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Estimating seabed pressure from demersal trawls, seines, and dredges based on gear design and dimensions

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This study assesses the seabed pressure of towed fishing gears and models the physical impact (area and depth of seabed penetration) from trip-based information of vessel size, gear type, and catch. Traditionally fishing pressures are calculated top-down by making use of large-scale statistics such as logbook data. Here, we take a different approach starting from the gear itself (design and dimensions) to estimate the physical interactions with the seabed at the level of the individual fishing operation. We defined 14 distinct towed gear groups in European waters (eight otter trawl groups, three beam trawl groups, two demersal seine groups, and one dredge group), for which we established gear "footprints". The footprint of a gear is defined as the relative contribution from individual larger gear components, such as trawl doors, sweeps, and groundgear, to the total area and severity of the gear's impact. An industry-based survey covering 13 countries provided the basis for estimating the relative impact-area contributions from individual gear components, whereas sediment penetration was estimated based on a literature review. For each gear group, a vessel size–gear size relationship was estimated to enable the prediction of gear footprint area and sediment penetration from vessel size. Application of these relationships with average vessel sizes and towing speeds provided hourly swept-area estimates by métier. Scottish seining has the largest overall gear footprint of $\sim$1.6 km^2 h^{-1} of which 0.08 km^2 has an impact at the subsurface level (sediment penetration $\geq$ 2 cm). Beam trawling for flatfish ranks low when comparing overall footprint size/hour but ranks substantially higher when comparing only impact at the subsurface level (0.19 km^{2}h^{-1}). These results have substantial implications for the definition, estimation, and monitoring of fishing pressure indicators, which are discussed in the context of an ecosystem approach to fisheries management.

Keywords: benthic impact, fishing pressure, gear footprint, indicators, logbooks, seabed integrity, swept-area, towed gears, vessel size.

Introduction

Mobile bottom contacting fishing gears have impacts on benthic ecosystems (Jennings *et al.*, 2001; Kaiser *et al.*, 2002). Short-term impacts include mortality of benthic invertebrates (Kaiser *et al.*, 2006), resuspension of sediments (O'Neill and Summerbell, 2011; Bradshaw *et al.*, 2012; Martin *et al.*, 2014), and physical disturbance of biogenic habitats (Kaiser *et al.*, 2006; Cook *et al.*, 2013), whereas long-term impacts may include changes in species composition (Kaiser *et al.*, 2006) and reduction in habitat complexity (Kaiser *et al.*, 2002).

The physical impact of fishing on benthic ecosystems is an issue that long has been the subject of public attention. Even in the late 1880s, the impacts of new steam driven bottom trawlers were widely debated (Graham, 1938) and similar debates still exist between the fishing industry and environmental organizations. In addition, consumer-driven mechanisms such as ecolabelling of seafood products (e.g. Marine Stewardship Council) increasingly include impacts of gears on ecosystems/habitats in their evaluative criteria (Olson *et al.*, 2014).

Impacts of fishing gears on benthic ecosystems are a central component in ecosystem-based fisheries management (Pikitch *et al.*, 2004) and the ecosystem approach to fisheries management (EAFM; Garcia *et al.*, 2003). In European marine environmental policy, impacts of human activities such as fishing on benthic habitats and species are currently being addressed in detail through the Marine Strategy Framework Directive (MSFD) (Anon., 2008). The MSFD aims for the achievement of good environmental status in European marine waters by 2020. Of 11 qualitative descriptors of environmental status, Descriptor 6 relates specifically to the condition of the seabed and benthic ecosystems (Anon., 2010; Rice *et al.*, 2012): "Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected". An indicator of direct relevance to fishing with mobile bottom contacting gear has been formulated (Anon., 2010): "Extent of the seabed significantly affected by human activities for the different substrate types".

With the introduction of satellite-based vessel monitoring systems (VMS), providing large-scale high-resolution information of European fishing activity, it has been proposed (Piet *et al.*, 2007; Piet and Hintzen, 2012) that the coupling of VMS and logbook data can serve as a proxy for the extent of affected seabed, given that it is not feasible to monitor the condition of all habitats in European seas regularly. There are, however, significant differences in the fishing gears deployed by commercial vessels, and in the corresponding nature of their physical contact with the seabed (Suuronen *et al.*, 2012), and it must be emphasized that VMS-based indicators take account of such differences in gear sizes and configurations. Unfortunately, this need for standard gear information is not reflected in the existing logbook statistics, where focus typically has been on catch rather than effort. Consequently, most logbook information is not well-suited for quantitative estimation of seabed impact (swept-area and impact severity) of the different fishing gears and trips.

In this paper, we present a new generic method to overcome this gear information deficiency, which substantially improves the ability to estimate seabed pressure (area and severity of seabed impact) by commercial fishing from logbook statistics and VMS data. The central approach is a systematic analysis and categorization of mobile bottom contacting fishing gears based on their design and catch principles, which has enabled the definition of gear footprints of the most common gear types; otter trawls (OTs), demersal seines (DSs), beam trawls (TBBs), and dredges (DRBs). A gear footprint is defined by its measures of overall size (e.g. door spread for OTs, which equals the total width of this gear type (Figure 1)) and a decomposition of this overall footprint size into relative footprint contributions from the individual gear components (e.g. the doors, sweeps, and bridles of an OT).

An industry-based vessel and gear survey covering 13 different countries provided the empirical basis for estimating the relative footprint contributions from individual gear components. Literature-based penetration depths were assigned to individual gear components, which were then added up to give proportions of total footprint impact at the surface and subsurface level, respectively, for otter trawlers, demersal seiners, beam trawlers, and dredgers.

A second methodological goal was to transcend the relative nature of the established gear footprints and enable the extension of individual logbook trips with absolute measures of gear size and related surface and subsurface seabed impact. Although EU logbooks do not hold information of gear size (e.g. the average door spread of an OT), they do hold trip-based information of gear type, vessel size, and catch composition. To enable superimposing absolute gear size (footprint size) on individual logbook observations, we estimated the relationships between overall gear footprint size and vessel size for 14 different métiers (fishing trips grouped by gear type and target species). The vessel size–gear size relationships by métier were estimated from the observations of the industry-based questionnaire survey.

The results obtained have the potential to substantially improve the accuracy of logbook-based calculations of benthic impacts and pressure from fishing. For any fishery statistics holding information of (i) vessel size, (ii) gear type, and (iii) target species, the established gear footprints and vessel size–gear size relationships can be combined to give total gear size (gear path width) as well as proportion of the path width, which has a benthic impact at the surface and the subsurface level, respectively. When combined with fishing activity information such as towing speed and duration (e.g. from VMS data), the established footprints and vessel size–gear size relationships significantly improve the ability to calculate seabed integrity indicators from current fisheries statistics, which can fulfil the requirements of an EAFM. Furthermore, the analysis of fishing gears and their seabed and target species interactions strongly suggest that the current logbook formats are outdated and need to be expanded by including the dimensions of those gear components that determine the nature of the seabed impact.

Background and material

High-impact demersal fisheries in European waters

With reference to existing literature and frameworks describing the impact mechanisms and ecological effects of fishing with mobile bottom contacting gears (e.g. Dayton *et al.*, 1995; Kaiser *et al.*, 2006; Tillin *et al.*, 2006; Buhl-Mortensen *et al.*, 2013), the benthic impacts of otter trawlers, demersal seiners, beam trawlers, and dredgers were identified as the most significant in the European and Black Sea fisheries. For these four gear groups, the major effects and mechanisms of impact were assessed to be: (i) mortality of benthic organism from direct gear–seabed gear contact during fishing, (ii) food subsidies from discards and gear track mortality, (iii) habitat alterations through disturbance of sediments and effects on seabed habitats, and (iv) change to geochemical processes (release of nutrients and chemical substances) from disturbance of sediment.

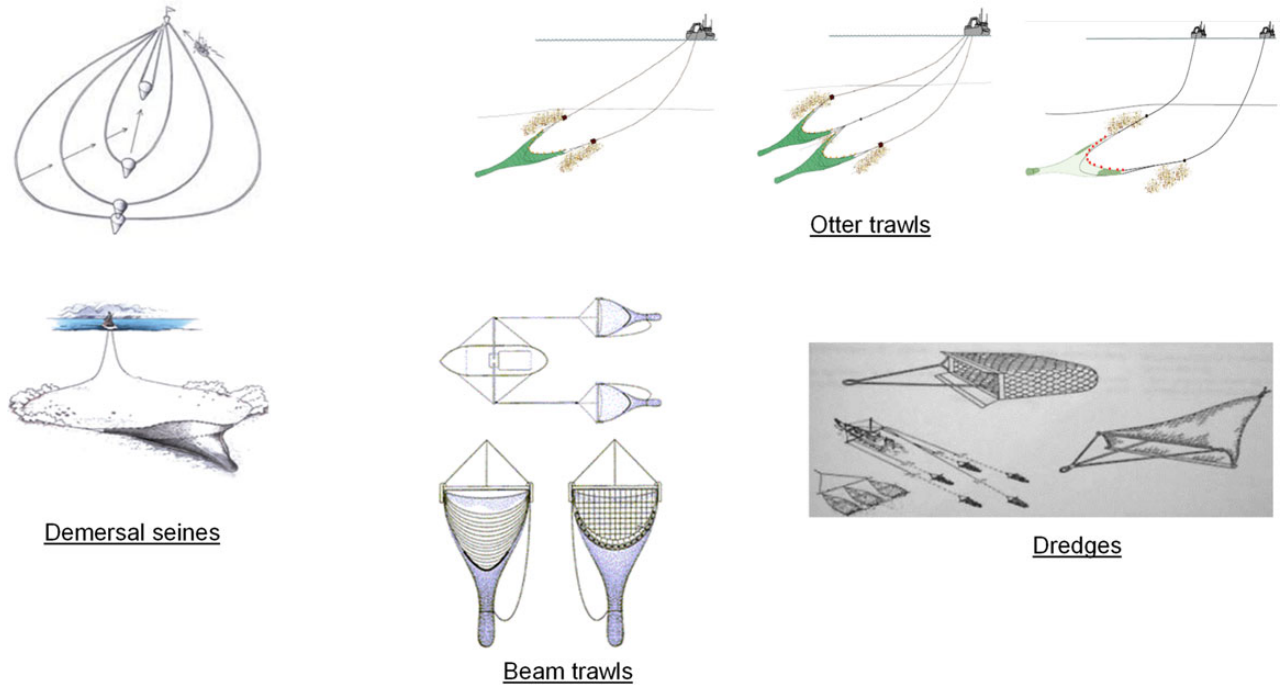

Figure 1. Towing principles of the four main high-impact demersal gear groups identified: DSs (left), OTs (top right), DRBs (bottom right), and TBBs (centre, bottom). Illustrations from FAO: http://www.fao.org/fishery/geartype/search/en. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

Based on a review of the official effort and landing statistics collected by the EU Scientific, Technical and Economic Committee for Fisheries and presented in their annual report for 2012 (STECF, 2012), it was assessed that the above definition of the high-impact group encompasses all common mobile bottom contacting fishing gears in the EU fleet. In addition to the EU fleet statistics, effort and landing information for the Turkish commercial fishery with trawlers and beam trawlers in the Black Sea was provided by CFRI (the Central Fisheries Research Institute in Turkey). The total 2010 fishing days and landings and the main target species for the high-impact fisheries are summarized below (Table 1). The STECF statistics do not distinguish between demersal seiners and otter trawlers, but the total effort of otter trawlers in European waters is assessed to be at least an order of magnitude larger than the effort of demersal seiners.

Demersal otter trawling

Demersal OTs are essentially conical nets that are dragged along the seabed. The trawlnet is held open using trawl floats, groundgear, and trawl doors (Figure 1). The trawl doors are connected to the vessel by warps and to the trawlnet by sweeps, typically made of steel wire or nylon rope with a steel wire core. The sweep length varies significantly depending on vessel and target species (Eigaard *et al.*, 2011). The groundgear mounted under the netting is designed to protect the net against wear, to help it across different terrain types, and to prevent target species from escaping beneath the trawl. Consequently, OT groundgears are very heterogeneous in design. In traditional otter trawling, the trawl doors, sweeps, and groundgear all come into contact with the seabed during trawling. Depending on the trawl type, vessel size, and length of the sweeps, the width of seabed affected by a single bottom trawl can vary substantially, typically in the range of 25–250 m. Towing speed over ground typically ranges from 2 to 4 knots in demersal otter trawling and fishing can take place at depths from 10 to 2500 m (Prado and Dremiere, 1990; Valdemarsen *et al.*, 2007). In modern bottom trawling, multi-rig trawling is also used, which involves two or more trawls being fished side by side by one vessel (Figure 1). Twin-rig trawling involves the use of two trawl doors, two trawls, and a weight located between the middle warp (towing cable) and the sweeps going to each of the trawls. A third type of bottom trawling is pairtrawling, where two vessels drag a single trawl (Figure 1). In that case there are no trawl doors, but there may be weights at the transition between the warps and sweeps.

Demersal seining

When fishing with a Danish (anchored) seine, the gear is set out from an anchor point in roughly a triangular area on the seabed using very long ropes (Figure 1; Supplementary Figure S1). As the two ropes are winched in from the anchored vessel, the area between the ropes diminishes and the seine gradually closes and, towards the end of the haul, moves forwards in the same way as a trawl. It should be noted that the geometrical shape of the individual anchored seine operations can vary substantially depending on the target species and the seabed conditions. Usually, the fished area is enlarged by completing maybe only three-fourths of a triangle and then towing the rope and seine the remaining distance back to the anchor before hauling (Sainsbury, 1996; Supplementary Figures S1 and S2). Following the first set from an anchor position, further sets are made to cover a circular area for which the anchor is centre (Supplementary Figure S1; Sainsbury, 1996; FAO, 2015). Fishing can take place from very shallow water down to around 180 m depth (Sainsbury, 1996). The length of the seine ropes deployed in Danish seining typically varies between 4400 and

Table 1. Effort, landings, and main target species for EU member states in the case study regions in 2010 (STECF, 2012).

	2010	OTs and DSs	DRBs	TBBs
Baltic Sea[a]	Days at sea (10^3)	32.8	0.5	
	Landings (10^3 t)	130.4	7.0	
	Main species	Cod	Blue mussels	
North Sea[a]	Days at sea (10^3)	150.7	31.0	88.5
	Landings (10^3 t)	864.6	54.6	116.4
	Main species	Cod, *Nephrops*, sandeel	Scallops	Sole, plaice
Western Waters[b]	Days at sea (10^3)	238.9	39.8	15.6
	Landings (10^3 t)	235.0	55.7	15.1
	Main species	*Nephrops*, sole, monkfish, hake	Scallops	Sole, plaice
Mediterranean[c]	Days at sea (10^3)	403.7	62.9	10.3
	Landings (10^3 t)	82.0	21.8	3.7
	Main species	Hake	Clams	Sole, brill, turbot
Black Sea[d]	Days at sea (10^3)	58.2		28.6
	Landings (10^3 t)	16.7		7.8
	Main species	Whiting, red mullet, turbot		Sea snail

Black Sea data are purely Turkish and provided by CFRI. Yearly landings (t) and days at sea are informed in thousands.
[a]Also including ICES Area I and II.
[b]Also including ICES Area V, X, and XII.
[c]No data available for Spain.
[d]TÜİK, National Statistics Institute's official yearly landing data.

7920 m depending mainly on vessel size. Winch speed typically ranges from ~1.5 to 3.5 knots and seine speed over ground gradually increases during the operation from 0 to ~2–3 knots (Sainsbury, 1996, Methods section).

Scottish seining (or fly shooting) can be considered a hybrid between anchored seining and demersal otter trawling, where the vessel moves forward while at the same time winching in the seine ropes (Figure 1). Fishing can take place at depths down to around 220 m (Sainsbury, 1996). Typically the gear is set out from a buoy in roughly a triangular area on the seabed and then winched in as the vessel moves forwards, mostly at speeds between 0.5 and 2.0 knots (Figure 1; Supplementary Table S1). Consequently, the seine will move forwards at speeds above vessel speed, and this is also true for the seine ropes, but with large variation depending on the individual section of the rope. From literature results and interviews, the speed of the seine over ground was identified to gradually increase from 0 knots to typically between 2.5 and 3.0 knots at the end of the operation, the lower value is reached when targeting mainly flatfish and the upper value when targeting round fish (Supplementary Table S1). The total seine rope lengths in flyshooting (4000–6000 m) are typically shorter than in Danish seining but the diameter typically larger, enabling the flyshooters to fish on rougher grounds.

Beam trawling and dredge fishing

Both TBBs and DRBs are typically used to target species that stay on the bottom or that are partly buried in the sediment. Therefore, the tickler chains of a beam trawl (Figure 1) and the teeth or shearing edge of a dredge (Figure 1) are specifically designed to disturb the seabed surface and penetrate the upper centimetres of the sediment. Tickler chains and shearing edge, respectively, are mounted along the whole width of the two gears (typical beam trawl widths roughly vary between 4 and 12 m, and dredge widths from 0.75 to 3 m). Beam trawl towing speed over the ground ranges from 2.5 to 7 knots (the higher speeds being deployed for flatfish and the lower for shrimp) and typically beam trawling is conducted at depths shallower than 100 m (FAO, 2015). Dredging for molluscs typically takes place at towing speeds from 2 to 2.5 knots and typically in shallow near-coastal waters (Prado and Dremiere, 1990). The beam trawl fishery for common shrimps (*Crangon crangon*) deploys TBBs without tickler chains and use a light bobbin rope. Typically, two TBBs are towed by each vessel, but as for dredgers, variation in towing methods and numbers can be quite large (Figure 1). TBBs that work in areas of hard bottoms deploy a chain mat in the net opening to avoid catching large stones.

Methods

Defining gear footprints from gear design

The first step in estimating the relative pressure on the benthic habitats when fishing with the different gears was to establish conceptual footprints of the four major gear types: OT, DSs, TBBs, and DRBs. The gear-specific footprints conceptualized and estimated here can also be considered as measures of fishing capacity in relation to benthic pressure; essentially, the footprints define gear widths and penetration depths for each métier by vessel size. To estimate the actual benthic pressure or impact of a given fishing operation, in terms of total area swept, the developed footprints need to be combined with additional data on fishing activity (i.e. trawling speed and haul duration) on a case-specific basis.

OT footprint

For a traditional single OT, there are three main types of seabed impacts during a haul: (i) from the otter boards, (ii) from the sweeps, and (iii) from the trawl groundgear, which together define the footprint of an OT fishing operation (Figure 2). Of these three impacts, the otter boards is the most severe but also has the narrowest track/path (Figure 2). Depending on the sediment type, the trawl doors can dig up a trench/furrow of up to 35 cm deep and transfer large amounts of sediments onto either side of their path (Lucchetti and Sala, 2012). In the following analysis, the simplification is made that the footprint of a trawl door is similar in impact to that of the clump used when twin-rig fishing and to the weights used when pairtrawl fishing (Figures 1 and 2). In general, the sweeps represent a large proportion of the total trawl gear path (Figure 2) but appear to have the least impact on the seabed, with penetration mostly limited to the top centimetres of sediment (Buhl-Mortensen *et al.*,

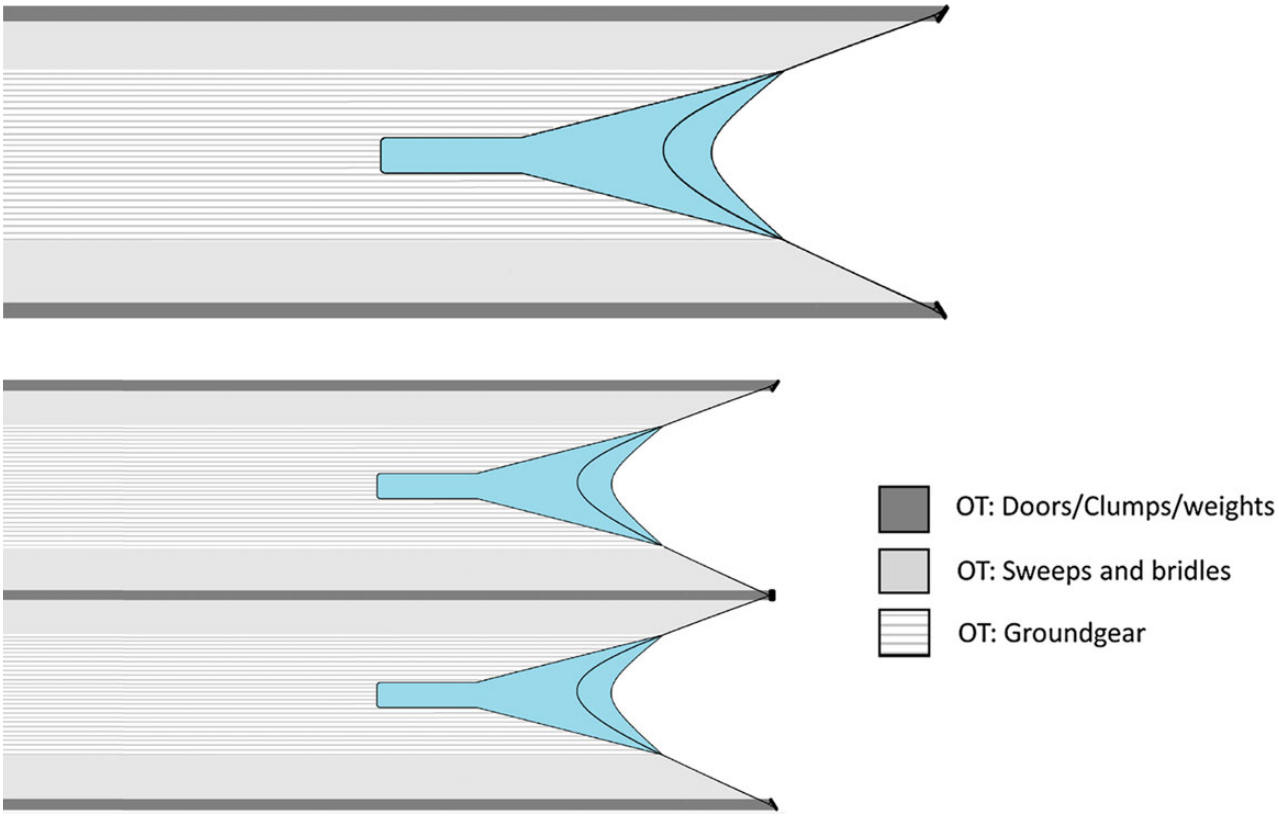

Figure 2. Conceptual gear footprints of single OTs fished by one vessel or with two vessels when pairtrawling (top) and of twin-rigged OTs fished by one vessel (bottom). The conceptual footprint consists of three types of seabed impacts: (1) the track affected by the doors/clumps/weights, (2) the track influenced by the sweeps and bridles, and (3) the track affected by the trawl/groundgear itself (modified from Figure 5.1, page 28, in Buhl-Mortensen *et al.*, 2013). This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

2013). The groundgear path of an OT is more heterogonous in design and varies significantly with the species targeted and the type of sediment fished.

In the context of seabed pressure, we define overall OT footprint size (for both single and twin trawls) as the total spread of the trawl doors during fishing (Figure 2). For pairtrawlers, this is equal to the total spread of the weights.

DS footprint

For a DS, there are two main types of seabed impacts during a seine haul: (i) from the seine rope, and (ii) from the seine groundgear, which together define the gear footprint of a Danish seine (anchor-seine) operation (Figure 3a) and a Scottish seine (flyshooting) operation (Figure 3b). The largest impact (by area) in both types of demersal seining comes from the seine ropes, whereas the seine groundgear only covers a small proportion of the total area fished. The physical impact of seining gear on seabed habitats is not documented in the scientific literature, but presumably for Danish seines the impact is less than for bottom trawling, since there are no trawl doors and the groundgear is lighter. The impact level of Scottish seining is probably somewhere in-between, as flyshooting can be considered a hybrid between anchored seining and demersal otter trawling, but no data exist to confirm this. Since demersal seining depends on the ropes not getting caught on obstacles during the herding phase, there are clear limitations on the sediment types

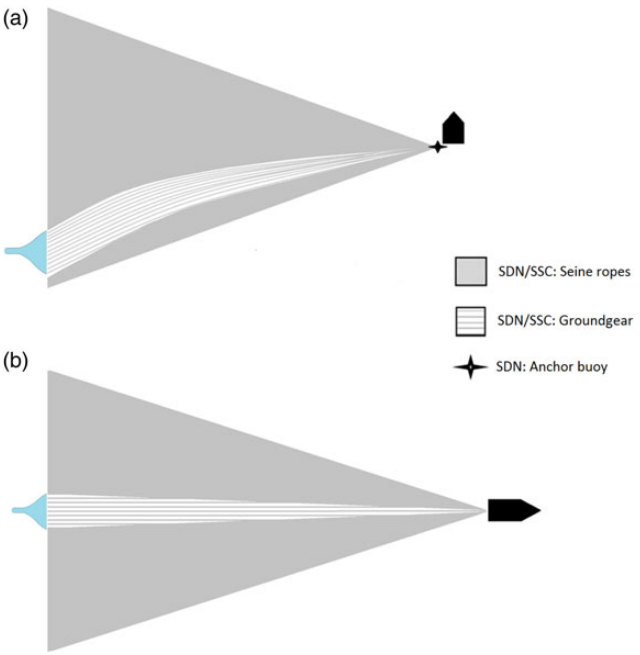

Figure 3. Conceptual gear footprints of DSs [(a) SDN and (b) SSC]. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

where it can be used. However, larger seine rope diameters and higher vessel engine power enables Scottish seiners to fish on rougher grounds and also implies heavier bottom contact compared with anchor-seines.

We define the overall DS footprint size as the total area swept by the seine ropes and groundgear during a fishing operation. For anchored seining, this footprint can be conceptualized as an isosceles triangle with a circumference of total seine rope length × 1.25 (Supplementary Figure S2) and an area of 1/2 × (seine rope length/4) × h, where *h* is the height of the isosceles triangle [Supplementary Figure S2 and Equations (S1) and (S2)]. For Scottish seining, this footprint can also be conceptualized as an isosceles triangle, but due to the differences in gear operation (Supplementary Methods section and Figures S2 and S3), the footprint area is calculated as 1/2 × (seine rope length/4) × 2 h, where h is the height of an equilateral triangle with a circumference equal to total seine rope length [Supplementary Figure S3 and Equations (S3) and (S4)].

Beam trawl footprint

For a traditional beam trawl, the footprint is more homogenous than for an OT and can be separated into two types of paths: (i) from the shoes of the beam, and (ii) from the groundgear (Figure 4), and before that by the tickler chains of the trawl, if such chains are deployed (Figure 1). Both tickler chains and beam shoes have been demonstrated to generate furrows of up 10 cm depth in the sediment (Paschen *et al.*, 2000; Depestele *et al.*, 2015).

The overall beam trawl (TBB) footprint size of a fishing operation is defined as the width of the beam multiplied with the number of TBBs deployed by the vessel.

Dredge footprint

DRBs used for catching molluscs (such as scallops, mussels, and oysters) typically have a simpler conceptual footprint than TBBs. That is, the groundgear is mostly homogenous across the entire width of the dredge and can be expected to produce a homogenous gear path (Figure 5). This does, however, depend on the presence/absence of dredge teeth, which are always used in scallop fishing and produce a more uneven sediment furrow (O'Neill *et al.*, 2013). Standard DRBs have been demonstrated to create furrows of up to 6 cm depth in soft sediments (Pravoni *et al.*, 2000) and the DRBs used for infaunal bivalves in the Adriatic Sea have been demonstrated to create furrows in the sediment up to 15 cm deep (Lucchetti and Sala, 2012).

The overall DRB footprint size of a fishing operation is defined as the width of the dredge multiplied by the number of DRBs deployed by a vessel.

Predicting overall footprint size from vessel and catch profiles

Industry survey

The defined conceptual gear footprints formed the basis of an industry directed questionnaire survey designed to give technical information of the high-impact gears currently in use in the European and Black Sea fisheries. The questionnaires were filled in during interviews with fisher and netmakers, conducted either by scientists in BENTHIS (EC, 2014) or by national observers routinely monitoring discards on-board individual vessels. Some questionnaires were also completed using information from national gear databases. It is a potential bias of such surveys that not all industry representatives and fishers are equally aware of accurate dimensions and characteristics of their gears and gear components. To maximize information quality, the questionnaires were completed during face-to-face interviews with the industry representatives. The four questionnaires can be found in Supplementary material, Figures S4–S7. Vessel size information of engine power (kW) and vessel overall length (LOA) in meters and target species information was collected together with the gear specifications to allow statistical modelling of the vessel size–gear size relationship for different métiers (combinations of gear types and target species).

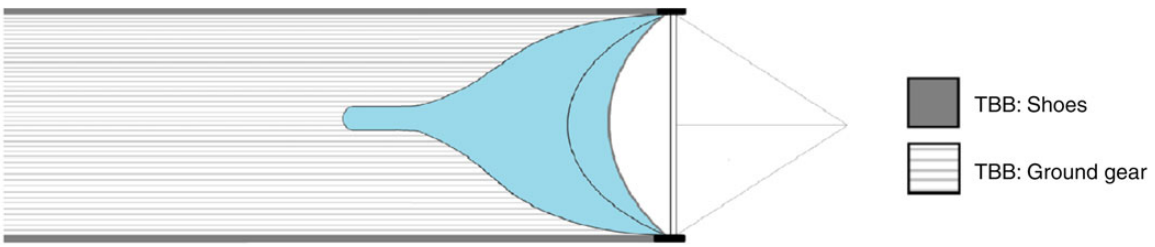

Figure 4. Conceptual gear footprints of TBBs. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

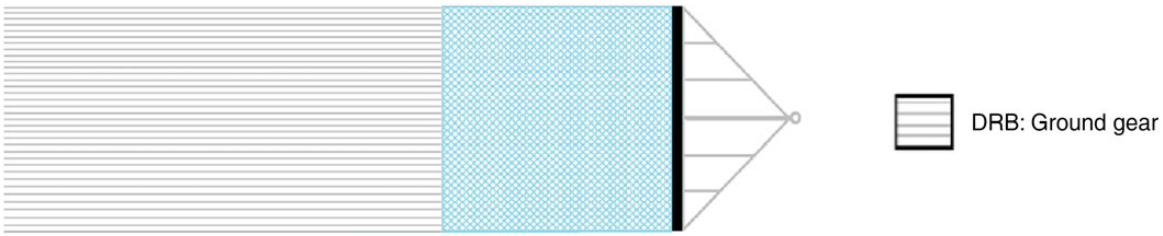

Figure 5. Conceptual gear footprints of DRBs. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

BENTHIS métiers

Based on the gear and target species information from the questionnaires, each of the vessel–gear observations was assigned to different towed gear groups (BENTHIS métiers). This grouping of questionnaire observations was made about the métier principles of the EU logbooks [the data collection framework métiers (DCF-métiers)] and to the biology (e.g. benthic or bentho-pelagic fish) and catch principles of the target species informed (e.g. herding or non-herding by sweeps). It was the ambition to define the BENTHIS métiers in a generic framework (i.e. not a case-specific basis) to make the estimated vessel size–footprint size relationships generally applicable.

Estimating relationships between vessel size and overall footprint size

Each of the four measures of overall footprint size was related to vessel size, measured as either engine power (kW) or vessel length over all (LOA) in meters, using simple statistical models. A minimal least-squares residual sum criteria was used for choosing the best fit between LOA and kW as a measure of vessel size and between a power function link and a linear link in the gear size–vessel size estimation procedure. A linear best fit will imply that gear size increases with vessel size throughout the size range of the sampled vessels of a métier, whereas a power function will imply that for the larger vessels of the métier sample, gear size becomes decoupled from vessel size. The 95% confidence intervals around the means were estimated by Monte Carlo simulations for non-linear fitting, resulting in asymmetric confidence bands (Bates and Watts, 2007; Spiess, 2014).

Path widths of individual footprint components

The gear information from the industry questionnaires was used to break down the overall footprint size into partial contributions from the key components of the four gear types: doors, sweeps, and groundgear for OTs; seine rope and groundgear for DSs; beam shoes, tickler chains, and groundgear for TBBs; groundgear for DRBs.

OT footprint components

Direct information of individual component path widths (e.g. groundgear path width) was rarely informed in the OT questionnaires. Consequently, component path widths were estimated indirectly by applying OT gear geometry theory (Kynoch, 1997; Valdemarsen *et al.*, 2007; SEAFISH, 2010) to those gear component measures that were informed in the questionnaires. Sweep path width of each OT was calculated from informed sweep and bridles length and a literature-based sweep/bridle angle assumption of a 13° average across all BENTHIS métiers [Equation (1); Supplementary Figure S8; SEAFISH, 2010; Notti *et al.*, 2013]. Groundgear path width was calculated from informed groundgear length and an assumption of a general wing end spread of 40% of groundgear length [Equation (2); Supplementary Figure S8; SEAFISH, 2010]. Each door path width was calculated from informed door width and an assumption of a general door path width of 40% of door length [Equation (3), Supplementary Figure S8; Valdemarsen *et al.*, 2007]. The clumps of multi-rig OTs and the weights of pairtrawls are extremely variable in size and design (Valdemarsen *et al.*, 2007), and a simplifying assumption of a path width of 0.75 m across all vessel sizes and types was made [Equation (3)]. For each paired vessel–gear questionnaire observation, the estimated individual component path widths (for sweeps, groundgears, and doors/clumps/weights) were multiplied with the number of components deployed by the vessel as informed in the questionnaire:

$$\text{Total sweep path width} = \text{sine}\,(13^\circ) \times (\text{Sweep\_length} + \text{Bridle length}) \times 2 \times \text{Trawl\_number}, \tag{1}$$

$$\text{Total ground gear path width} = \text{Ground gear\_length} \times 0.4 \times \text{Trawl-number}, \tag{2}$$

$$\text{Total Door/clump/weight path width} = (\text{Door\_length} \times 0.4 \times \text{Door\_number}) + (0.75\text{nm} \times (\text{Trawl\_number} - 1)). \tag{3}$$

DS footprint components

Very little empirical data exist on the groundgear geometry of DS operations, and the assumption was made that, for both Danish and Scottish seine fishing operations, the groundgear path constitutes 10% of the overall seine footprint and the seine ropes the remaining 90%. This assumption was based on industry interviews and the available literature on demersal seining (Supplementary Methods section), which also made it clear that individual DS hauls can vary substantially in shape, size, and duration depending on target species, seabed conditions, and skipper skills. Consequently, both the geometry and the 10% groundgear coverage assumption should be treated with some caution.

Beam trawl footprint components

For beam trawls, the individual component path widths could be estimated directly from the questionnaire information. Total beam shoe path width was calculated from informed shoe width, shoe numbers, and trawl numbers [Equation (4)]; total groundgear track width was calculated from beam width, shoe width, shoe number, and trawl number [Equation (5)]; and total tickler chain path width was calculated from beam width, shoe width, shoe number, trawl number, and presence/absence of tickler chains [Equation (6)].

$$\text{Total beam shoe path width} = \text{Beamshoe\_width} \times \text{Beamshoe\_number} \times \text{Trawl\_number}, \tag{4}$$

$$\text{Total ground gear path width} = (\text{Beam\_width} - (\text{Beamshoe\_width} \times \text{Beamshoe\_number})) \times \text{trawl-number}, \tag{5}$$

$$\text{Total tickler chain path width} = (\text{Beam\_width} - (\text{Beamshoe\_width} \times \text{Beamshoe\_number})) \times \text{trawl-number} \times \text{Tickler\_chain}. \tag{6}$$

Dredge footprint components

DRBs used for catching molluscs, such as scallops and mussels, are mostly homogenous across the entire width of the dredge even

if teeth are used. The groundgear (shearing edge) is assumed to constitute 100% of the total dredge footprint size, and for each questionnaire observation, the total shearing edge path width is calculated as dredge width multiplied by the number of DRBs deployed by a vessel.

Surface and subsurface impact

Penetration depth of individual gear components was reviewed in relation to the affected types of the seabed substrate. The results from impact measurements and experiments worldwide were reviewed and listed by gear type, component, and sediment type.

To distinguish between potential effects on benthic epifauna and infauna, penetration depth of the individual components was indexed as either surface (<2 cm) or subsurface (≥ 2 cm). For a first approach to add severity to the area impact of the individual gear components, this indexing was made across all sediments based on the penetration depths by the sediment type as identified in the literature review.

Adding impact severity to individual component contributions

The extent to which towed fishing gears penetrate the seabed is highly variable and depends on gear type and the sediment on which it is towed. For a given gear, there will be variation between the components and, at the individual component level, penetration will depend on the specific design, orientation, and rigging of the particular component. Measurements of penetration depth have been made for a range of gear components such as trawl doors, clumps, sweeps and bridles, groundgear, beam shoes, tickler chains, and shearing edges. These measurements, however, are generally for components on a given sediment type and the variation of penetration depth with sediment is only reported in a few cases. Here, to carry out a broad analysis, we assume that the relative penetration depths of the gear components are similar across sediment types. In this way, we allow the distinction of the surface impacts from the subsurface impacts of the different gears, although the actual depth of the subsurface impact will differ across sediments.

Due to highly different designs and sediment types of this particular gear component, there will be large variations in penetration depths between groundgears (Esmaeili and Ivanović, 2014; Ivanović and O'Neill, 2015). Therefore, expert opinions (BENTHIS gear technologists) were used to subjectively assign groundgear surface and subsurface impact proportions to each of the métiers. In the industry questionnaires, some information (mostly qualitative) of groundgears was provided, enabling identification of typical groundgear type by métier. In combination with a few available studies on the seabed contact of particular groundgears (Ivanović *et al.*, 2011), these questionnaire-based groundgear typologies formed the basis of assigning surface/subsurface impact proportions to the full groundgear path widths of each BENTHIS métier (Supplementary Table S2). Given the lack of documented information, the impact proportions should be treated with caution.

For DSs, no penetration depth studies have been conducted, and for both Danish and Scottish seining, the assumption is made that the seine rope has a penetration depth equal to that of OT sweeps and that the groundgear has an impact similar to OT groundgears of the same type (Supplementary Table S2).

Ranking of BENTHIS métiers according to relative subsurface impact

By combining (i) the individual component path width percentages (estimated from gear questionnaire information), (ii) the penetration depth associated with each component (based on literature review), and (iii) the groundgear proportions of surface/subsurface impact (expert opinion based), it was possible to rank the fourteen BENTHIS métiers according to their relative surface–subsurface impact.

Swept-area per fishing hour of average vessels by métier

The gear footprints and vessel size–gear size relationships obtained allow us to estimate the total swept-area per fishing hour for each BENTHIS métier. The estimated vessel size–gear size relationships were applied to the average vessel size (obtained from the questionnaires) to provide absolute footprint sizes (e.g. total door spread). Total swept-area per hour was calculated from average towing speed (trawls and dredgers) and haul duration (seines) also informed in the questionnaires, and surface–subsurface proportions of the area swept were calculated from the component-based footprint proportions.

Results

Industry survey and BENTHIS métiers

The industry consultations resulted in 1132 questionnaires being filled: 939 for OTs, 78 for TBBs, 82 for DSs, and 33 for DRBs (Table 2). Not all questionnaires were filled completely and for a number of variables analysed in the following only a subset of the total observation number (Table 2) held relevant information.

Based on their gear and target species information, the questionnaire observations were grouped into 14 different towed gear groups (BENTHIS métiers) (Table 3). This level of grouping roughly corresponds to a DCF métier grouping somewhere between levels 5 and 6.

Vessel size and overall footprint size by BENTHIS métiers

The relationships between vessel size and overall footprint size were fitted with either a linear link or a power function link for each defined BENTHIS métier (Figures 6–9). Of the 1132 filled questionnaires, 997 held sufficient information on both vessel and footprint size to be included in the analysis and for all métiers and the resulting fits show that footprint size increases with vessel size. A linear link was estimated for three BENTHIS métiers (OT_MIX_DMF_BEN, OT_MIX_CRU_DMF, and OT_SPF) and a power function link was estimated for the remaining 11 métiers (Table 4). LOA and kW were equally abundant as vessel size descriptors with seven métiers each. For the linear relationships, the strongest increase in footprint size with vessel length was observed for

Table 2. The pairwise vessel and gear observations obtained from the industry survey.

Areas	Institutes	OT	TBB	DS	DRB
Western Baltic/North Sea	DTU Aqua	72	2	65	
	SLU	98			
North Sea	IMR	6		17	
	IMARES	5	16		
	ILVO	8	29		
	Marine Lab	115			
Western Waters	MI	60			33
	IFREMER	9			
Mediterranean	CNR	508	9		
	HCMR	37			
Black Sea	CFRI	21	22		
	Total	939	78	82	33

Table 3. BENTHIS métiers.

BENTHIS-metier	List of single species fisheries included in métier											List of primary target species in the various mixed fisheries (secondary target species in parentheses)										
OT_CRU	NEP	PRA	TGS	ARA	DPS																	
OT_SPF	SAN	SPR	CAP																			
OT_DMF	COD	PLE	SOL	LEM	WHG	POK	PDS	HAD	HKE	MON	MUT											
OT_MIX_NEP												NEP	PRA	CSH								
OT_MIX_DMF_BEN												PLE	SOL	LEM	MON							
OT_MIX_DMF_PEL												COD	WHG	POK	PDS	HAD	HKE	MUT	PDS			
OT_MIX_MED												ARA	DPS	TGS	(CTC)	(OCC)						
OT_MIX												MIX[a]	WHG	(MUT)	(TUR)	(SHC)	(BLU)	(HMM)				
TBB_CRU	CRG																					
TBB_DMF	PLE	SOL										SOL	PLE	TUR	BLL							
TBB_MOL	RPW																					
SDN_DMF	PLE	COD										PLE	COD	(PLE)	(COD)							
SSC_DMF	COD	PLE	HAD									PLE	COD	HAD	(PLE)	(COD)	(HAD)	(SAI)				
DRB_MOL	SCE	MUS	OYF																			

Explanations for the species abbreviations can be found in Supplementary Table S3. OT, otter trawl; TBB, beam trawl; SDN, anchored seine/Danish seine; SSC, flyshooting/Scottish seine; DRB, Dredge.
[a]Species not specified in questionnaire, only "MIX" informed.

OT_MIX_CRU_DMF ($a = 3.93 \pm 0.92$ SD) and for the power function relationships, the strongest increase with vessel length was observed for DRB_MOL ($b = 1.25 \pm 0.11$ SD) and with engine power for TBB_DMF ($b = 0.51 \pm 0.04$ SD).

Individual component contributions to overall footprint size

Of the completed OT questionnaires, 132 held sufficient information on sweeps and bridles, groundgear, and doors/clumps/weights to allow estimation of individual path widths for these components (Table 5). Across all OT métiers, the contribution from doors/weights/clumps path width to total footprint size varied from $1.1 \pm 0.1\%$ (OT_MIX_CRU) to $2.8 \pm 0.1\%$ (OT_SPF). The contribution from sweeps and bridles path width varied from $58.5 \pm 29.3\%$ (OT_MIX_DMF_PEL) to $86.0 \pm 19.2\%$ (OT_DMF) and the contribution from groundgear path width to total footprint size varied from $12.4 \pm 2.5\%$ (OT_DMF) to $39.0 \pm 16.5\%$ (OT_MIX_DMF_PEL).

For the beam trawl métiers, 63 questionnaires formed the basis of estimating component contributions to total footprint size: beam shoes contribution varied from $4.3 \pm 2.1\%$ (TBB_CRU) to $8.3 \pm 3.4\%$ (TBB_DMF) and groundgear contribution varied from $91.7 \pm 3.4\%$ (TBB_DMF) to $95.6 \pm 2.1\%$ (TBB_CRU).

For DRBs, the shearing edge gear component was assumed to contribute 100% to the total footprint size, and for seiners, the assumption was a 90% contribution from the seine rope gear component and a 10% contribution from the groundgear component (Table 5).

Seabed penetration by gear component

The literature review identified significant differences in the sediment penetration depths of gears. The impact varies substantially between gear types, between gear components and between sediment types (Table 6). Trawl doors of OTs leave the deepest seabed footprint, especially on muddy substrates (penetration depth up to 35 cm). On coarse and mixed sediments, trawl doors and beam trawl shoes leave marks up to 10 cm deep, as did ticklers chains of both gear types. Ticklers and rock-hoppers may also turn and displace larger pebbles and boulders in areas with mixed sediments. The few surveys of DRBs targeting molluscs were restricted to sandy mud and sand and the maximal gear penetration reported was $\leq$15 cm. On similar substrates, several of the individual gear components penetrated to different depths, for example, on muddy substrates OT door penetration ranged between $\leq$15 and 35 cm. This variation can be explained by differences in towing speed, size, weight, and rigging of similar gear types depending on target species and expected substrate conditions as well as fisheries tradition in different geographical regions.

To enable the development of a global model to assess the impact of fisheries on benthic habitats, we classified the gear component penetration depths that are reported in the literature as being either surface or subsurface impacts where penetrations of $<$2 cm are considered surface and those $>$2 cm are considered subsurface (Table 6). Maximum penetration depths are informed in parenthesis. Further details of the literature review results are provided in Supplementary material, Table S4, including comprehensive references to the individual information.

For all groundgears, an additional, partly literature and partly expert opinion based, assignment of surface and subsurface impact proportions was made (Supplementary Table S2). Of the groundgear typologies of the BENTHIS métiers, the cookie groundgear (Figure 10), when used for Danish seining (SDN_DMF) and for otter trawling for small

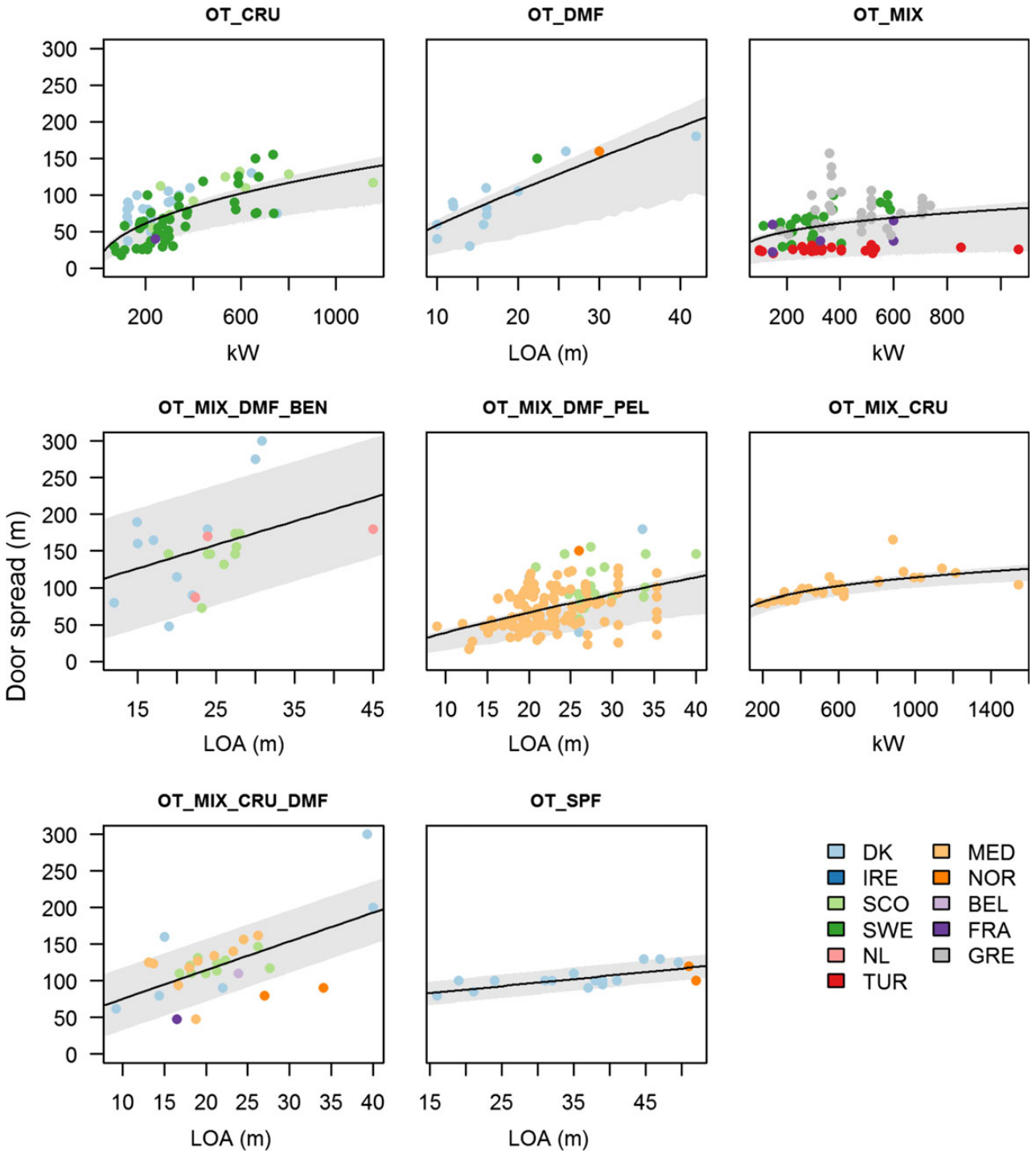

Figure 6. Relationship between total gear width (door spread) and vessel size by BENTHIS métier for OT. The shaded (grey) areas define Monte Carlo boot-strapped 95% confidence intervals.

pelagic fish on sandy bottom (OT_SPF), was ranked as having only surface level impact. In contrast, the OT bobbin/roller/chain groundgear for Nephrops or shrimp on soft bottom (OT_CRU), and also beam trawl tickler chains used for sole and plaice on sandy bottom (TBB_DMF), was assigned to have impacts entirely at the subsurface level (Supplementary Table S2). Noticeably the beam trawl groundgear used for fishing crustaceans (*Crangon crangon*) was found to have less subsurface impact (50%) owing among other to the fact that they do not deploy tickler chains (Verschueren *et al.*, 2012).

Ranking of BENTHIS métiers according to the proportion of subsurface impact

The literature-based benthic impact levels, surface or subsurface (Table 6), were assigned to individual component path width percentages (Table 5) and joined with the expert opinion-based groundgear proportions of surface and subsurface impact levels (Supplementary Table S2) to provide a ranked list of BENTHIS métiers, according to the proportion of their total footprint size having benthic impact at the subsurface level (Figure 11a). For some métiers (e.g. TBBs for

sole and plaice), the gear has both tickler chains/mats and traditional groundgear (e.g. bobbins), and in such a case, the ticklers "overrule" the less heavy bobbins gear and total groundgear impact is estimated at 100% subsurface level. The gear footprints of DRBs and TBBs for both molluscs and demersal fish all have 100% impact at the subsurface level, whereas Danish seines have zero impact at the subsurface level and OTs for small pelagic species (herring, sprat, and sandeel) have very little subsurface impact (2.8%).

Swept-area per fishing hour of average vessels by métier

Average towing speed over ground (Table 5) was highest for the beam trawlers targeting demersal fish with an average value informed of 5.2 ± 1.3 knots (mean ± standard deviation) and lowest for otter trawlers targeting crustaceans with a value of 2.5 ± 0.3 knots. Haul duration of Danish seiners was 2.6 ± 0.6 h and for Scottish seiners it was 1.9 ± 0.5 h (Table 5). In Scottish seining, the average seine rope diameter was substantially larger (43.4 mm ± 6.0) than in Danish seining (27.2 ± 6.0). Across all OT métiers, the average vessel size in kW varied from 345.5 ± 210.0 (OT_ CRU) to 691.0 ± 439.4 (OT_MIX_DMF_BEN). OT vessel length was very homogenous across métiers with all average values close to 20 m (Table 5). Beam trawlers targeting demersal fish were substantially larger than beam trawlers targeting crustaceans (822.2 ± 376.2 kW compared with 210.6 ± 62.6 kW). Danish seiners generally had little engine power (167.7 ± 54.9 kW), Scottish seiners had an average length of 23.1 ± 4.5 m, and beam trawlers fishing for molluscs in the Black Sea had an average length of 10.1 ± 2.7 m.

When calculating hourly swept-area estimates by métier (Figure 11b), Scottish seining has the largest overall gear footprint of ~1.6 km^2 of which 95% is estimated to be impact only at the surface level. This is ~30% more than the total swept-area estimate of otter trawling for Nephrops and mixed demersal fish (~1.2 km^2), for which impact at the subsurface level is estimated to be the highest of all métiers (~0.3 km^2). Beam trawlers and dredgers rank very low when comparing total swept-area per hour, but substantially higher when comparing only swept-area with impact at the subsurface level (Figure 11b).

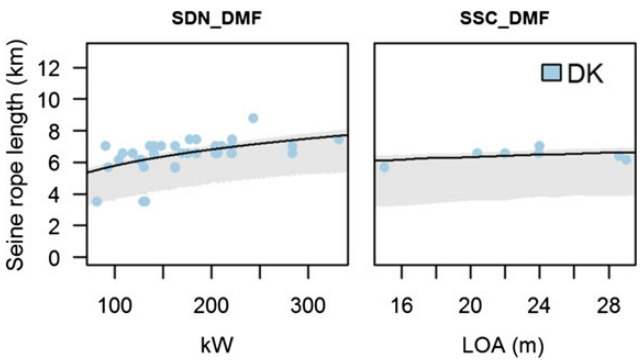

Figure 7. Relationship between total gear size (seine rope length) and vessel size for demersal seiners (DS). The shaded (grey) areas define Monte Carlo boot-strapped 95% confidence intervals. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

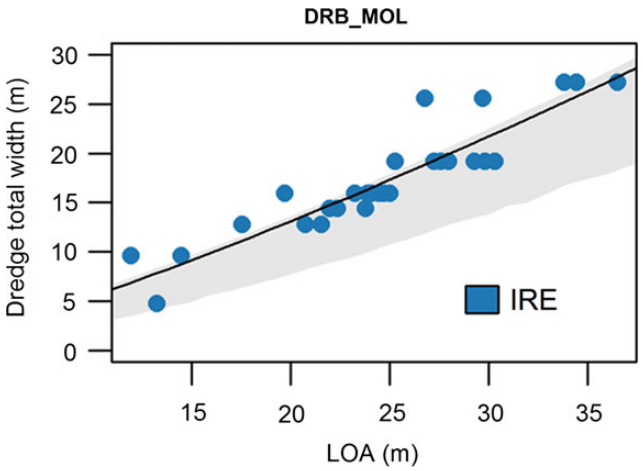

Figure 9. Relationship between total gear width (dredge width) and vessel size by BENTHIS métier for scallop DRBs. The shaded (grey) areas define Monte Carlo boot-strapped 95% confidence intervals. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

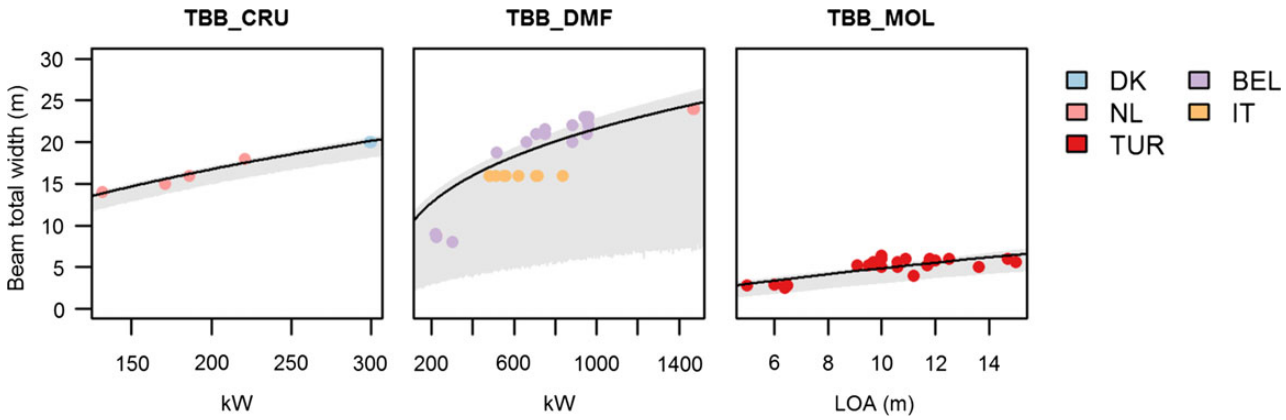

Figure 8. Relationship between total gear width (beam width) and vessel size by BENTHIS métier for beam trawlers (TBB). The shaded (grey) areas define Monte Carlo boot-strapped 95% confidence intervals. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

Table 4. Parameter estimates for the relationships between vessel size (in kW) or overall length in meters (LOA) and overall footprint size for each BENTHIS métier.

Gear path type	BENTHIS métier	Param. a	Param. b	Std. Error a	Std. Error b	Model for Path Width	Number of observations
OT door spread	OT_CRU	5.1039	0.4690	1.8153	0.0598	$a(\mathrm{kW}^b)$	124
	OT_DMF	9.6054	0.4337	3.9823	0.0676	$a(\mathrm{kW}^b)$	39
	OT_MIX	10.6608	0.2921	6.6939	0.1044	$a(\mathrm{kW}^b)$	94
	OT_MIX_CRU	37.5272	0.1490	10.6718	0.0450	$a(\mathrm{kW}^b)$	271
	OT_MIX_DMF_BEN	3.2141	77.9812	1.6785	40.9298	$a\mathrm{LOA}+b$	48
	OT_MIX_DMF_PEL	6.6371	0.7706	2.6909	0.1261	$a(\mathrm{LOA}^b)$	190
	OT_MIX_CRU_DMF	3.9273	35.8254	0.9284	21.0229	$a\mathrm{LOA}+b$	53
	OT_SPF	0.9652	68.3890	0.2052	7.4518	$a\mathrm{LOA}+b$	19
Beam trawl width	TBB_CRU	1.4812	0.4578	0.2784	0.0347	$a(\mathrm{kW}^b)$	7
	TBB_DMF	0.6601	0.5078	0.1729	0.0389	$a(\mathrm{kW}^b)$	42
	TBB_MOL	0.9530	0.7094	0.3157	0.1384	$a(\mathrm{LOA}^b)$	22
Dredge width	DRB_MOL	0.3142	1.2454	0.1100	0.1061	$a(\mathrm{LOA}^b)$	33
Seine rope length	SDN_DMF	1948.8347	0.2363	637.2515	0.0637	$a(\mathrm{kW}^b)$	47
	SSC_DMF	4461.2700	0.1176	1665.5023	0.1188	$a(\mathrm{LOA}^b)$	8

Discussion

Indicators of fishing pressure and seabed integrity

In marine ecosystems, biological indicators have mostly been defined and implemented within traditional fisheries science and management. Examples include reference points such as F_{MSY} (fishing mortality associated with maximum sustainable yield) and B_{lim} (stock biomass below which recovery may be threatened), which are used to provide guidance on sustainable exploitation of single fish and shellfish stocks (Mace, 2001). As we move towards more integrated approaches to marine management, e.g. ecosystem approach to fisheries management (EAFM), the demand for more diverse indicators is growing (Jennings, 2005; Johnson, 2008; Greenstreet *et al.*, 2012). One vitally important case would be indicators informing on the impacts of mobile bottom contacting fishing gears on benthic ecosystems, in other words, benthic fishing pressure indicators (Piet and Hintzen, 2012; ICES, 2014a).

Among the major benthic effects from such fishing are direct mortality of organisms from gear–seabed contact and habitat alterations through disturbance of sediments (Dayton *et al.*, 1995, Kaiser *et al.*, 2002). As many benthic organisms are sedentary, information on the exact spatial location of fishing activity is required to properly study and monitor the effects on the benthic ecosystem (Rijnsdorp *et al.*, 1998). Naturally, high-resolution fishing activity information is essential for the development and use of fishing pressure indicators in relation to seabed integrity (Lee *et al.*, 2010). Before the introduction of the Vessel Monitoring System (VMS) in the early 2000s, fishing activity information was only available at the ICES rectangle scale from EU logbooks. With VMS data available on a much higher spatial scale, the impact of bottom fishing on benthic ecosystem components can now be studied in more detail. A central component for such studies is the translation of fishing activity data to a measure of fishing pressure on the benthic ecosystem. Often fishing pressure is expressed as the number of times a given section of the seabed is impacted by a given fishing gear of a given size within a given period, i.e. a total swept-area (or impact) intensity estimate. The most commonly calculated fishing pressure indicators in the Northeast Atlantic are the EU Data Collection Framework indicators 5, 6, and 7 (EC, 2008; Piet and Hintzen, 2012; ICES, 2014b), which describe the distribution and total surface area that has been fished by bottom trawlers within a year, the aggregation or intensity of fishing effort, and the surface area unfished, respectively. These indicators may be considered over a full management area or could be evaluated for given habitat types (such as soft or hard substrates), depths, natural disturbance profile (Diesing *et al.*, 2013), or a combination of these. Other indicators developed for fishing pressure or seabed integrity have focused on recovery time of benthos (Hiddink *et al.*, 2006), changes in biological traits of epifauna (de Juan and Demestre, 2012) and the relationship between natural and fisheries disturbance (Diesing *et al.*, 2013).

The availability of spatially fine-scale information of fishing activity from VMS and the development of associated interpolation techniques to reconstruct fishing tracks (e.g. Hintzen *et al.*, 2010) are key elements of benthic fishing impact studies (e.g. Bastardie *et al.*, 2014). This has also significantly boosted the development of operational and meaningful pressure indicators as described above. However, a general shortcoming of practically all the indicators developed so far is their inability to incorporate detailed gear specifications/dimensions (e.g. door spread or beam width), which is a prerequisite for meaningful and reliable calculations of actual area swept and for assessing the scale and nature of the contact between the fishing gears and the benthic habitats.

Modelling gear dimensions and footprints from logbook observations

We present a generic framework to provide the basis for calculating improved indicators of seabed fishing pressure from standard effort information, typical of national fisheries statistics worldwide. The framework is based on empirical observations of mobile bottom contacting fishing gears. It is developed in a bottom-up manner with a starting point in the specific seabed contact of the different gear types (gear footprints) during the actual fishing operation. A central component has been the compilation of a large *trans*-national inventory holding pairwise observations of vessels and gears currently in use in the Northeast Atlantic, the Mediterranean, and the Black Sea. These industry-based data have allowed the estimation of widely applicable gear size–vessel size relationships for 14 different fisheries métiers. We then have the possibility of combining this quantitative information on gear dimensions with trip-based logbook data of catch and effort, which was not previously available.

The approach requires further development, in particular, to quantify the seabed contact of the different groundgear components in more detail and to allow the estimated penetration depth of the different components to be varied in relation to the sediment type. The established relationships also do not allow us take into account recent

Table 5. Averages of component proportions of total gear footprint, of towing speed over ground, of seine haul duration and rope diameter, and of vessel size for the BENTHIS métiers.

			Proportion of total footprint size (%)							Towing speed, seine haul duration and seine rope diameter				Vessel size	
Main gear type	BENTHIS métier	Typical target species	Observations	Doors/ clumps/ weights	Sweeps and bridles	Groundgear	Beam shoes	Tickler chains	Seine rope	Observations	Towing speed (knots)	Seine haul duration (hours)	Seine rope diameter (mm)	Observations	Length (m) or Engine power (kW)
OTs	OT_CRU	*Nephrops* or shrimps	19	2.6 (± 0.9)	67.9 (± 20.5)	29.4 (± 18.1)				54	2.5 (± 0.3)			122	345.5 kW (± 210.0)
	OT_DMF	Cod or plaice	5	1.6 (± 0.3)	86.0 (± 19.2)	12.4 (± 2.5)				7	3.1 (± 0.2)			33	441.7 kW (± 265.3)
	OT_MIX	Species not informed	7	1.7 (± 0.5)	80.9 (± 15.9)	17.4 (± 12.4)				66	2.8 (± 0.2)			93	400.7 kW (± 186.3)
	OT_MIX_DMF_BEN	Mixed benthic fish	8	1.4 (± 0.6)	84.1 (± 5.8)	14.5 (± 8.2)				45	3.0 (± 0.2)			46	691.0 kW (± 439.4)
	OT_MIX_DMF_PEL	Mixed bentho-pelagic fish	71	2.5 (± 1.2)	58.5 (± 29.3)	39.0 (± 16.5)				50	2.6 (± 0.4)			48	24.4 m (± 6.5)
	OT_MIX_CRU	Mixed shrimp	6	1.1 (± 0.1)	70.8 (± 8.9)	28.1 (± 9.7)				18	2.9 (± 0.2)			192	23.7 m (± 5.6)
	OT_MIX_CRU_DMF	*Nephrops* and mixed fish	12	1.4 (± 0.6)	70.0 (± 12.2)	28.6 (± 11.2)				182	3.4 (± 0.4)			44	21.7 m (± 4.1)
	OT_SPF	Sprat or sandeel	4	2.8 (± 0.1)	63.5 (± 2.0)	33.6 (± 0.2)				2	2.9 (± 0.1)			66	19.9 m (± 6.2)
TBBs	TBB_CRU	*Crangon*	7			95.6 (± 2.1)	4.3 (± 2.1)			8	2.9 (± 0.5)			8	210.6 kW (± 62.6)
	TBB_DMF	Sole and plaice	34			91.7 (± 3.4)	8.3 (± 3.4)	91.7 (± 3.4)		47	5.2 (± 1.3)			48	822.2 kW (± 376.23)
	TBB_MOL	Thomas' Rapa whelk	22			94.5 (± 0.8)	5.5 (± 0.8)	94.5 (± 0.8)		21	2.4 (± 0.3)			22	10.1 m (± 2.7)
DRBs	DRB_MOL	Scallops. mussels	33			100 (± 0.0)				33	2.5 (± 0.0)			33	24.6 m (± 5.6)
DSs	SDN_DMF	Plaice. cod	47			*10.0*[a]			*90.0*[a]	43	*0–2.5*[b]	2.6 (± 0.6)	27.2 (± 6.0)	46	167.7 kW (± 54.9)
	SSC_DMF	Cod. haddock. flatfish	8			*10.0*[a]			*90.0*[a]	6	*0–3.0*[b]	1.9 (± 0.5)	43.4 (± 6.0)	8	23.1 m (± 4.5)

Standard deviations in parentheses.
[a]For the DSs, the component percentages of the total footprint size are based on assumptions as detailed in the methods section.
[b]The towing speed range for DSs informs start and endpoint of a gradual increase in seine speed over ground during the individual fishing operation (Supplementary Methods section).

gear developments, which have not yet been deployed on a large-scale basis. Examples would include the introduction of pelagic doors in bottom trawl fisheries (Valdemarsen *et al.*, 2007) and similar bottom contact reducing developments such as buoyant sweeps, sweeps with discs/bobbins, raised footropes, dropper chains, etc. Each of these has the potential to influence both the gear footprint and its impact and thus the reliability of the estimated relationships for some of the OT métiers that we have developed here. The sum wing and pulse trawl developments in beam trawl fisheries (van Marlen *et al.*, 2014) will also likely affect the foot print or impacts of these gears. Technological development is a continuous process in fisheries (Eigaard *et al.*, 2014) and with time some of these and other impact-reducing technologies will become more widespread. This has the potential to undermine the validity of our generic footprints and métier-based relationships between vessel size and gear size. Consequently, the list of métiers and gear components should be revisited regularly and new relationships estimated at appropriate time steps, once new gear innovations become widespread in the fishery.

Notwithstanding the caveats above, we believe that the proposed framework represents a substantial step forward in the efforts to develop and implement operational large-scale fishing pressure indicators with clear causal links to expected benthic impacts: For any fishery statistics holding information of (i) vessel size, (ii) gear type, and (iii) target species composition, the established gear footprints and vessel size–gear size relationships can be combined to give overall footprint size as well as the surface and subsurface proportion of the area impacted. By subsequently merging such gear footprints with matching fishing activity information (trawl speed and haul duration) from VMS data, the estimation of seabed pressure indicators can be provided with much more detail and relevance. Applying the framework to the "average vessels" by métier (Figure 11b) demonstrated the usefulness of the methodology. The results show a very large variation in hourly swept-area and severity of impact. This can be seen not only between the major gear types, but also within gear types (e.g. between TBBs targeting Crangon and those targeting demersal fish, and between Scottish and Danish seiners). This detail would be lost with other commonly used seabed pressure indicators (e.g. ping rates) and clearly enhances the value and the reliability of fishing pressure/impact indicators.

Penetration depth across gears and sediments

In our analysis, we have assumed that the relative penetration depths by gear component for a given gear are similar for all sediments. Cleary, this is a crude assumption and the results of the literature review (Table 6) suggest that penetration depth will vary with sediment type. In general, the penetration of a particular component will be deeper on finer and softer sediments and Ivanović *et al.* (2011) found that a roller clump that penetrated 10–15 cm into muddy sand only compacted the 4–5 cm high ripples on clean sand. The consequences of this assumption are probably not too great in our analysis as we only distinguish between penetrations that are greater or less than 2 cm. A possible refinement to our current approach would be to consider penetration depth at the métier level. As a given métier will often focus on a particular substrate, this would account for changes in sediment type, to some extent. An even more sophisticated approach would be to allow component penetration to vary as sediment varies. Predictive models of the type presented by Ivanović and O'Neill (2015) demonstrate how this could be done. Such an approach would also require much higher

Table 6. Penetration depths (cm) of main gear components as estimated from literature review together with an impact index condensed across sediment types (surface level impact, subsurface level impact, and maximum penetration depth in parenthesis).

Gear types	Gear components	Coarse sediment	Sand	Mud	Mixed sediments	Indexed component impacts (maximum depth in brackets in cm)
OT	Sweeps and bridles		0–2	0		Surface (<2)
	Sweep chains		0–2	2–5		Subsurface (≤5)
	Tickler chains	2–5	2–5		2–5	Subsurface (≤5)
	Trawl doors	5–10	0–10	≤15–35	10	Subsurface (≤35)
	Multi-rig clump		3–15	10–15		Subsurface (≤15)
	Groundgear		0–2	0–10	1–8	[a]
DS	Seine ropes[b]					Surface (<2)
	Groundgear[b]					[a]
Beam trawl	Shoes	≤5–10	≤5–10	≤5–10	≤5–10	Subsurface (≤10)
	Tickler chains	≤3–10	≤3–10	≤10	≤3	Subsurface (≤10)
	Groundgear		1–8		0	[a]
Dredge	Groundgear		1–15	6		[a]

A more comprehensive review of the studies behind the condensed list can be found in Supplementary Table S4 together with a reference list. Groundgear impact indices of each BENTHIS métier are provided in Supplementary Table S2.
[a]Supplementary Table S2.
[b]No data exist for DS gears; impacts for seine ropes are assumed to be equivalent those of OT sweeps and impacts for seine groundgear is assumed to be equivalent to those of OT groundgears.

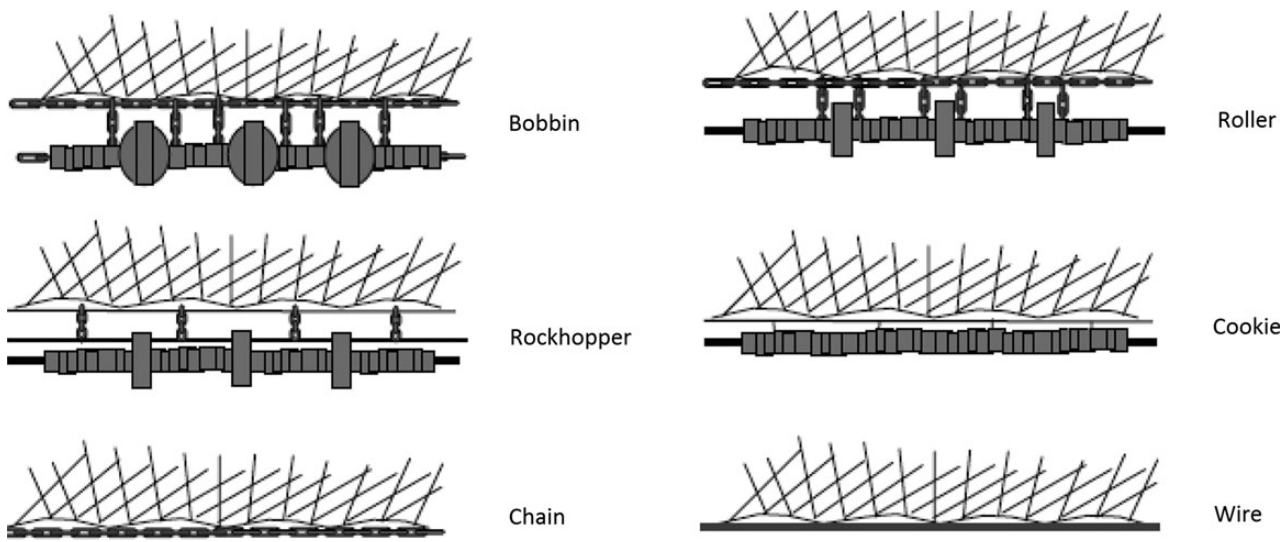

Figure 10. Examples of groundgear designs for bottom trawling (illustration from He and Winger, 2010).

data resolution and spatial information on sediment type and fishing effort.

Research and management implications

An obvious conclusion from this research is the potential gain in understanding of the seabed impacts of commercial fishing activity if we were able to access operational gear variables. In particular, variables such as door spread, wing spread, groundgear length and beam width would be invaluable. Changes in the data collected in the EU logbooks would thus be very useful for an improved EAFM.

The main outcome of the present research is a framework for predicting gear dimensions and sediment penetration depths based on data for vessel size, gear type, and target species at the level of the individual fishing operation. This framework was used to rank the most common demersal fisheries (métiers) in the northeast Atlantic. The ranking was based on the proportion of their total footprint size resulting in subsurface benthic impact. Not surprisingly, DRBs and TBBs came out as the gear types with the largest proportion of impact at the subsurface level (Figure 11a). However, we also established absolute footprint size for average-size vessels of each métier, which demonstrated that the same two gear types were among those with the smallest hourly footprint (total impact area) when standardized by vessel size (Figure 11b). The demersal seiners had the largest hourly footprints of the major gear types, but also had some of the smallest proportions of impact at the subsurface level (Figure 11). This general result is confirmed by Sainsbury (1996) who estimates swept-areas of up to 2 $km^2\ h^{-1}$ when fishing with DSs. Individual trawling speed and haul duration will, of course, determine the actual area swept for any vessel. So the ranked list of métiers is not by itself a full measure for comparing overall benthic impacts of, for example, beam trawls and OTs for given management areas.

To provide full-scale regional assessments of benthic fishing pressure by métiers, the established gear-based indicators need to

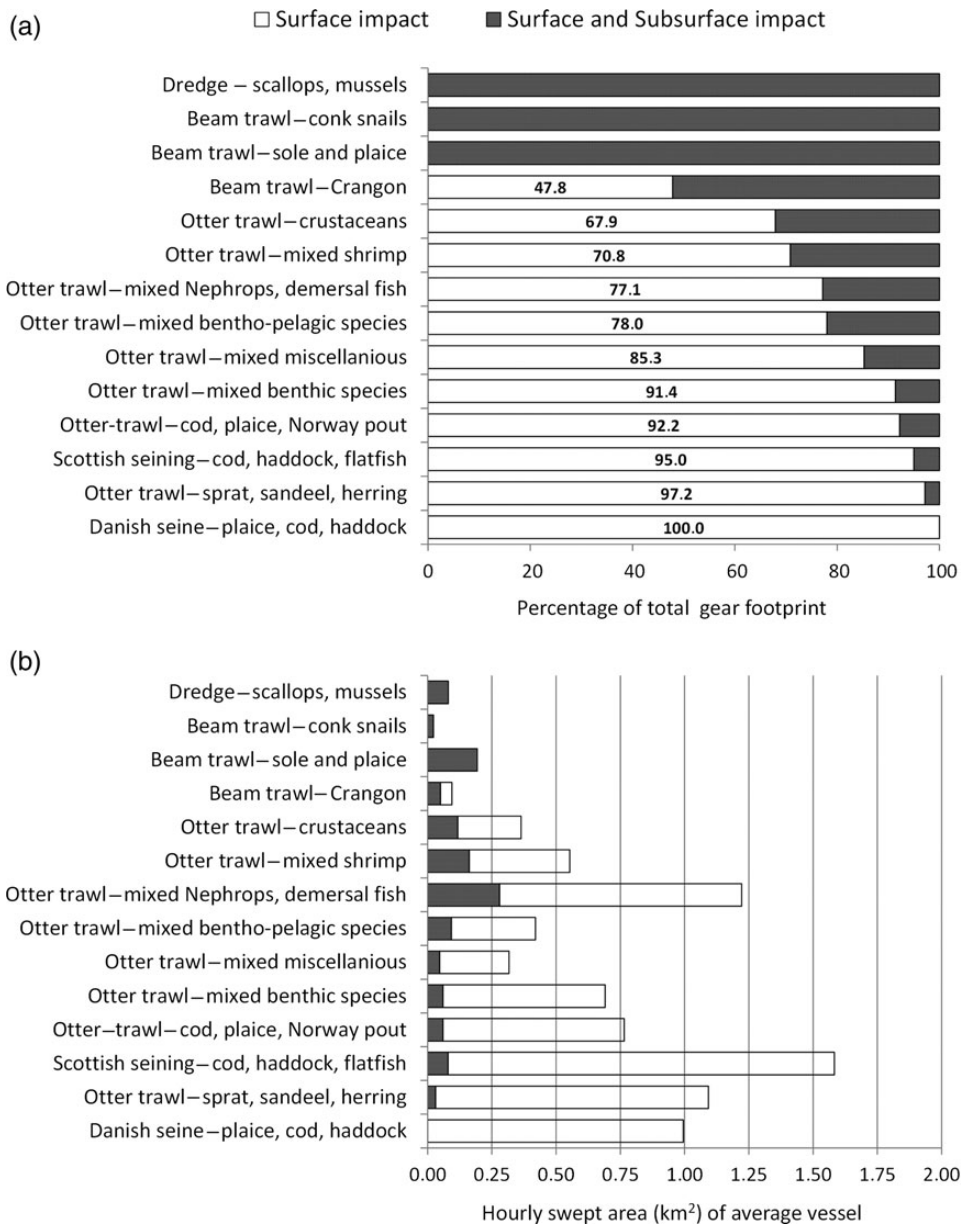

Figure 11. Proportion of total gear footprint (a) and the area of seabed swept in 1 h of fishing with an average-sized vessel (b) with impact at the surface level and at both the surface and the subsurface level for the 14 BENTHIS métiers.

be scaled up from the level of the individual fishing operation to the level of the fleet. This can be done by aggregating logbook information on effort and vessel size with modelled gear footprints. Care should be taken when extrapolating the vessel size–gear size relationships as management constraints on vessel size or gear towed may affect this relationship. For instance in the North Sea, TBBs of vessels >225 kW are restricted to a maximum of 2 × 12 m width (Rijnsdorp *et al.*, 2008) and in the Norwegian DS fishery, vessels are restricted in the length of rope they are allowed to deploy. In such cases, a fixed threshold value (management-defined) should be included in the calculations of gear dimensions from vessel size.

An obvious next step in the development of full-scale, high-resolution indicators of benthic fishing pressure would be to combine the logbook and footprint data on fishing effort with fine-scale spatial information of fishing activity from VMS. Equally useful would be to include substrate/habitat information (e.g. from EMODnet, 2015) as actual impact depends on the habitat type as well as the gear and its operation. Methodology for linking EU logbook and VMS data is already well established (Bastardie *et al.*, 2010; Hintzen *et al.*, 2012; Russo *et al.*, 2014). By adding an additional layer of gear footprint information, as established in this paper, to the state-of-the-art indicators of fishing intensity, substantial progress towards operational indicators with a stronger mechanistic link to actual benthic impact can be achieved.

Supplementary data

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

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