for the years 2010, 2011 and 2012, based on methodology developed by Hintzen et al. (2012). Individual logbook observations from 13 countries were assigned to 14 different functional gear groups (‘BENTHIS métiers) based on target species and gear type information obtained though industry interviews (Eigaard et al. 2015). Relationships between gear dimensions and vessel size (e.g. trawl door spread and vessel kW) for each métier were used to assign quantitative information of bottom contact (e.g. width of gear) to each logbook trip. The extended logbook data were combined with interpolated vessel tracks based on VMS data (Hintzen et al., 2010). In this way the total sea bed area swept by a given vessel and fishing gear over the three year period could be estimated taking account of the foot print of the métiers. The total swept area was estimated within grid cells of 1x1 minute longitude and latitude, which corresponds to approx. 1.9 km^2 at 56 ^oN with cell size gradually increasing or decreasing the more southern or northern 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 scale bottom trawling can be considered to be randomly distributed within a grid cell (Rijnsdorp, et al. 1998; Lee et al., 2010). The analyses were done on national level using a standardized R-workflow through a common web based platform and swept areas were added over the countries. (https://code.google.com/p/vmstools/source/browse/trunk/vmstools/inst/scripts/Benthis_WP2_workflow.r)

3 RESULTS

3.1 Distribution

Bottom trawling is widely distributed over the continental shelf of Europe, although large parts, indicated in blue, are trawled at an intensity of less than once in every two years (Figure 4). Moderate trawling intensities between 1 and 10 times per year occur in the Norwegian Sea around Bjørnøya and along the coast off northern Norwegian, in large areas of the northern and southern North Sea, around Bornholm in the Baltic Sea, south of Ireland in the Celtic Sea and along the narrow continental shelf off Portugal. In the Mediterranean Sea, moderate trawling occurs in a large part of the Adriatic Sea, The Tyrrhenian Sea and the waters east of Tunisia, and along the coast of Greece.

The trawling hot spots with significant areas of intensities exceeding 10 times per year, indicated in red, occur in localised areas, along the coast of northern Norway, along the edge of the Norwegian deep in the northern North Sea and Skagerrak, in areas off the coast of Ireland, south of Portugal and along the Adriatic coast of Italy.

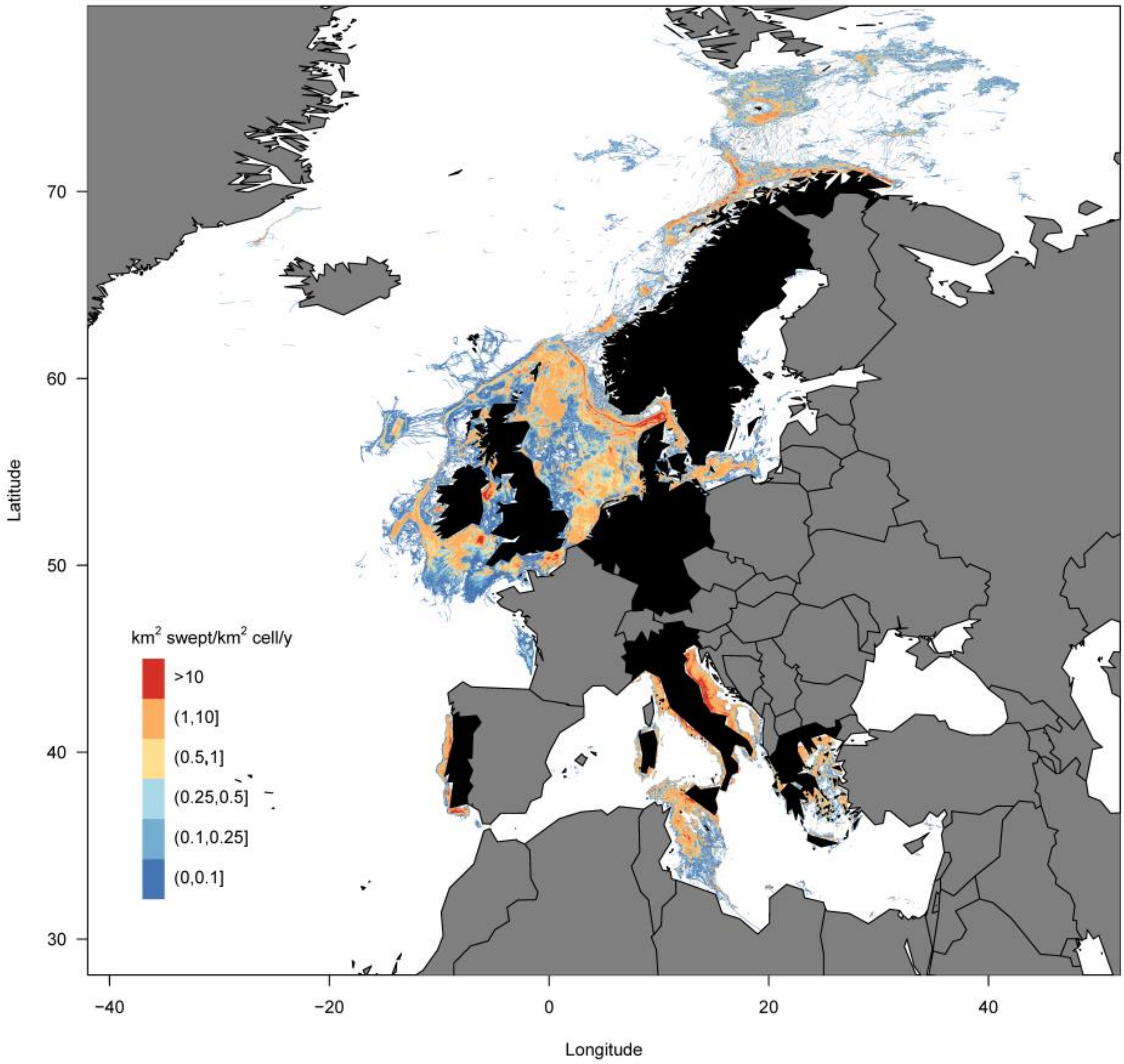

Figure 4. Mean annual trawling intensity in the period 2010-2012 at the surface layer (total swept area) estimated from VMS and logbook data of bottom trawl fleets. Countries marked black provided data.

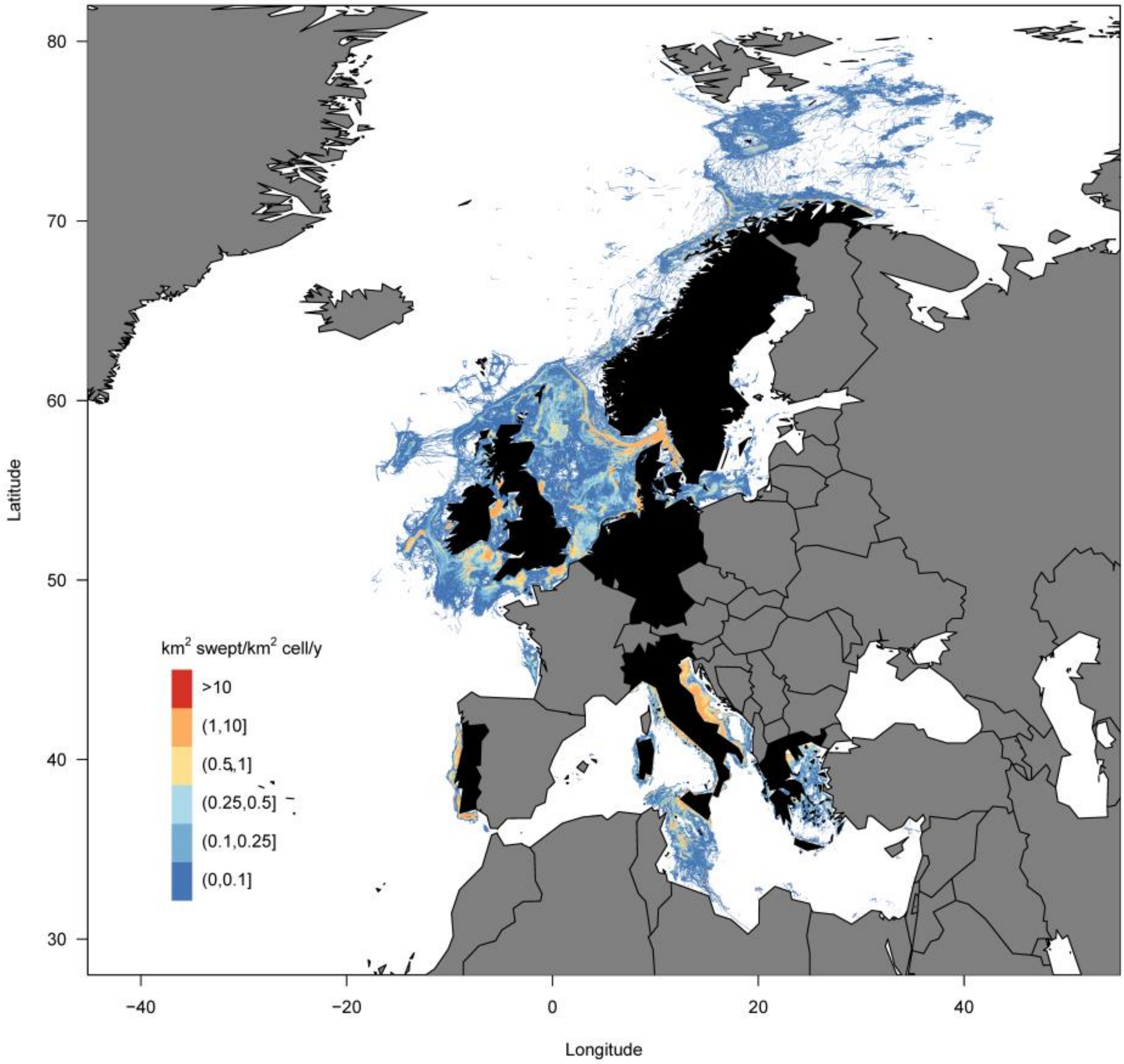

Figure 5. Mean annual trawling intensity in the period 2010-2012 at the sub-surface level estimated from VMS and logbook data of bottom trawl fleets. Countries marked black provided data.

At the sub-surface level, bottom trawling intensities are generally much lower (Figure 4). The lower sub-surface intensities are due to the generally lower sub-surface footprint of most of the bottom trawl métiers (Table 2). The relatively high sub-surface footprint in the southern North Sea, Irish, Celtic Sea and Adriatic Sea are largely due to the trawling activities of the beam trawl and dredge fisheries which have similar surface and sub-surface footprints, but also some of the otter trawl métiers contribute significantly in some of areas. In the Northern North Sea and Skagerrak the high sub-surface footprint is almost exclusively a result of high fishing intensities with bottom trawls targeting Nephrops and mixed fish, which have a significant sub-surface impact (Table 2).

It should be noted that the trawling intensities shown in Figure 4 and 5 represent part of the bottom trawling activities in Europe. In particular bottom trawling will be underestimated in the Bay of Biscay and western Mediterranean Sea, and to a lesser extent in the Celtic Sea, due to the lack of data of France and Spain which have a large fleet of bottom trawlers operating in these areas. The lack of data from the Baltic countries will have less of an effect as the bottom trawlers are a minor component of the fishing fleet. In the Adriatic Sea, the lack of data from the former Yugoslavian countries will have a small effect as bottom trawling in these countries operate in the nearshore shallow waters.

The distribution 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 less than 200 metres (Figure 6). This is more pronounced in the Atlantic than in the Mediterranean, but in both Seas the fishing effort and the benthic impact below 1000 metres is very limited. The gear types deployed also relates to the bathymetry; where beam trawls and dredges are deployed in shallower waters (almost exclusively at depths from 20 to 100 meters) the demersal otter trawls and seines are universal gears that are deployed at all depths.

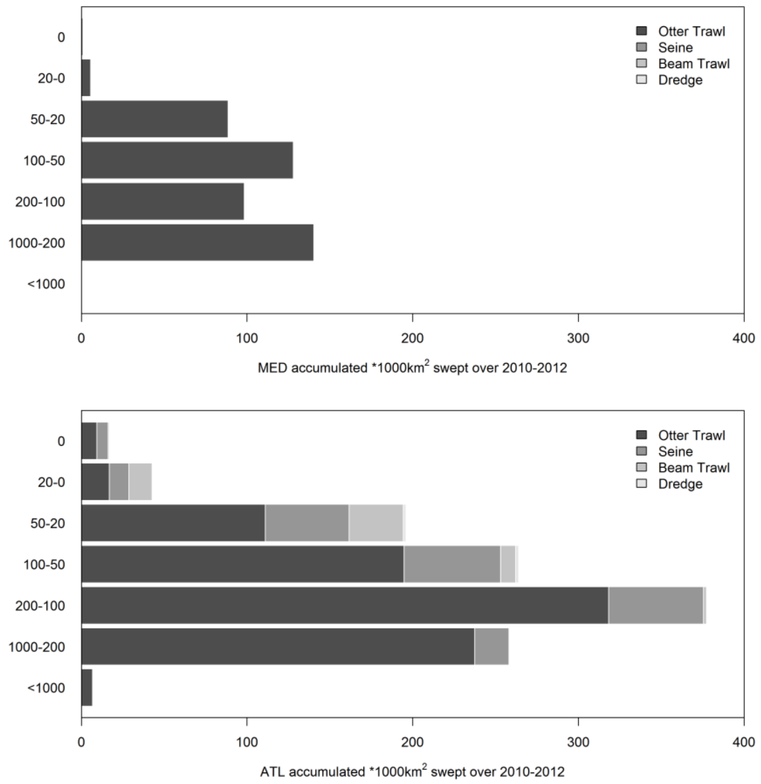

Figure 6. The total swept area of fishing effort (2010-2012) with mobile, bottom contacting gears in the Atlantic and the Mediterranean by depth band and gear type.

Figure 7 shows the maps of trawling intensity of the four gear groups. The otter trawl has by far the largest distribution area in both the Atlantic and Mediterranean shelf areas. Demersal seines have a wide distribution in the Norwegian Sea, North Sea, waters around the UK and the Baltic Sea. Beam trawls are mostly deployed in the southern North Sea, the Celtic Sea and the Adriatic Sea, while the dredge is restricted to the coastal waters around the UK and France. This distribution of different gears can largely be attributed to bathymetry, as described above, but presumably also sediment type and species abundance play a key role in the patterns of gear deployment.

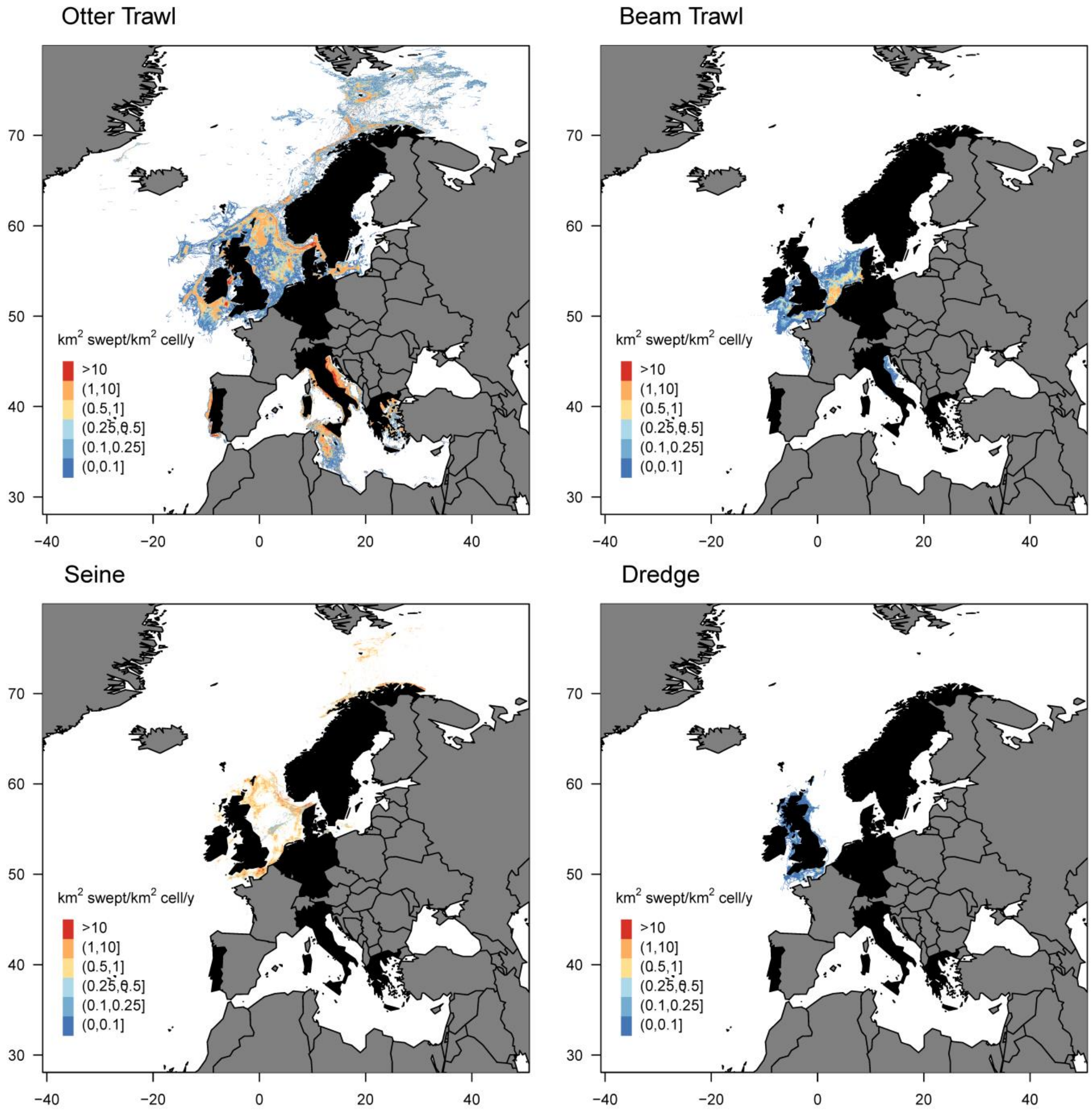

Figure 7. Fishing intensity (total swept area) by main gear groups (demersal otter trawls, beam trawls, demersal seines and dredges) for the areas analysed.

3.2 Indicators of trawling pressure

Mean annual trawling intensities were estimated by grid cell from the ratio of the total yearly swept area over the size of the grid cell as described above, and three indicators of fishing pressure (Piet and Hintzen, 2012; Rijnsdorp et al. 2015) were estimated for the analyzed management areas (Figure 8). The first indicator gives the proportion of the habitat that is not trawled during the three years of the analysis. The untrawled area is defined as the surface areas of the grid cells where no fishing was recorded plus the untrawled part (proportion) of the grid cells which were trawled less than once a year. The second indicator gives the proportion of the habitat that is trawled at least once a year. The third pressure indicator reflects the surface area of habitat where most of the trawling occurs, i.e. the smallest surface area within which 90% of the trawling can be located.

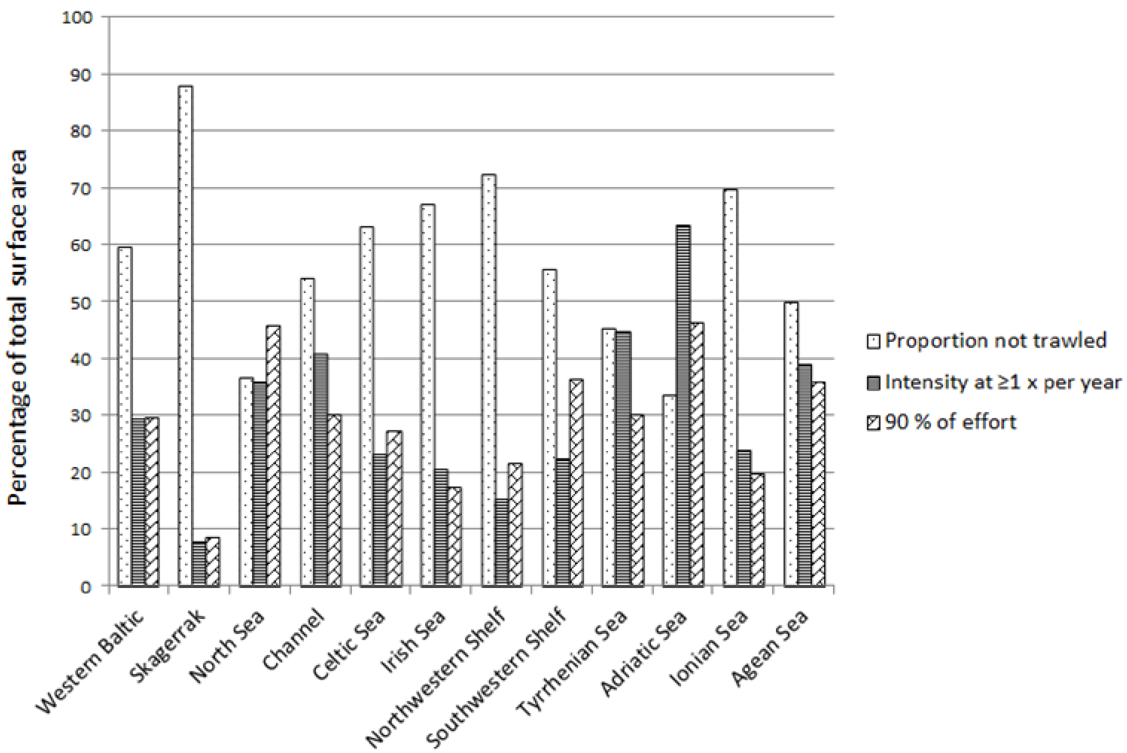

Figure 8.The proportion of the total management area, which is untrawled, which has an annual fishing intensity at ≥ 1, and which has 90% of the effort (for the period 2010-2012).

All three indicators imply the lowest fishing pressure for the Skagerrak-Kattegat area, but the estimated indicator values are not realistic (c.f. figure 4 with fishing intensity of the area) and are most likely the result of poor availability and quality of habitat data for this management area. For the other management areas, between 33 % (Adriatic Sea) and 72 % (Northwestern Shelf) of the sea bed down to 200 m was not trawled during the study period. The management area with the largest proportion of surface area being trawled ≥ 1 time a year was the Adriatic Sea (64%) and the management area with the lowest proportion of surface area being trawled ≥ 1 time a year was the Northwestern Shelf (15%). In the Irish Sea 90% of the effort was located within only 17% of the total surface area, whereas for the North Sea and Adriatic Sea it was 46%

3.3 Distribution and intensity of bottom trawling

Bottom trawling shows a heterogeneous distribution across the analysed management areas with certain areas being trawled heavily while other areas are trawled lightly or not at all. The heterogeneous distribution is illustrated by the relationship between the proportions of the surface area trawled at a certain trawling intensity (Figure 9). As for the fishing pressure indicators described above, the fishing intensity estimates for Skagerrak-Kattegat in Figure 9 area are not realistic given the high fishing effort in the area (Figure 4) and are most likely the result of poor habitat data for this management area.

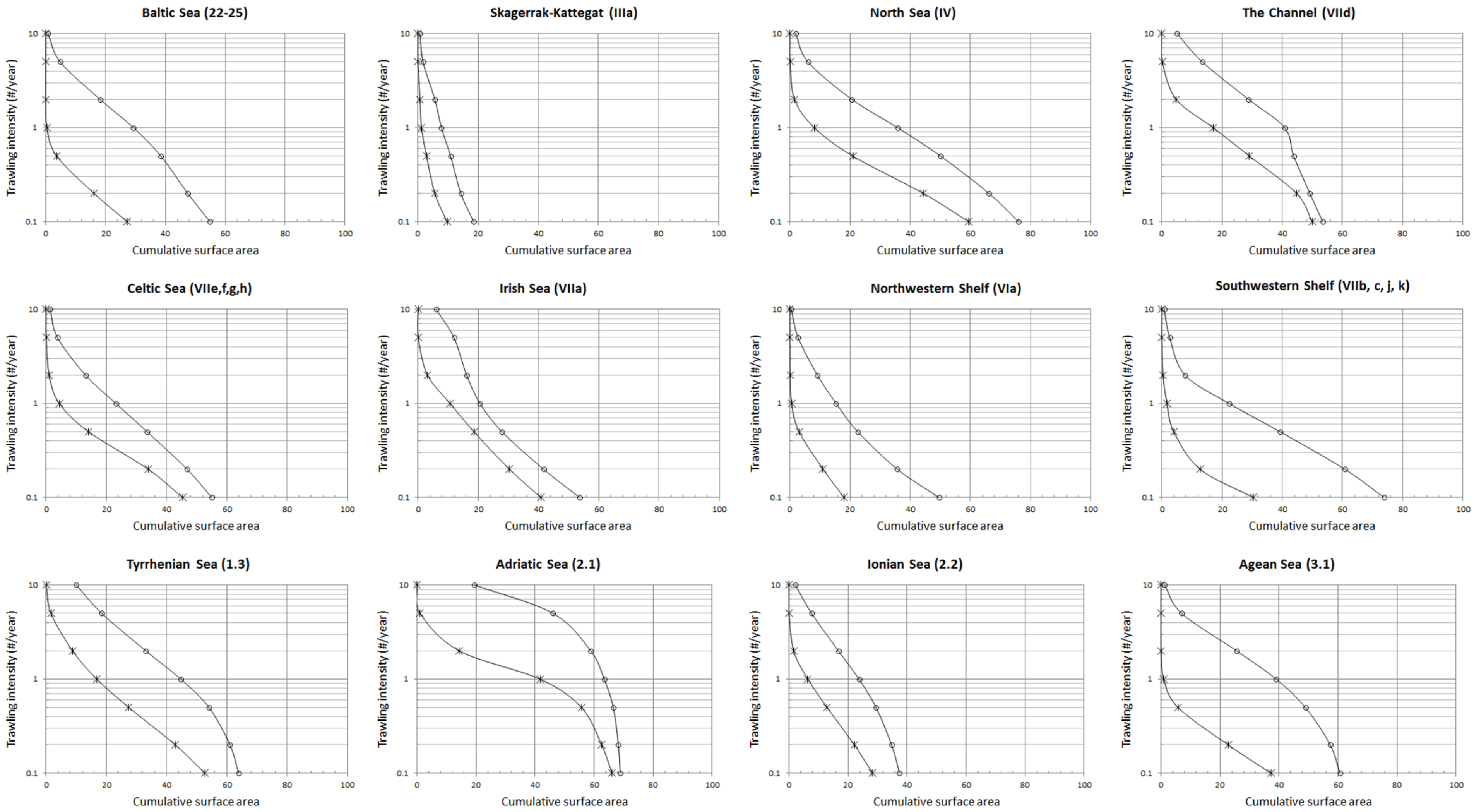

Figure 9. Cumulative swept area intensities at the surface (circles) and subsurface level (crosses) for 12 management areas.

Four management areas (not considering the Skagerrak-Kattegat area) display similarities in terms of low swept area intensities at the sub-surface level (< approx. 1) in relatively small proportions of the total surface area. The Western Baltic, the Northwestern shelf, the Southwestern Shelf, and the Agean Sea also have relatively large distance between the surface and the sub-surface lines of the intensity plots, meaning that the vast majority of the total trawled seabed area is swept only at the surface level. For the seven other management areas, the sub-surface intensity is substantially higher (> approx. 2) in a substantially larger proportion of the total surface area, and the North Sea, the Channel, the Celtic Sea, the Irish Sea, the Tyrrhenian Sea, the Adriatic Sea, and the Ionian Sea also have relatively little distance between the surface and the sub-surface lines of the intensity plots, meaning that the a substantial part of the total trawled seabed area is swept at the sub-surface level. The Tyrrhenian Sea, the Adriatic Sea, the Irish Sea and the Channel have the highest intensities (up to about 5) and the North Sea and the Adriatic Sea the largest proportion of total seabed area (>=60%) swept at the sub-surface level.

3.4 Intensity of bottom trawling by sea bed habitat

The trawling intensity is clearly related to sea bed habitat (Figure 10). Mud habitats (EUNIS habitat A5.3 or Baltic circalittoral mud) are widely trawled. The proportion of this habitat type that is trawled more than once per year ranges from about 55% (VIIa) to almost 70% (Baltic). Also the proportion trawled more than 10 times per year is substantially higher than in other sea bed habitats. Sublittoral sand and sublittoral sand or mixed sediments in the Baltic are trawled less intensively. Larger proportions of this habitat are trawled less than 0.1 per year.

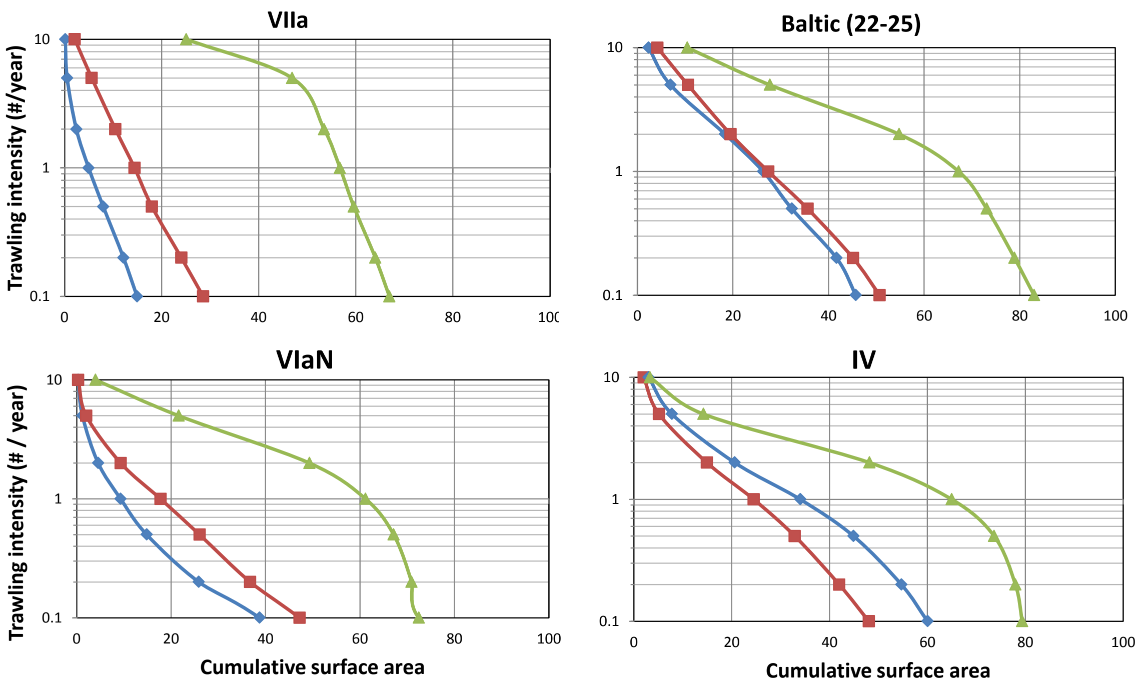

Figure 10. Cumulative swept area intensities at the surface level for 3 sea bed habitats (A5.1 Sublittoral coarse sediment (blue diamond); A5.2 Sublittoral sand (red square); A5.3 Sublittoral mud (green triangle)) in four management areas (VIIa - Irish Sea; Baltic Sea (22-25); VIaN - Northwestern shelf, IV – North Sea. Habitats in Baltic are Baltic circalittoral mixed sediment (blue diamond), Baltic circalittoral sand (red square), and Baltic circalittoral mud (green triangle).

4 DISCUSSION

From the modelled high-resolution maps of fishing intensity it is evident that large parts of the European seas are impacted by bottom trawling. It is also evident that the distribution and intensity of fishing effort is very heterogeneous and that there are also large areas of the seabed which are not impacted by mobile, bottom contacting fishing gears. The trawling hot spots with significant areas of high swept area intensities (> 10 times per year) occur in localised areas, along the coast of northern Norway, in the northern North Sea and Skagerrak, in areas off the coast of Ireland, south of Portugal and along the Adriatic coast of Italy. Moderate trawling intensities are less localised and cover larger parts of the North Sea, the Channel, the Western Baltic, the Celtic Sea and the continental shelf off Portugal. The Northwestern and Southwestern shelf had large areas with low trawling intensities.

4.1 Comparison of pressure indicators across management areas.

4.1.1 Area untrawled

The results of the analysis showed that in all European seas, between 33% and 72% of the sea bed down to 200 m was not trawled during the study period. The North Sea had the lowest proportion of untrawled area and the Northwestern Shelf the highest. All other management areas, apart from the Tyrrhenian Sea (45%) had a predominance of untrawled seabed (approx. 50-65%). These results represent the trawling intensity during an average year in the study period (2010-2012) and this does not necessarily imply that these areas will not be trawled if larger time periods are considered. Piet and Quirijns (2009) showed for the Dutch beam trawl fleet that the patterns were rather similar between successive years but gradually changed over longer time periods of up to 10 years.

4.1.2 Area trawled at least once per year

The management area with the largest proportion of surface area being trawled ≥ 1 time a year was the Adriatic Sea (64%) and the management area with the lowest proportion of surface area being trawled ≥ 1 time a year was the Northwestern Shelf (15%). Also the Tyrrhenian Sea (45%), the Channel (41%) and the North Sea (36%) have a substantial part the seabed trawled at intensities above 1, indicating a high level of fishing pressure on the benthic habitats.

4.1.3 Area where 90% of effort is concentrated

The area where 90% of the fishing effort is concentrated ranges between 17% for the Irish Sea and 46% for the North Sea, with the remaining areas evenly distributed in between. This 90% effort area also represents the area where most of the landings are taken and for the two areas mentioned above, the distribution of the main fishing resource is apparently very different, local areas of high resource abundance and very high fishing intensity in the Irish Sea, and larger areas of high resource abundance and moderate to high fishing intensities in the North Sea.

4.2 Surface and sub-surface effects of different gears

The analysis of trawling intensities at the surface and sub-surface level, respectively, separated the European seas into two groups differing with respect to the nature or severity of the physical trawling impact on the benthic community. Four of the analysed management areas fall into the surface impact group; the Western Baltic, the Northwestern Shelf, the Southwestern Shelf , and the Agean Sea, and seven management areas fall in the sub-surface group; The North Sea, the Channel, the Celtic Sea, the Irish Sea, the Tyrrhenian Sea, the Ionian Sea, and the Adriatic Sea. The main explanation behind this difference is the gear types used, which in turn is a result of species abundance and sediment type. The surface group areas are almost exclusively fished with otter trawls targeting finfish across different habitat types, whereas the sub-surface group in addition has a substantial effort with beam trawls and dredges targeting finfish and molluscs on sandy and mixed sediments (apart from the Tyrrhenian and Ionian sea) and otter trawls targeting crustaceans on soft bottoms, which have a substantial sub-surface impact.

4.3 Sea bed habitats

Our analysis revealed that sea bed habitats differed in their exposure to bottom trawling. The proportion of seabed trawled more than once per year increased from coarse (A5.1) and sand habitat (A5.2) and was highest for mud habitat (A5.3 and Baltic circalittoral mud), while the proportion of untrawled habitat was lowest in mud habitat and highest in coarse or mixed sediments.

Grain size and energy level of the environment are also important determinants of the benthic community with an increasing proportion of short lived opportunistic taxa with an increase in the energy level of the habitat (Gray and Elliott, 2009; Hiddink et al., 2006b; van Denderen et al., 2014; Bolam et al., 2015). Opportunistic taxa, characterised by a high growth rate, early maturation and high reproductive rate, will have a fast recovery rate as compared to long lived taxa characterised by a slow growth rate, late maturation and low reproductive rate. This implies that the benthic community in stable environments habitats will be most sensitive for the adverse impact of bottom trawling (Diesing et al., 2013).

The stability of the sea bed habitat is to some degree reflected in the grain size. Habitats that are exposed to a high level of natural disturbance are generally characterised by coarse sediments while stable environments are characterised by fine sediments. Because wave energy, disturbing the sea bed, decreases with increasing depth, sediment grain size is negatively correlated with depth (Hall, 1994; Diesing et al., 2013). Hence, the benthic community in deeper and muddier habitats are likely to be more sensitive for trawling than shallower sandy and coarser sea bed habitats. This inference is a crude approximation and deviations of this rule of thumb may occur.

Within the range of soft sediment habitats, the mud habitat, that is expected to be more sensitive for trawling impacts, is trawled more intensively than the sandy and coarse sediment habitats that are expected to be less sensitive for trawling.

The EUNIS level 3 habitat classification used in the present study only distinguish abiotic factors and does not distinguish biogenic habitats that are particularly sensitive for bottom trawling. Further research is needed to analyse the trawling intensities in relation with more refined sea bed habitats classification that allows the distinction of biogenic habitats. Further work is also required to estimate the sensitivity of sea bed habitats based on the typical community composition in absence of trawling disturbance. In particular the analysis of the longevity distribution of the benthic community in relation to depth, sediment type and energy level could provide predictive relationships that can be applied to quantify the sensitivity of sea bed habitats that can be directly linked to the trawling intensity distribution to estimate indicators for trawling impact as a contribution to the MSFD (Rijnsdorp et al., 2015)

4.4 Conclusion

When considering all three fishing pressure indicators jointly (proportion of area untrawled, proportion with an annual intensity ≥ 1, and with 90% of the effort) four management areas draw attention; the North Sea, the Channel, the Tyrrhenian Sea and the Adriatic Sea. These four areas all score relatively high on all three pressure indicators, and also have a substantial part (> 50%) of the total area impacted at the sub-surface level. Within the soft sediment habitats that dominate the continental shelf areas of Europe, mud habitats appear to be trawled most intensively while at the same time they likely have a higher sensitivity to bottom trawling as compared to the sandy and coarser sediments. Consequently, current fishing practices in parts of these four management areas could potentially compromise seafloor integrity.

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6 SUPPLEMENTARY DATA

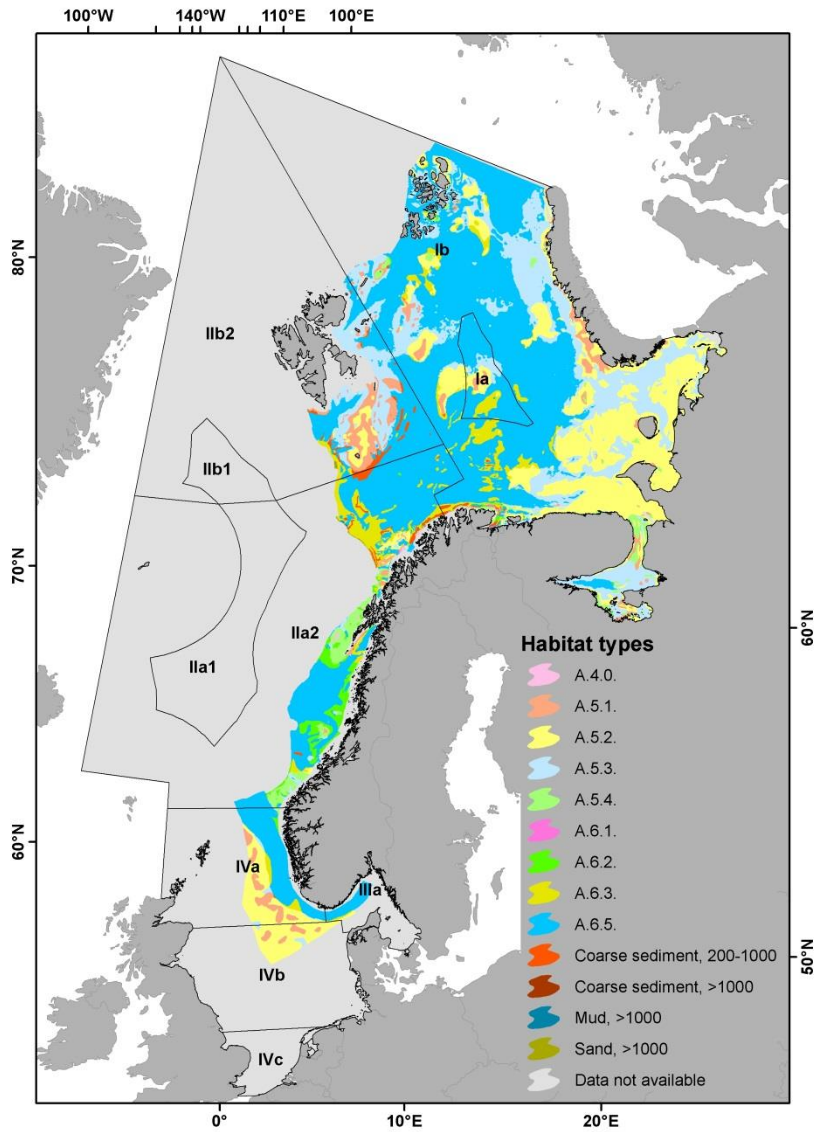

Figure 1, supplementary. Habitat distribution of the Norwegian and Barents Sea according to the EUNIS categorization. Modelled from sediment and bathymetry data (http://mareano.no).

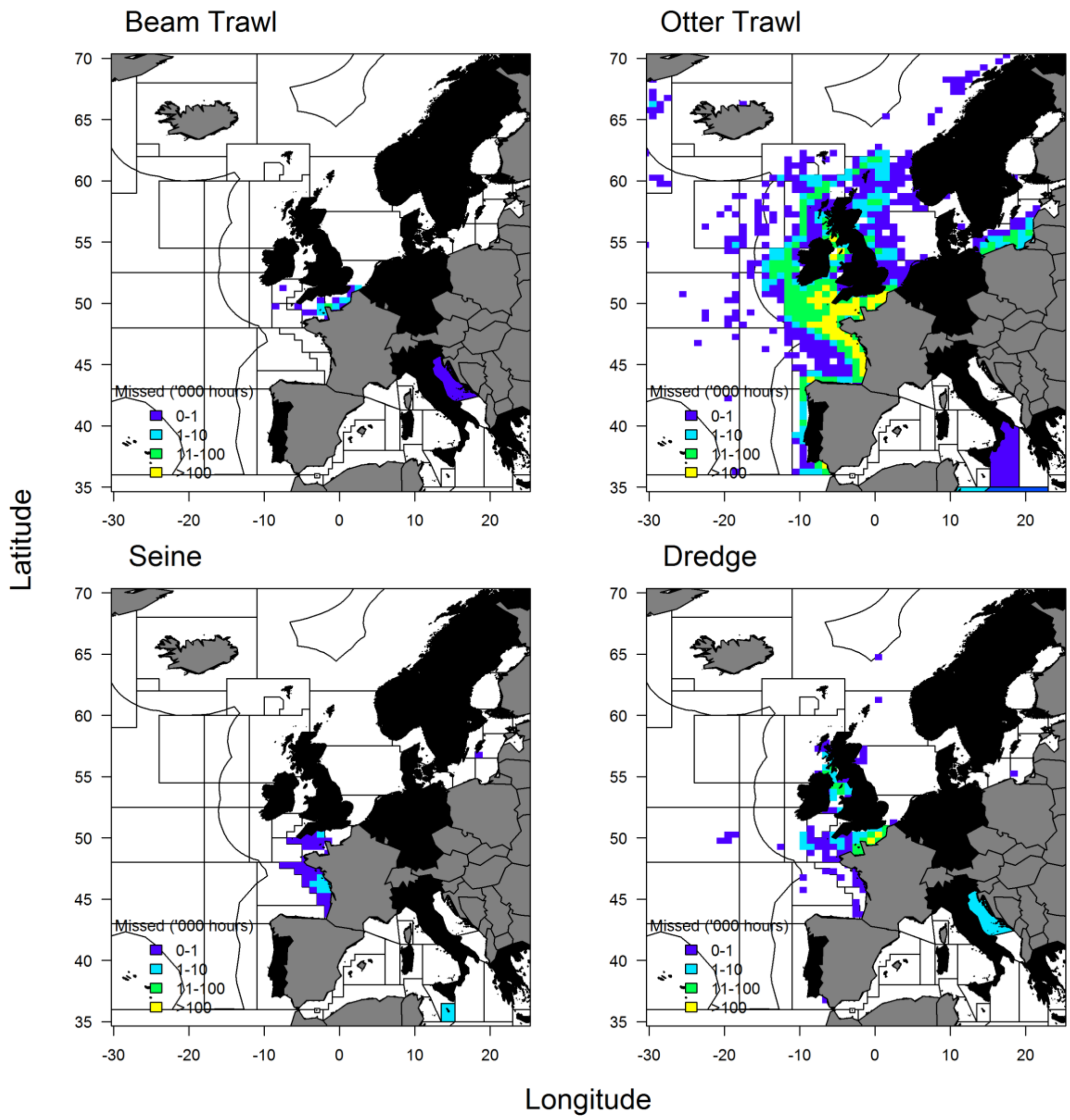

Figure 2, supplementary. Map of missing effort (non-VMS monitored effort) for the case study regions as estimated from logbooks of the countries included in the analysis.