Deliverable 2.2

Peer review paper on definition and parameterisation of impact proxies based on gear and vessel data from Industry surveys

Due date of deliverable: month 20 (May 2014)
Actual submission date: month 27 (Jan 2015)

Grant Agreement number:	312088
Project acronym:	BENTHIS
Project title:	Benthic Ecosystem Fisheries Impact Study
Funding Scheme:	Collaborative project
Project coordination:	IMARES, IJmuiden, the Netherlands
Project website:	www.benthis.eu

Ole R. Eigaard, Francois Bastardie, Grete E. Dinesen, J. Rasmus Nielsen Thomas K. Sørensen
(Partner 9, DTU Aqua, Denmark)

Niels T. Hintzen, Adriaan D. Rijnsdorp
(Partner 1, IMARES, Netherlands)

Michael Breen,
(Partner 13, IMR, Norway)

Pascal Laffargue
(Partner 7, IFREMER; France)

Hans Nilsson, Mattias Sköld
(Partner 12, SLU, Sweden)

Finbarr O'Neil
(Partner 6, Marlab, Scotland)

Hans Polet
(Partner 2, ILVO, Belgium)

Dave Reid, Oliver Tully
(Partner 8, MI, Ireland)

Antonello Sala
(Partner 14, CNR, IT)

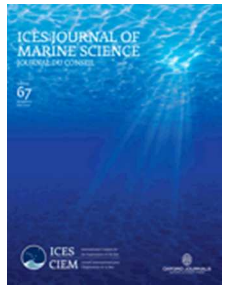
Chris Smith
(Partner 14, HCMR, Greece)

Mustafa Zengin
(Partner 16, CRFI, Turkey)

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 312088

DOCUMENT CHANGE RECORD

Authors	Modification	Issue	Date
Ole Ritzau Eigaard	Final	1	16-01-2015



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

Journal:	*ICES Journal of Marine Science*
Manuscript ID:	ICESJMS-2015-032
Manuscript Types:	Original Article
Date Submitted by the Author:	16-Jan-2015
Complete List of Authors:	Eigaard, Ole; DTU Aqua, Department of Marine Research and Technology Bastardie, François Breen, Michael; Institute of Marine Research, Research Group Fish Capture Dinesen, Grete; DTU Aqua, Hintzen, Niels; IMARES, Part of Wageningen UR, Fisheries Laffargue, Pascal Nielsen, J. Rasmus; DTU Aqua, Section Man. Systems Nilsson, Hans; Swedish University of Agricultural Sciences, Aquatic Resources O'Neill, Finbarr; Marine Scotland, Marine Laboratory Polet, Hans; ILVO, Ankerstraat 1 , 8400 Oostende, BE, Reid, Dave; Marine Institute, Sala, Antonello; CNR-ISMAR, Section of Ancona Sköld, Mattias Smith, Chris Sørensen, Thomas Tully, Oliver Zengin, Mustafa Rijnsdorp, Adriaan; IMARES, Fisheries; Wageningen University, Aquaculture and Fisheries
Keyword:	benthic impact, gear footprint, logbooks, seafloor integrity, towed gears, vessel size

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

Ole R. Eigaard[1*], Francois Bastardie[1], Michael Breen[2], Grete E. Dinesen[1], Niels T. Hintzen[3], Pascal Laffargue[4], J. Rasmus Nielsen[1] Hans Nilsson[5], Finbarr O'Neil[6], Hans Polet[7], Dave Reid[8], Antonello Sala[9], Mattias Sköld[5], Chris Smith[10], Thomas K. Sørensen[1], Oliver Tully[8], Mustafa Zengin[11], Adriaan D. Rijnsdorp[3].

[1]National Institute for Aquatic Resources, Technical University of Denmark, Charlottenlund Castle, 2920 Charlottenlund, Denmark. [2]Institute of Marine Research, P.O. Box 1870, 5817 Bergen, Norway. [3] IMARES, P.O. Box 68, 1970 AB Ijmuiden, the Netherlands, [4]IFREMER, Nantes, France. [5]Department of Aquatic Resources, Swedish University of Agricultural Sciences, Turistgatan 5, Lysekil 45330, Sweden. [6]Marine Scotland Science, 375 Victoria Rd, AB11 9DB, Aberdeen, Scotland. [7]Institute for Agricultural and Fisheries Research, Animal Sciences Unit - Fisheries and Aquatic Production, Ankerstraat 1, 8400 Oostende, Belgium. [8]Marine Institute, Galway, Ireland. [9]CNR, Ancona, Italy. 10Hellenic Centre for Marine Research, Crete, Greece, [11]Central Fisheries Research Institute, Kasüstü, Trabzon, 61100, Turkey. . *Corresponding Author: tel: +45 35883374; fax: +45 35883333; e-mail: ore@aqua.dtu.dk

Abstract

This study assesses the seafloor impact of towed fishing gears from a bottom-up perspective and models the physical impact (area and depth of seafloor penetration) from standard logbook trip information of vessel size, gear type and catch. Traditionally fishing pressure is calculated top-down by making use of fishing effort information available in large-scale statistics such as logbook and VMS data. Here we take a different approach starting from the gear itself (design and dimensions) to understand and estimate the physical interactions with the seafloor at the level of the individual fishing operation. With reference to the métier groupings of EU logbooks, we defined 14 distinct towed gear groups in European waters (8 otter trawl groups, 3 beam trawl groups, 2 demersal seine groups, and 1 dredge group), for which we established seafloor "footprints". The footprint of a gear is defined as the relative contribution from individual larger gear components, such as the trawl doors, sweeps and ground gear, to the total area and severity of the gear impact. An industry-based vessel and gear survey covering 13 different countries provided the basis for estimating the relative impact-area contributions from individual gear components, whereas seafloor penetration was estimated based on a review of the scientific literature. For each defined gear group a vessel-size (kW or total length) – gear size (total gear width or circumference) relationship was estimated to enable the prediction of gear footprint area and sediment penetration from vessel size. The implications for the definition, estimation and monitoring of fishing pressure indicators are far-reaching, and are discussed in context of an ecosystem approach to fisheries management (EAFM).

Keywords: benthic impact, gear footprint, logbooks, seafloor integrity, 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), physical disturbance of biogenic habitats (Kaiser et al. 2006; Cook et al. 2013), while 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 1880's the impacts of new steam driven bottom trawlers were widely debated (Graham 1938) and similar debates still exist between the fishing industry and environmental organisations. In addition, consumer driven mechanisms such as eco-labelling 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 (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 seafloor 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 is 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 on a regular basis. There are, however, significant differences in the fishing gears deployed by commercial vessels, and in the corresponding nature of their physical contact with the seafloor (Suuronen et al. 2012), and it is important 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 seafloor 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 seafloor pressure (area and severity of seafloor 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, demersal seiners, beam trawls and dredges. A gear footprint is defined by its measures of overall size (e.g. door spread for otter trawls) 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 otter trawl).

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 sub-surface 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 sub-surface seafloor impact. Although EU logbooks do not hold information of gear size (e.g. the average door spread of an otter trawl) 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 relationships between overall gear footprint size and vessel size for fourteen different metiers (fishing trips grouped by gear type and target species). The vessel size ~ gear size relationships by metier 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 gear size relationships significantly improves the ability to calculate seafloor integrity indicators from current fisheries statistics, which can fulfil the requirements of an EAFM. Furthermore the analysis of fishing gears and their seafloor 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 seafloor 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 seines**, **beam trawlers** and **dredges** 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: 1) Mortality of benthic organism from direct gear- sea bed gear contact during fishing, 2) food subsidies from discards and gear track mortality, 3) habitat alterations through disturbance of sediments and effects on sea bed habitats, and 4) geo-chemical processes (release of nutrients and chemical substances) from disturbance of sediment.

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 includes the bulk of benthic fishing pressure from 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 with otter trawlers in European waters is assessed to be at least an order of magnitude larger than the effort with demersal seiners.

[Table 1]

Demersal otter trawling

Demersal otter trawls are essentially conical nets that are dragged along the sea floor (Valdemarsen et al. 2007). The trawl net is held open using trawl floats, ground gear and trawl doors (Figure 1). The trawl doors are connected to the vessel by warps and to the trawl-net 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 ground gear mounted under the netting is designed to protect the net against wear, to help it across many different terrains, and to prevent target species from escaping beneath the trawl. Consequently, otter trawl ground gears are very heterogeneous in design. In traditional otter trawling, the trawl doors, sweeps and ground gear all come into contact with the seabed during trawling. Depending on 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 from 25 to 250 meters. In modern bottom trawling, multi-rig trawling is also used, which involves two or more trawls being fished side by side by one vessel (Figure1). 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 pair trawling, 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.

[Figure 1]

Demersal seining

When fishing with Danish (anchored) seine, the gear is laid out in roughly a circular area on the seabed using very long ropes (Figure 1). As the two ropes are hauled in from the anchored vessel, the net gradually closes and towards the end of the haul it moves forwards in the same way as a trawl. It should be noted that the geometrical shape of the individual demersal seine hauls can vary substantially (sometimes triangular in shape) depending on the target species and the seabed conditions. In many cases the fished area is enlarged by completing maybe only 2/3 of a circle and then dragging the rope and seine the remaining distance back to the anchor before hauling, which also adds to the variation in geometry of the seabed area swept. The length of the seine ropes deployed in Danish seining typically varies between 5000 and 8000 meters depending on mainly vessel size. Scottish seining (or fly shooting) is a more engine power demanding variation of Danish seining, where the vessel moves forward while at the same time hauling in the ropes. Fly shooting can be considered a hybrid between anchored seining and demersal otter trawling (Figure1) and the seine rope lengths are typically shorter than in Danish seining (4000-6000 meters) but the diameter typically larger, enabling the flyshooters to fish on rougher grounds.

Beam Trawling and dredge fishing

Both beam trawls and dredges are typically used to target species that stay on the bottom or that are partly buried in the sediment. Accordingly, 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 sea bed 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 to 12 m, and dredge widths from 0.75 to 3 m). The beam trawl fishery for common shrimps (*Crangon Crangon*) deploys beam trawls without tickler chains and use a light bobbin rope. Typically two beam trawls are towed by each vessel, but as for dredgers variation in towing methods and numbers can be quite large (Figure 1). Beam trawls 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

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. The gear specific footprints conceptualized and estimated in the following can also be considered as measures of fishing capacity in relation to benthic pressure; essentially the footprints inform gear widths and penetration depths of each metier by vessel size. In order 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 of fishing activity (i.e. trawling speed and duration) on a case specific basis.

Otter trawl footprint

For a traditional single otter trawl there are three main types of sea bed impacts during a trawl haul: a) from the otter boards, b) from the sweeps and c) from the trawl itself (the trawl ground gear), which together define the footprint of an otter trawl fishing operation (Figure 2). Of these three impacts the one from the otter boards is the most severe but also the one with the narrowest track/path (Figure 2). Depending on 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 (Luchetti 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 pair-trawl fishing (Figure 1 and Figure 2). In general the sweeps represent a large proportion of the total trawl gear path (figure 2), but they appear to have the least impact on the seabed with penetration mostly limited to the top centimetres of sediment (Buhl-Mortensen et al. 2013). The ground gear path of an otter trawl is more heterogonous in design and varies significantly with the species targeted and the type of sediment fished. In the context of seafloor pressure we define overall Otter trawl (OT)-footprint size (for both single and twin trawls) as the total spread of the trawl doors during fishing (Figure 2). For pair trawlers this is equal to the total spread of weights.

[Figure 2]

Demersal seine footprint

For a demersal seine there are two main types of sea bed impacts during a seine haul: a) from the seine rope, and b) from the seine itself (the seine ground gear), which together define the gear footprint of a Danish seine operation (Figure 3, left) and a Scottish seine operation (Figure 3, right). The biggest impact (largest area of impact) in both types of demersal seining comes from the seine ropes, whereas the seine ground gear only covers a smaller 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 ground gear 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. Since demersal seining is dependent on the ropes not getting caught on obstacles during the herding phase, there are clear limitations on the sediment types where it can be used. However, larger seine rope diameters and higher vessel engine power enables Scottish seiners to fish also rougher grounds and also implies heavier bottom contact compared to anchored seiners. In the context of seafloor pressure we define the overall Demersal seine (DS)-footprint size as the total area swept by the seine ropes and ground gear during a fishing operation. For anchored seining this footprint can be conceptualised as a circle with a circumference of total seine rope length and an area of $\pi*r^2$, where r is the total seine rope length/2 π. For Scottish seining the overall footprint is defined as 1.5 times a circle with an area of $\pi*r^2$, where r is total seine rope length/2 π (Figure 3).

[Figure 3]

Beam trawl footprint

For a traditional beam trawl the footprint is more homogenous than for an otter trawl and can be separated in two types of paths: a) the path being affected by the shoes of the beam, and b) the path being affected by the ground gear (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 inflict furrows of up 10 cm depth in the sediment (Paschen et al. 2000; Depestele et al. in prep). The overall Beam trawl (TBB)-footprint size of a fishing operation is defined as the width of the beam multiplied with the number of beam trawls deployed by the vessel.

[Figure 4]

Dredge footprint

Dredges used for catching molluscs such as scallops, mussels and oysters typically have a simpler conceptual footprint than beam trawls in that mostly the ground gear is 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 not uncommon and which produce a more uneven sediment furrow (O'Neill et al. 2013). Standard dredges have been demonstrated to create furrows of up to 6 cm depth in soft sediments (Pranovi et al. 2000) and the dredges used for infaunal bivalves in the Adriatic Sea have been demonstrated to create furrows in the sediment up to 15 cm deep (Luchetti and Sala 2012). The overall Dredge (DRB)-footprint size of a fishing operation is defined as the width of the dredge multiplied by the number of dredges deployed by a vessel.

[Figure 5]

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 fishermen and net-makers, conducted either by principal scientist in BENTHIS (EC 2014) or by national observers routinely monitoring discards on board individual vessels. Some questionnaires were filled in using information from national gear databases. The four questionnaires can be found in the supplementary material (SM) of this paper (SM, Figure 1, 2, 3 and 4). 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 metiers (combinations of gear types and target species).

BENTHIS metiers

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 metiers). This grouping of questionnaire observations was made with reference to the métier principles of the EU logbooks (the data collection framework metiers (DCF-metiers)) 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 metiers 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*

For OT fishing operations, the overall footprint size was defined as total door spread, for DS fishing operations it was defined as total area swept by the seine ropes or ground gear during a fishing operation, and calculated from total seine rope length, for TBB fishing operations it was defined as beam width * beam trawl number, and for DRB-vessels it was defined as dredge width * dredge number. Each of these measures of footprint size was related to vessel size measured either as engine power (kW) or vessel length over all (LOA) in meters. 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. The 95% confidence intervals around the means were estimated by Monte Carlo simulations in case of non-linear fitting, resulting in asymmetric confidence bands.

Path widths of individual footprint components

The gear information of 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 ground gear for otter trawls; seine rope and ground gear for demersal seines; beam shoes, tickler chains and ground gear for beam trawls; ground gear for dredges.

Otter trawl footprint components

Direct information of individual component path widths (e.g. ground gear path width) was rarely informed in the otter trawl questionnaires. Consequently, component path widths were estimated indirectly by applying otter trawl gear geometry theory (Kynoch 1997; Valdemarsen et al. 2007; SEAFISH 2010) to those gear component measures that were informed in the questionnaires. I.e.; sweep path width of each otter trawl was calculated from informed sweep and bridles length and a literature-based sweep/bridle angle assumption of a 13° average across all BENTHIS metiers (equation 1; SM, Figure 5; SEAFISH 2010; Notti et al. 2013), ground gear track width was calculated from informed ground gear length (Equation 2; SEAFISH 2010), and each door path width was calculated from informed door width (Equation 3, Valdemarsen et al. 2007). The clumps of multi-rig otter trawls and the weights of pair trawls are extremely different in size and design (Valdemarsen et al. 2007), and a simplifying assumption of a path width of 0.75 meter 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, ground gears and doors/clumps/weights) were multiplied with the number of components deployed by the vessel as informed in the questionnaire:

(1) Total sweep path width = sinus (13°) * (Sweep_length + Bridle length) * 2 * Trawl_number

(2) Total ground gear path width = Ground gear_length * 0.4 * Trawl-number

(3) Total Door/clump/weight path width = (Door_length * 0.4 * Door_number) + (0.75 m * (Trawl_number -1))

Demersal seine footprint components

Very little empirical data exists on the geometry of demersal seine operations and the assumption was made that, for both Danish and Scottish seine fishing operations, the ground gear path constituted 10% of the total seine footprint size and the seine ropes the remaining 90%. This assumption was based partly on qualitative information of Danish and Scottish seine fishing operations from net maker interviews ('Rays Vodbinderi' in Hirtshals and 'Strandby Net' in Strandby, both Denmark), and partly on observations in the BENTHIS gear questionnaire and the Danish discard database holding observer sampled catch and effort information from a number of demersal seine trips. The interviewees also pointed out that particularly for Danish seine fishing operations individual demersal seine hauls can vary highly (sometimes triangular in shape) depending on the target species, seabed conditions and skipper skills, therefore both the circular and the 10% ground gear coverage assumption should be treated with 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 ground gear 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).

(4) Total beam shoe path width = Beamshoe_width * Beamshoe_number * Trawl_number

(5) Total ground gear path width = (Beam_width – (Beamshoe_width * Beamshoe_number)) * trawl-number

(6) Total tickler chain path width = (Beam_width – (Beamshoe_width * Beamshoe_number)) * trawl-number * Tickler_chain (1/0)

Dredge footprint components

Dredges used for catching molluscs such as scallops and mussels are mostly homogenous across the entire width of the dredge (although in some fisheries dredge teeth are not uncommon). The ground gear (shearing edge) is assumed to constitute 100 % of the total dredge footprint size, and for each questionnaire observation total shearing edge path width is calculated as dredge width multiplied by the number of dredges deployed by a vessel.

Surface and sub-surface impact

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

To distinguish between potential effects on benthic epifauna and infauna, penetration depth of the individual components was indexed as either surface or subsurface. 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 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, ground gear, 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, in order 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 sub-surface 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 ground gears (Ivanović and O'Neill, 2015; Esmaeili and Ivanović, 2014). Therefore expert opinions (BENTHIS gear technologists) were used to subjectively assign ground gear surface and sub-surface impact proportions to each of the metiers. In the industry questionnaires some information (mostly qualitative) of ground gears was provided, enabling identification of typical ground gear type by metier. In combination with a few available studies on the seafloor contact of particular ground gears (Ivanović et al. 2011) these questionnaire-based ground gear typologies formed the basis of assigning surface/sub-surface impact proportions to the full ground gear path widths of each BENTHIS metier (SM, Table 3).

For demersal seines no penetration depth studies have been conducted, and for Danish seining (anchored seines) the assumption is made that the seine rope has a penetration depth equal to that of otter trawl sweeps, and that the ground gear impact is equal to the lightest impact of the eight different OT-metier ground gears. For Scottish seining (Fly-shooting) the assumption is made that the seine ropes have a 10 % sub-surface impact. This assumption is based partly on the questionnaire information of substantially larger seine rope diameters in this type of seining (43.4 ± 6.0 mm; mean ± SD) compared to Danish seines (27.2 ± 6.0 cm; mean ± SD)) and partly on the fact that fly-shooters deploy substantially more engine power for their fishing operations. For both seine types it is assumed that the ground gear has an impact equal to the median impact level of the of the eight different OT-metier ground gears.

Ranking of BENTHIS metiers according to relative sub-surface 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 ground gear proportions of surface/sub-surface impact (expert opinion based), it was possible to rank the fourteen BENTHIS metiers according to their relative surface – sub-surface impact.

Swept area per fishing hour of average vessels by metier

The gear footprints and vessel size ~ gear size relationships obtained allow us to estimate the total swept area per fishing hour for each BENTHIS metier. 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 dredges) and haul duration (seines), and surface - subsurface proportions of the area swept were calculated from the component-based footprint proportions.

Results

Industry survey and BENTHIS metiers

The industry consultations resulted in 1132 questionnaires being filled; 939 for otter trawls, 78 for beam trawls, 82 for demersal seines and 33 for dredges (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.

[Table 2]

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

[Table 3]

Vessel size and overall footprint size by BENTHIS metiers

The relationships between vessel size and footprint size were fitted with either a linear link or a power function link for each defined BENTHIS metier (Figure 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 metiers, the resulting fits show that footprint size increases with vessel size. A linear link was estimated for three BENTHIS metiers (OT_MIX_DMF_BEN, OT_MIX_CRU_DMF and OT_SPF) and a power function link was estimated for the remaining eleven metiers (Table 4). LOA and kW were equally abundant as vessel size descriptors with seven metiers each. For the linear relationships the strongest increase in footprint size with vessel length was observed for OT_MIX_CRU_DMF ($a=3.93 \pm 0.92$ SD) and for the power 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).

[Figure 6, 7, 8 & 9]

[Table 4]

Individual component contributions to overall size

Of the completed otter trawl questionnaires, 132 held sufficient information on sweeps and bridles, ground gear and doors/clumps/weights to allow estimation of individual path widths for these components (Table 5). Across all otter trawl metiers, the contribution from doors/weights/clumps path width to total footprint size varied from 1.1% ± 0.1 (OT_MIX_CRU) to 2.8% ± 0.1 (OT_SPF). The contribution from sweeps and bridles path width varied from 58.5% ± 29.3 (OT_MIX_DMF_PEL) to 86.0% ± 19.2 (OT_DMF) and the contribution from ground gear path width to total footprint size varied from 12.4% ± 2.5 (OT_DMF) to 39,0% ± 16.5 (OT_MIX_DMF_PEL).

[Table 5]

For the beam trawl metiers, 63 questionnaires formed the basis of estimating component contributions to total footprint size; beam shoes contribution varied from 4.3% ± 2.1 (TBB_CRU) to 8.3% ± 3.4 (TBB_DMF) and ground gear contribution varied from 91.7% ± 3.4 (TBB_DMF) to 95.6% ± 2.1 (TBB_CRU).

For dredges 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 ground gear component (Table 4).

Seafloor 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 otter trawls leave the deepest footprint in the seabed, especially on muddy substrates (penetration depth up to 35 cm). On course 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 dredges targeting molluscs were restricted to sandy mud and sand and the maximal gear penetration reported was ≤ 15 cm. On similar substrates, several of the individual gear components penetrated to different depths, for example, on muddy substrates demersal otter trawl door penetration ranged between ≤ 15–35 cm. This variation can be explained by differences in 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 a global model development for a fisheries impact assessment of benthic habitats, we indexed all literature reported gear component penetration depths into two modalities: surface and sub-surface impacts (Table 6). Maximum penetration depths are informed in parenthesis. Further details of the literature review results are provided in the supplementary material (SM, Table 2) including comprehensive references to the individual information.

[Table 6]

For all ground gears an additional, partly literature and partly expert opinion based, assignment of surface and sub-surface impact proportions was made (SM, Table 3). Of the ground gear typologies of the BENTHIS metiers, the cookie ground gear (SM, Figure 2), when used for small pelagic fish on sandy bottom (OT_SPF), was ranked as having only surface level impact. In contrast, the otter trawl cookie/discs ground gear 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), were assigned to have impacts entirely at the subsurface level (SM, Table 3). Noticeably the beam trawl ground gear used for fishing crustaceans (*Crangon crangon*) was found to have less subsurface impact (50%) owing to the fact that they do not deploy tickler chains.

Ranking of BENTHIS metiers according to proportion of sub-surface 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 ground gear proportions of surface and subsurface impact levels (SM, Table 3) to provide a ranked list of BENTHIS metiers according to the proportion of their total footprint size having benthic impact at the subsurface level (Figure 10, left panel). For some metiers (e.g. beam trawls for sole and place) the gear has both tickler chains/mats as well as traditional ground gear (e.g. bobbins) and in such a case the ticklers "overrule" the less heavy bobbins gear and total ground gear impact is estimated at 100% subsurface level. For the Crangon beam trawls (TBB_CRU) tickler chains are absent and subsurface impact of this ground gear is set at 50% (Verschueren 2012). The gear footprints of dredges and beam trawls for both molluscs and demersal fish all have 100% impact at the subsurface level, whereas Danish seines and otter trawls for small pelagic species (herring, sprat and sandeel) have relatively little impact at the sub-surface level (< 5%).

[Figure 10]

Swept area per fishing hour of average vessels by metier

Average towing speed (Table 5) was highest for the beam trawlers targeting demersal fish with an average value informed of 5.2 knots ±1.3 (SD) and lowest for otter trawlers targeting crustaceans with a value of 2.5 knots ± 0.3. Haul duration of Danish seiners was 2.6 hours ±0.6 and of Scottish seiners 1.9 hours ±0.5 (Table 5). Across all otter trawl metiers, the average vessel size in kW varied from 345.5 ± 210.0 (OT_ CRU) to 691.0 ± 439.4 (OT_MIX_DMF_BEN). Otter trawl vessel length was very homogenous across metiers with all average values close to 20 meters (Table 5). Beam trawlers targeting demersal fish were substantially larger than beam trawlers targeting crustaceans (822.2 kW ± 376.2 compared to 210.6 kW ± 62.6). Danish seiners generally had little engine power (167.7 kW ± 54.9), Scottish seiners had an average length of 23.1 m ± 4.5, and beam trawls fishing for molluscs in the Black Sea had an average length of 10.1 m ± 2.7. When calculating hourly swept area estimates by metier, Scottish seining has the highest area impact at both the surface and the subsurface level with a combined value of approx. 2.6 km^2 (Figure 10, right panel). This is about twice as much as the second highest combined swept area estimate for Danish seines, which is closely followed by otter trawling for small pelagic fish and otter trawling for nephrops and mixed demersal fish. The latter metier has the second highest swept area with impact at the subsurface level (approx. 0.3 km^2 per hour), only surpassed by Scottish seining with approx. 0.4 km^2 swept per hour. Beam trawlers and dredges rank very low when comparing total swept area per hour, but more intermediate when comparing only swept area with impact at the subsurface level.

Discussion

Indicators of fishing pressure and seafloor integrity

In the marine ecosystems biological indicators have mainly been defined and implemented within traditional fisheries science and management, where reference points such as F_{MSY} and B_{lim} are used to provide guidance on sustainable exploitation of single fish and shellfish stocks (Mace, 2001). With the strong global movement towards more integrated approaches to marine management (i.e.

EAFM) the demand for additional indicators is growing (Jennings 2005; Johnson 2008; Greenstreet 2012). This demand has resulted in a substantial effort within scientific communities and advisory bodies to establish the required indicators such as those addressing the impacts of fishing gears on benthic ecosystems, i.e. benthic fishing pressure indicators (Piet and Hintzen 2012, ICES 2014a).

Some of the major benthic effects from fishing with mobile, bottom contacting gears is direct mortality of organisms from gear- sea bed 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 seafloor integrity (Lee et al. 2010). With the introduction of VMS in around the 2000's, fishing activity information on a much higher spatial scale became available (compared to the ICES rectangle scale of most EU logbooks) and the impact of bottom fishing on ecosystem components, such as the benthic layer, could be studied in more detail. A central component in spatially defined studies of benthic fishing impacts is the translation of fishing activity data to a measure of fishing pressure. Often fishing pressure is expressed as the number of times a certain section (defined area) of the seabed is impacted by the fishing gear within a given time period, i.e. a total swept area (or impact intensity) estimate. The most commonly calculated fishing pressure indicators in the North east Atlantic are the EU Data Collection Framework indicators 5, 6 and 7 (EC 2008; Piet & 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 management area wide or could be evaluated including habitat type (such as soft or hard substrates), depth, natural disturbance (Diesing et al., 2013), or a combination of these. Other indicators developed on fishing pressure or seafloor 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).

Obviously 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), and 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 reliable calculations of actual area swept and for assessing the nature of the contact between the fishing gears and the benthic habitats.

Modelling gear dimensions and footprints from logbook observations

We here present a generic framework providing the basis for calculating improved indicators of seafloor fishing pressure from the standard effort information, typical of national fisheries statistics worldwide. The framework is based on empirical observations of mobile, bottom contacting fishing gears, and is developed in a bottom-up manner with starting point in the specific seafloor 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 pair-wise 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 universal gear size ~ vessel size relationships for fourteen different fisheries metiers and with that the possibility to superimpose quantitative information of gear dimensions onto trip-based logbook observations of catch and effort, for which such data is rarely informed.

The approach requires further development, in particular to quantify the ground gear components and their seafloor contact in more detail, and to allow the estimated penetration depth of the individual components to vary in relation to the grain size of the sea bed. Neither do the established relationships take into account recent gear developments, which are not yet deployed on a large-scale basis. In particular the introduction of pelagic doors in bottom trawl fisheries (Valdemarsen et al. 2007) and similar bottom-contact reducing developments such as negatively buoyant sweeps, sweeps with discs/bobbins, raised footropes, dropper chains, etc , has the potential to influence the footprints and the reliability of the estimated relationships for some of the otter trawl metiers. Also the sum wing and pulse trawl developments in the beam trawl fisheries (van Marlen et al., 2014) will affect the foot print of the beam trawls. Technological development is a continuous process in fisheries (Eigaard et al. 2014) and with time some of these impact-reducing technologies will become more widespread and constitute a source of error. When this happens the list of metiers and gear components should be revisited and new relationships estimated.

Despite this identified improvement potential, we find that the developed 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 total gear 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 e.g. VMS data, the estimation of seafloor pressure indicators can be taken to a new level. Applying the framework to the "average vessels" by metier (Figure 10, right panel) demonstrated the usefulness of the methodology. The results show a very large variation in hourly swept area and severity of impact not only between the major gear types, but also within these gear types (e.g. between beam trawls targeting Crangon and those targeting demersal fish, and between Scottish and Danish seiners). Such variation is not reflected in many commonly used seafloor pressure indicators (e.g ping rate intensity), and clearly this weakens the reliability of such indicators.

Penetration depth across gears and sediments

In the analysis presented here it has been assumed that the relative component penetration depths of a given gear are similar for all sediments. Cleary this is a crude assumption and as shown in the results of the literature review of table 6, penetration depth will vary somewhat disproportionally with sediment type. In general, the penetration of a particular component will, however, 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 sand. Therefore the consequences of this assumption are not great in our analysis as we basically distinguish only between penetrations that are above or below 2cm in depth. A possible refinement to the approach set out here would be to consider penetration depth at the metier level. This would, to a certain extent, implicitly account for changes in sediment type, as a given metier often takes place on a characteristic substrate. 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; however, such an approach would also require much higher data resolution and spatial information on sediment type and fishing effort.

Research and management implications

The main outcome of the work presented is a framework for predicting or modelling gear dimensions and sediment penetration depths from observations of vessel size, gear type and target species at the level of the individual fishing operation. This framework has been used for ranking the most common demersal fisheries (metiers) of the North east Atlantic according to the proportion of their total footprint size having benthic impact at the subsurface level, and dredges and beam trawls came out as the gear types with highest proportion of subsurface impact (Figure 10). However, we also established relationships between vessel size and absolute footprint size for the metiers, which demonstrated that the same two gear types were among those with the smallest footprint (impact area) when standardized by vessel size (Figure 11). Also trawling speed and haul duration will influence the actual area swept by equally sized vessels of different metiers, and therefore the ranked list of metiers is not by itself a useful measure for comparing overall benthic impacts of e.g. beam trawls and otter trawls for given management areas.

To provide full scale assessments of regional benthic pressure from different metiers, the established gear-based indicators need to be scaled up from the level of the individual fishing operation to the level of the fleet by aggregating logbook observations, which have been extended with modelled gear footprints. Care should, however, be taken when extrapolating the vessel size – gear size relationships to large-scale fisheries statistics, as these will be affected by management that constrains the dimensions of gears or vessels. For instance in the North Sea, beam trawls of vessels >225 kW are restricted to a maximum of 2x12 meters width (Rijnsdorp et al. 2008) and in the Norwegian demersal seine fishing vessels are restricted with respect to the length of rope they are allowed to deploy. In such cases a fixed threshold value should be integrated in the calculations of gear dimensions from vessel size. An obvious next step in the development of benthic fishing pressure indicators would be to merge the extended logbook observations of fishing effort with fine-scale spatial information of fishing activity from VMS data. Methodology for linking EU logbook and VMS data is already well established (Bastardie et al. 2010; Hintzen et al. 2012) and by adding an additional layer of gear footprint information to the state of the art indicators of fishing intensity, substantial progress towards operational indicators with a stronger mechanistic link to actual benthic impact will be achieved.

Finally the results obtained here also imply the need to revise the format of the effort information currently collected in the EU logbooks, where clearly variables such as door spread, ground gear length, beam width and more, are crucial for meeting the monitoring requirements of EAFM.

Supplementary material

The following supplementary material is available at ICESJMS online: a list detailing the species abbreviations integrated in the BENTHIS metier names (Table 1), a full review table of the studies estimating penetration depth of gear components (Table 2), a table of typical ground gear composition and associated impact severity of the BENTHIS metiers (Table 3), the format of the industry questionnaires for the four major gear types (Figures 1-4), a figure of the geometrical principals underlying the estimations of component path widths of otter trawl metiers (Figure 5), a figure of different types of otter trawl ground gears (Figure 6), and a list of the literature referred to in the supplementary material (Reference list).

Acknowledgements

The above described work has been funded through the EU-FP7 project 'BENTHIS' (grant agreement number 312088). We also thank Sonia Mehault from IFREMER for data provision and the anonymous referees for their constructive criticism.

References

Anon. 2010. Commission Decision of 1 September 2010 on criteria and methodological standards on good environmental status of marine waters. 2010/477/EU.

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

Bastardie, F., Nielsen, J. R., Eigaard, O. R., Fock, H. O., Jonsson, P., and Bartolino, V. 2014. Competition for marine space: modelling the Baltic Sea fisheries and effort displacement under spatial restrictions. – ICES Journal of Marine Science, doi: 10.1093/icesjms/fsu215

Bradshaw, C., Tjensvoll, I., Sköld, M., Allan, I.J., Molvaer, J., Magnusson, J., Naes, K., Nilsson, H.C. 2012. Bottom trawling resuspends sediment and releases bioavailable contaminants in a polluted fjord. Environmental Pollution, 170: 232–241.

Buhl-Mortensen, L., Aglen, A., Breen, M., Buhl-Mortensen, P., Ervik, A., Husa, V., Løkkeborg, S., Røttingen, I., Stockhausen, H.H. 2013. Impacts of fisheries and aquaculture on sediments and benthic fauna: suggestions for new management approaches. Fisken og Havet 3, 69 pp.

Cook, R., Fariñas-Franco, J.M., Gell, F.R., Holt, R.H.F., Holt, T., Lindenbaum, C., Porter, J.S., Seed, R., Skates, L.R., Stringell, T.B., Sanderson, W.G. 2013. The Substantial First Impact of Bottom Fishing on Rare Biodiversity Hotspots: A Dilemma for Evidence-Based Conservation. PLoS ONE 8: e69904.

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

Diesing, M., Stephens, D., and Aldridge, J. 2013. A proposed method for assessing the extent of the seabed significantly affected by demersal fishing in the Greater North Sea. ICES Journal of Marine Science, 70: 1085-1096.

EC 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environment policy (Marine Strategy Framework Directive). Official Journal of the European Union, 25.6.2008 L 164: 19–40.

EC 2014. 7th Framework Programme Project: Benthic Ecosystem Fisheries Impact Studies (BENTHIS). www.benthis.eu [Accessed 15-01-2015]

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

Eigaard, O.R., Marchal, P., Gislason, H. and Rijnsdorp, A.D. 2014. Technological development and fisheries management. Reviews in Fisheries Science & Aquaculture, 22: 156-174.

Esmaeili, M. and Ivanovic, A. 2014. 'Numerical modelling of bottom trawling ground gear element on the seabed'. Ocean Engineering, 91: 316.

FAO 2014. Food and Agriculture Organization of the United Nations, Fisheries and Aquaculture Department. http://www.fao.org/fishery/geartype/search/en [Accessed 15-01-2015]

Garcia, S. M., Zerbi, A., Aliaume, C., Do Chi, T., Lasserre, G. 2003. The ecosystem approach to fisheries. Issues, terminology,principles, institutional foundations, implementation and outlook. FAO Fisheries Technical Paper, 443. 71 pp.

Graham, M. 1938. The trawl fisheries: A scientific and national problem. Nature, 142: 1143–1146.

Greenstreet, S.P.R., Rossberg, A.G., Fox, C.J., Le Quesne, W.J.F, Blasdale, T., et al. (2012) Demersal fish biodiversity: species-level indicators and trends-based targets for the Marine Strategy Framework Directive. ICES Journal of Marine Science, 69: 1789-1801.

Hiddink, J. G., Jennings, S., and Kaiser, M. J. 2006. Indicators of the Ecological Impact of Bottom-Trawl Disturbance on Seabed Communities. Ecosystems, 9: 1190.

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

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

ICES. 2014a. Report of the Workshop to review the 2010 Commission Decision on criteria and methodological standards on good environmental status (GES) of marine waters; Descriptor 6, 2-3 September 2014, ICES Headquarters, Denmark. ICES CM 2014/ACOM: 61. 37pp.

ICES. 2014b. 2nd Interim Report of Working Group on Spatial Fisheries Data (WGSFD). 106 pp.

Ivanović A., Neilson R.D. and O'Neill F.G., 2011 Modelling the physical impact of trawl components on the seabed. Ocean Engineering, 38: 925-933.

Ivanović, A. and O'Neill, F.G. (2015). Towing cylindrical fishing gear components on cohesive soils. Computers and Geotechnics (in press).

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

Jennings, S. 2005. Indicators to support an ecosystem approach to fisheries.

Fish and Fisheries, 6: 212–232.

Johnson, D. (2008) Environmental indicators: their utility in meeting the OSPAR Convention's regulatory needs. ICES Journal of Marine Science, 65: 1387-1391.

de Juan, S., Demestre, M. (2012) A Trawl Disturbance Indicator to quantify large scale fishing impact on benthic ecosystems. Ecological indicators, 18: 183-190.

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

Kaiser, M.J., Collie, J.S., Hall, S.J., Jennings, S., Poiner, I.R. 2002. Modification of marine habitats by trawling activities: prognosis and solutions. Fish and Fisheries, 3: 114–136.

Kynoch, R.J. 1997. Engineering performance of three Scottish demersal trawling gears used in ICES sub area Iva. Marine Laboratory Aberdeen Report No 2/97, 29 pp.

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

Lucchetti, A. and Sala, A. 2012. Impact and performance of Mediterranean fishing gear by side-scan sonar technology. Canadian Journal of Fishery and Aquatic Sciences, 69: 1–11

Mace 2001. A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. Fish and Fisheries, 2: 2-32.

van Marlen, B., Wiegerinck, J. A. M., van Os-Koomen, E., and van Barneveld, E. 2014. Catch comparison of flatfish pulse trawls and a tickler chain beam trawl. Fish. Research, 151: 57-69.

Martin, J., Puig, P., Palanques, A., Ribo, M. (2014). Trawling-induced daily sediment resuspension in the flank of a Mediterranean submarine canyon. (J. D. Veerle Huvenne, Ed.) DEEP-SEA RESEARCH PART II-TOPICAL STUDIES IN OCEANOGRAPHY, 104, 174-183. doi:10.1016/j.dsr2.2013.05.036

Notti E, De Carlo F., Brčić J, Sala A, 2013. Technical specifications of Mediterranean trawl gears. In Paschen (eds) Contributions on the Theory of Fishing Gears and Related Marine Systems Vol. 8. Proceedings of the 11th International Workshop on methods for the development and evaluation of maritime technologies (Rostock, 9-12 Oct. 2013), ISBN 978-3-8440-2251-3, ISSN 0945-0874: 163-169

Olson, J., Clay, P.M., da Silva, P.P. 2014. Putting the seafood in sustainable food systems. Marine Policy, 43: 104–111.

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

O'Neill, F.G., Robertson, M., Summerbell, K., Breen, M., Robinson, L.A. 2013. Mobilisation of sediment and benthic infauna by scallop dredges. Marine Environmental Research, 90:104-112.

Paschen, M., Richter, U., Köpnick, W. 2000. TRAPESE – Trawl penetration in the seabed. Final Report EI Contract 96-006, University of Rostock, ASBN 3-86009-185-9

Piet, G.J., Quirijns, F.J., Robinson, L., Greenstreet, S. P. R. 2007. Potential pressure indicators for fishing, and their data requirements. ICES Journal of Marine Science, 64: 110–121.

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

Pikitch, E.K., Santora, C., Babcock, E.A., Bakun, A., Bonfil, R., Conover, D.O., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., Houde, E.D., Link, J., Livingston, P.A., Mangel, M., McAllister, M.K., Pope, J., Sainsbury, K.J. 2004. Ecosystem-based fishery management. Science, 305: 346-347.

Pravoni, F., Raicevich, S., Franceschini, G., Farrace, M.G., Giovanardi, O. 2000. Rapido trawling in the northern Adriatic Sea: effects on benthic communities in an experimental area. ICES Journal of Marine Science, 57: 517-524

Rice, J., Arvanitidis, C., Borja, A., Frid, C., Hiddink, J.G., Krause, J., Lorance, P., Ragnarsson, S.A., Sköld, M., Trabucco, B., Enserink, L., Norkko, A. 2012. Indicators for sea-floor integrity under the European marine strategy Framework Directive. Ecological Indicators, 12: 174–184.

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

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

SEAFISH 2010. Bridle angle and wing end spread calculations. SEAFISH Research & Development Catching sector Fact Sheet January 2010, 6 pp.

STECF 2012. The 2012 Annual Economic Report on the EU Fishing Fleet (STECF-12-10)

Suuronen, P., Chopin, F., Glass, C., Løkkeborg, S., Matsushita, Y., Queirolo, D., and Rihan, D. 2012. Low impact and fuel efficient fishing—looking beyond the horizon. Fisheries Research, 119–120: 135–146.

Tillin, H.M., Hiddink, J.G., Jennings, S., Kaiser, M.J. 2006. Chronic bottom trawling alters the functional composition of benthic invertebrate communities on a sea-basin scale. Marine Ecology-Progress Series, 318: 31-45.

Valdemarsen, J.W., Jørgensen, T., Engås, A. 2007. Options to mitigate bottom habitat impact of dragged gears. FAO Fisheries Technical Paper. No. 506. Rome, FAO. 29p.

Verschueren, B., Vanelslander, B. en Polet, H. 2012. Verduurzaming van de garnalenvisserij met de garnalenpuls: eindrapport. ILVO Mededeling nr 116, oktober 2012.

836 **Table 1.** Effort, landings and main target species for EU member states in the case study regions in
837 2010 (STECF 2012). Black Sea data are purely Turkish and provided by CFRI. Yearly landings
838 (tonnes) and days at sea are informed in thousands.

839

	2010	Demersal otter trawls and seines	Dredges	Beam trawl
Baltic Sea*	Days at sea (10^3)	32.8	0.5	
	Landings (10^3tonnes)	130.4	7.0	
	Main species	Cod	Blue mussels	
North Sea*	Days at sea (10^3)	150.7	31.0	88.5
	Landings (10^3 tonnes)	864.6	54.6	116.4
	Main species	Cod, Nephrops, sandeel	Scallops	Sole, plaice
Western Waters**	Days at sea (10^3)	238.9	39.8	15.6
	Landings (10^3 tonnes)	235.0	55.7	15.1
	Main species	Nephrops, sole, monkfish, hake	Scallops	Sole, plaice
Mediterranean***	Days at sea (10^3)	403.7	62.9	10.3
	Landings (10^3 tonnes)	82.0	21.8	3.7
	Main species	Hake	Clams	Sole, brill, turbot
Black Sea****	Days at sea (10^3)	58.2		28.6
	Landings (10^3 tonnes)	16.7		7.8
	Main species	Whiting, red mullet, turbot		Sea snail

840 * also including ICES area I and II

841 ** also including ICES area V, X and XII

842 *** no data available for Spain

843 **** TÜİK: National Statistics Institute's official yearly landing data

844

845

846

Table 2. The pair-wise 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 Metiers. Explanations for the species abbreviations can be found in the supplementary material (SM, table 1)

BENTHIS-Metier	List of single species fisheries included in metier	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* 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	

* Species not specified in questionnaire, only "MIX" informed

OT = otter trawl

TBB = beam trawl

SDN = anchored seine/Danish seine

SSC = flyshooting/Scottish seine

DRB = Dredge

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 metier.

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

Table 5. Averages of component proportions of total gear footprint, of trawl speed and seine haul duration, and of vessel size for the BENTHIS metiers. Standard deviations in brackets.

			Proportion of total footprint size (%)							Trawl speed and seine haul duration			Vessel size	
Main gear type	BENTHIS metier	Typical target species	Obser-vations	Doors/clumps/ weights	Sweeps and bridles	Ground gear	Beam shoes	Tickler chains	Seine rope	Obser-vations	Towing speed (knots)	Seine haul duration (hours)	Obser-vations	Length (m) or Engine power (kW)
Otter trawls	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 or Norway pout	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	Individual 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	19,9m (±6,2)
Beam trawls	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)
Dredges	DRB_MOL	Scallops, mussels	33			100 (±0,0)				33	2,5 (±0,0)		33	24,6 m (±5,6)
Demersal seines	SDN_DEM	Plaice, cod	47			10,0			90,0	43		2,6 (±0,6)	46	167,7 kW (±54,9)
	SSC_DEM	Cod, Haddock, flatfish	8			10,0			90,0	6		1,9 (±0,5)	8	23,1 m (±4,5)

* For the demersal seines the component percentages of the total footprint size are based on assumptions

Table 6. Penetration depths of main gear components as estimated from literature review together with an impact index condensed across sediment types (surface level impact, sub-surface level impact, and maximum penetration depth in parenthesis). A more comprehensive review of the studies behind the condensed list can be found in supplementary material (SM, Table 2) together with a reference list. Ground gear impact indices of each BENTHIS metier are provided in Table 3 of the supplementary material.

Gear types	Gear components	Coarse sediment	Sand	Mud	Mixed sediments	Indexed component impacts (max. depth in brackets)
Otter trawl	Sweeps and bridles		0-2	0		Surface (<2)
	Sweep chains		0-2	2-5		Sub-surface (≤5)
	Tickler chains	2-5	2-5		2-5	Sub-surface (≤5)
	Trawl doors	5-10	0-10	≤15-35	10	Sub-surface (≤35)
	Multirig clump		3-15	10-15		Sub-surface (≤15)
	Ground gear		0-2	0-10	1-8	**
Demersal seine	Seine ropes*					Surface (<2)
	Ground gear*					**
Beam trawl	Shoes	≤5-10	≤5-10	≤5-10	≤5-10	Sub-surface (≤10)
	Tickler chains	≤3-10	≤3-10	≤10	≤3	Sub-surface (≤10)
	Ground gear		1-8		0	**
Dredge	Ground gear		1-15	6		**

*No data exist for demersal seine gears, impacts for seine ropes are assumed to be equivalent those of otter trawl sweeps and impacts for seine ground is assumed to be equivalent to those of otter trawl ground gears .

** See supplementary material Table 3

Figure 1: Towing principles of the four main high-impact demersal gear groups identified; Demersal seines (left), Otter trawls (top right), Dredges (bottom right) and Beam trawls (centre, bottom). Illustrations from FAO: http://www.fao.org/fishery/geartype/search/en.

Figure 2: Conceptual gear footprints of single otter trawls (OT) fished by one vessel or with two vessels when pair trawling (top) and of twin-rigged otter trawls fished by one vessel (bottom). The conceptual footprint consists of three types of sea bed 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/ground gear itself.

Figure 3: Conceptual gear footprints of demersal seines (SDN, left and SSC right).

Figure 4: Conceptual gear footprints of beam trawls (TBB).

Figure 5: Conceptual gear footprints of dredges (DRB).

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

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.

Figure 8. Relationship between total gear width (beam width) and vessel size by BENTHIS metier for beam trawlers (TBB). The shaded (grey) areas define Monte Carlo boot-strapped 95% confidence intervals.

Figure 9. Relationship between total gear width (dredge width) and vessel size by BENTHIS metier for dredgers (DRB). The shaded (grey) areas define Monte Carlo boot-strapped 95% confidence intervals.

Figure 10. Proportion of total gear footprint (left panel) and the area of seafloor swept in one hour of fishing with an average sized vessel (right panel) with impact at the surface level and at both the surface and subsurface level for the 14 BENTHIS metiers.

Figure 1

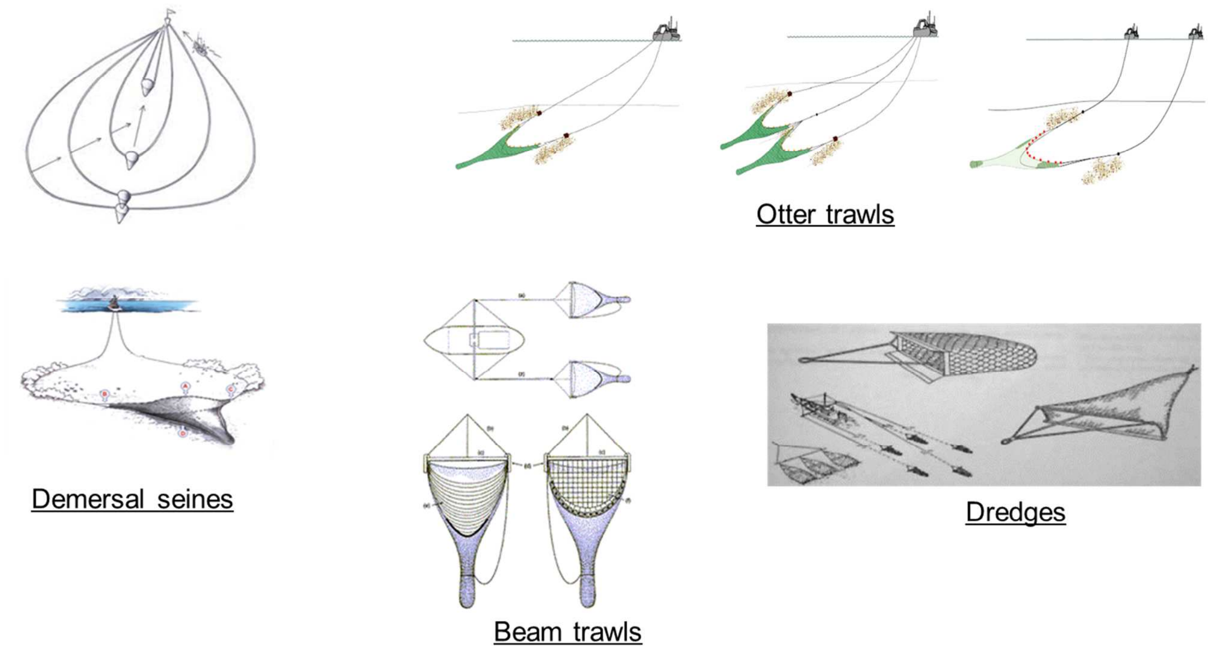


Figure 2

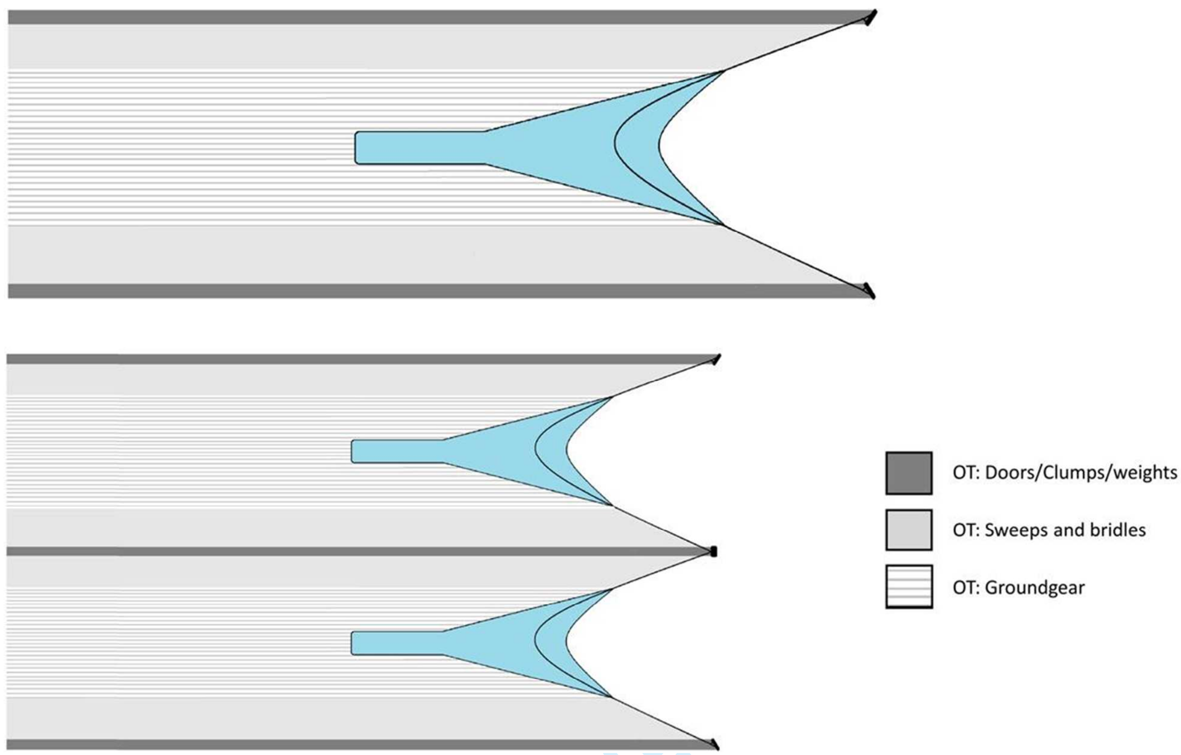

OT: Doors/Clumps/weights
OT: Sweeps and bridles
OT: Groundgear

Figure 3

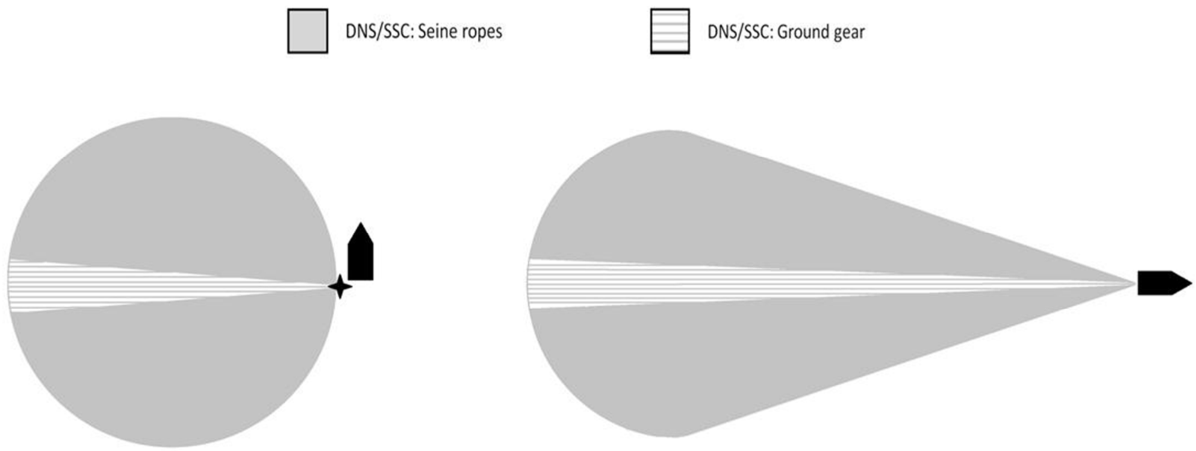


Figure 4

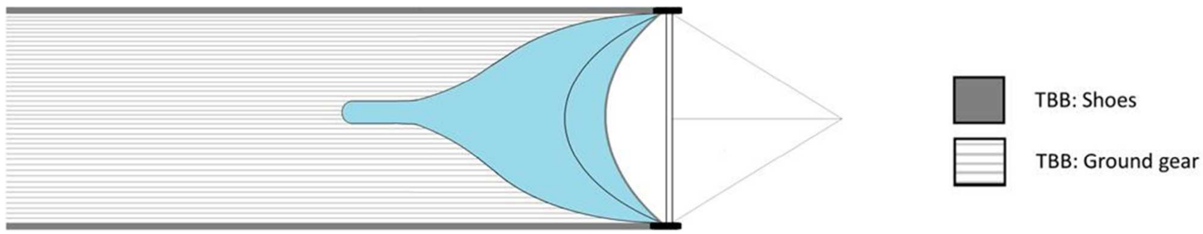


Figure 5

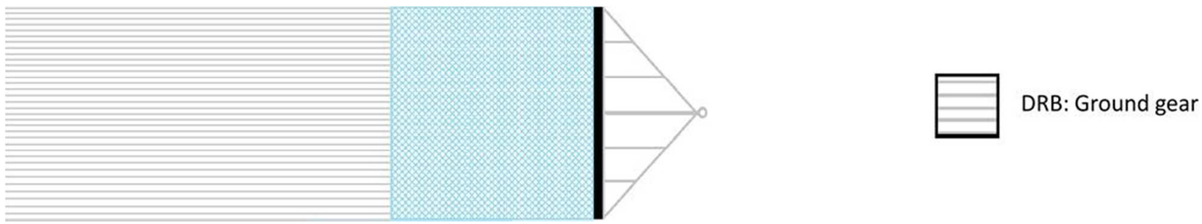
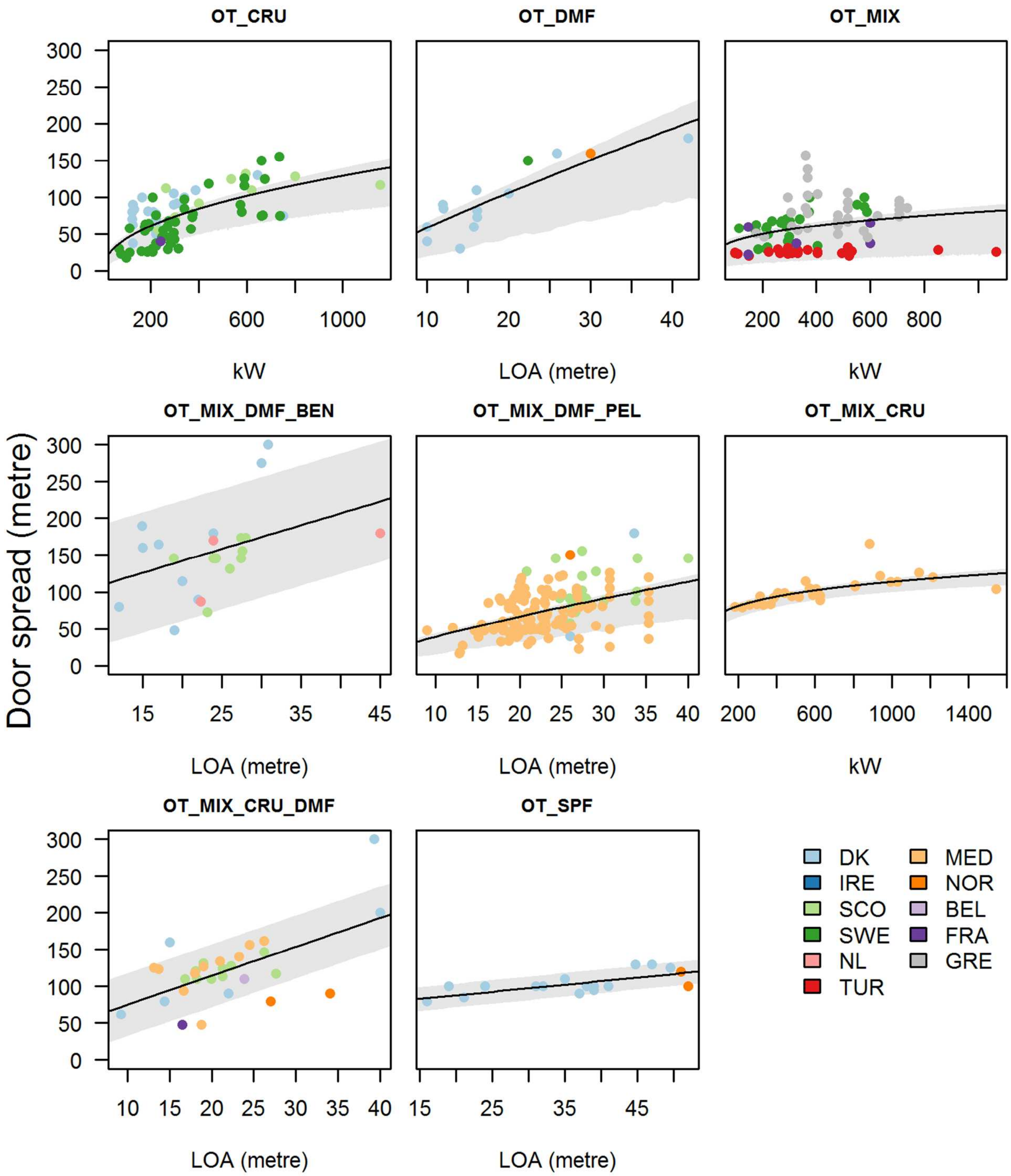


Figure 6.



OT_CRU
OT_DMF
OT_MIX
OT_MIX_DMF_BEN
OT_MIX_DMF_PEL
OT_MIX_CRU
OT_MIX_CRU_DMF
OT_SPF
Door spread (metre)
kW
LOA (metre)
DK
IRE
SCO
SWE
NL
TUR
MED
NOR
BEL
FRA
GRE

Figure 7.

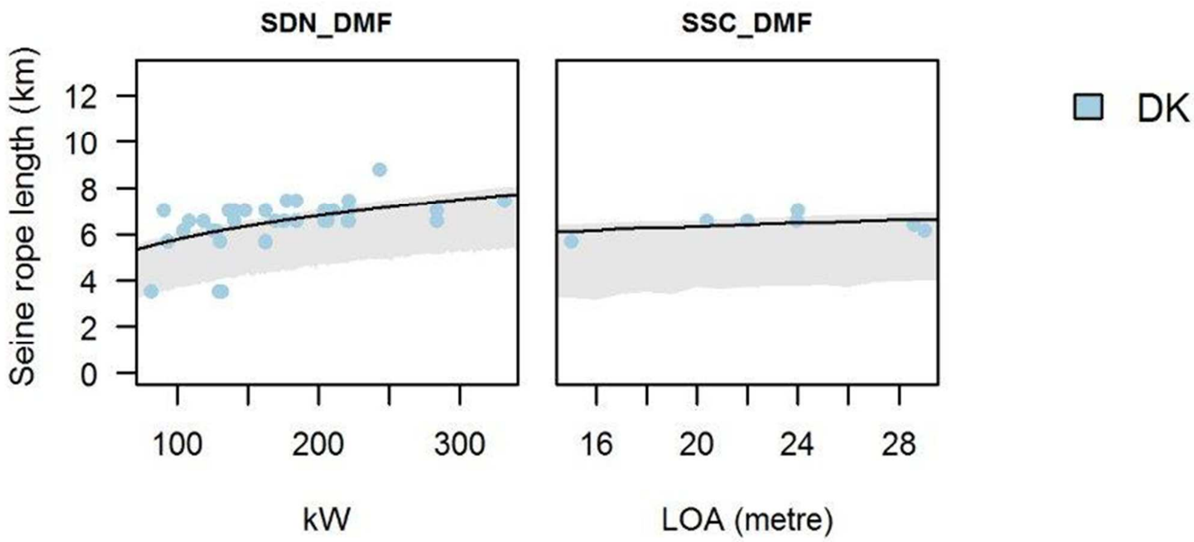

SDN_DMF
SSC_DMF
Seine rope length (km)
0
2
4
6
8
10
12
100
200
300
16
20
24
28
kW
LOA (metre)
DK

Figure 8

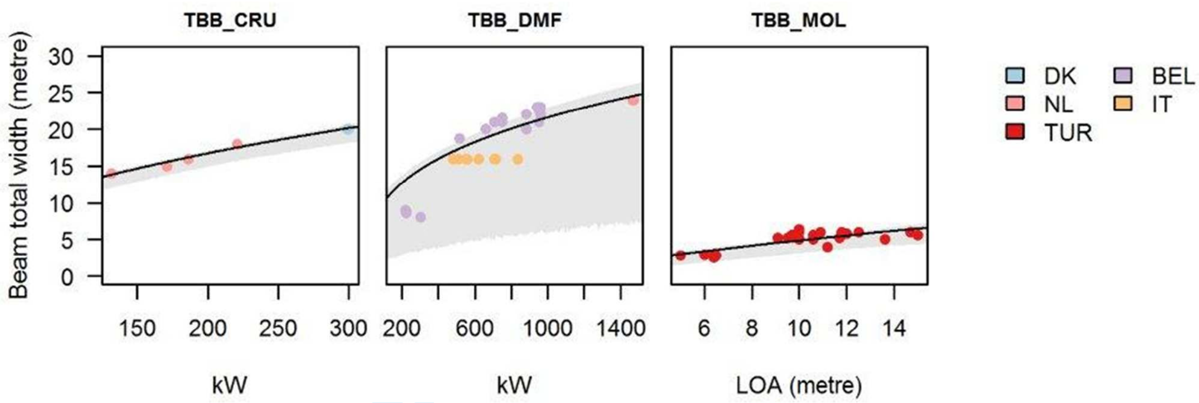

TBB_CRU
TBB_DMF
TBB_MOL
Beam total width (metre)
0
5
10
15
20
25
30
150
200
250
300
kW
200
600
1000
1400
kW
6
8
10
12
14
LOA (metre)
DK
NL
TUR
BEL
IT

Figure 9

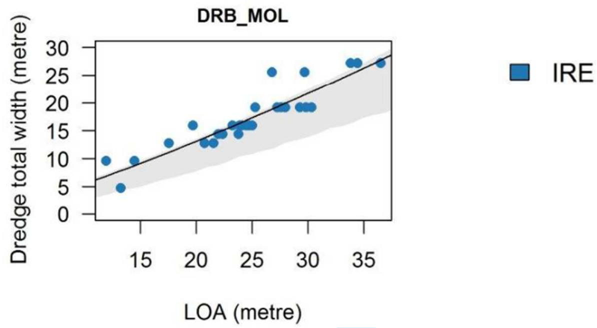
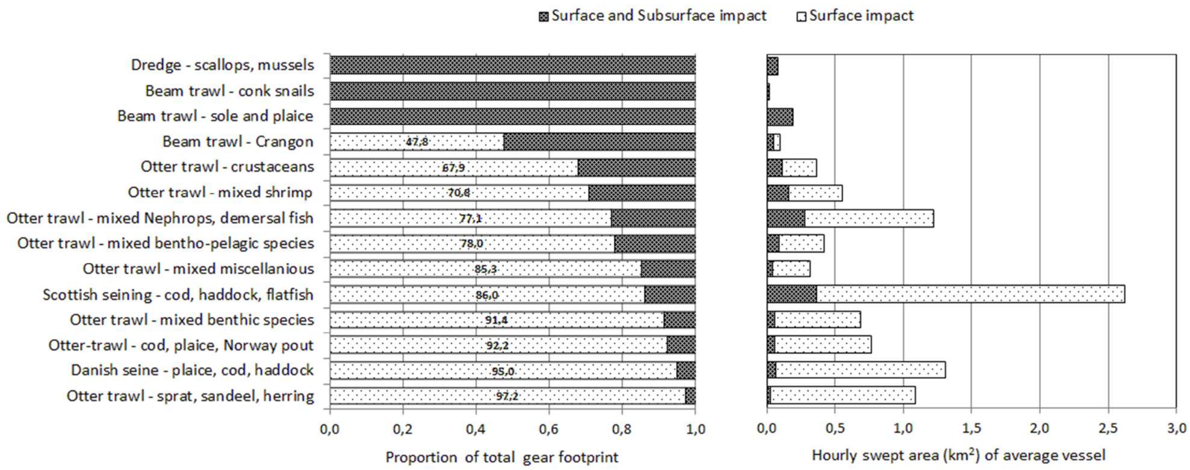

DRB_MOL
Dredge total width (metre)
30
25
20
15
10
5
0
15
20
25
30
35
LOA (metre)
IRE

Figure 10


Surface and Subsurface impact
Surface impact
Dredge - scallops, mussels
Beam trawl - conk snails
Beam trawl - sole and plaice
Beam trawl - Crangon
Otter trawl - crustaceans
Otter trawl - mixed shrimp
Otter trawl - mixed Nephrops, demersal fish
Otter trawl - mixed bentho-pelagic species
Otter trawl - mixed miscellanious
Scottish seining - cod, haddock, flatfish
Otter trawl - mixed benthic species
Otter-trawl - cod, plaice, Norway pout
Danish seine - plaice, cod, haddock
Otter trawl - sprat, sandeel, herring
47,8
67,9
70,8
77,1
78,0
85,3
86,0
91,4
92,2
95,0
97,2
0,0 0,2 0,4 0,6 0,8 1,0
Proportion of total gear footprint
0,0 0,5 1,0 1,5 2,0 2,5 3,0
Hourly swept area (km2) of average vessel

Supplementary material

The following supplementary material is available at ICESJMS online: a list detailing the species abbreviations integrated in the BENTHIS metier names (Table 1), a full review table of the studies estimating penetration depth of gear components (Table 2), a table of typical ground gear composition and associated impact severity of the BENTHIS metiers (Table 3), the format of the industry questionnaires for the four major gear types (Figures 1-4), a figure of the geometrical principals underlying the estimations of component path widths of otter trawl metiers (Figure 5), a figure of different types of otter trawl ground gears (Figure 6), and a list of the literature referred to in the supplementary material (Reference list).

Supplementary material table 1. Species list

FAO code	Scientific name	Common name
NEP	*Nephrops norvegicus*	Norway lobster
PRA	*Pandalus borealis*	Northern prawn
TGS	*Penaeus kerathurus*	Caramote prawn
ARA	*Aristeus antennatus*	Blue and red shrimp
DPS	*Parapenaeus longirostris*	Deep-water rose shrimp
SAN	*Ammodytes spp*	Sandeels (=Sandlances) nei
SPR	*Sprattus sprattus*	European sprat
CAP	*Mallotus villosus*	Capelin
COD	*Gadus morhua*	Atlantic cod
PLE	*Pleuronectes platessa*	European plaice
SOL	*Solea solea*	Common sole
LEM	*Microstomus kitt*	Lemon sole
WHG	*Merlangius merlangus*	Whiting
POK	*Pollachius virens*	Saithe (=Pollock)
PDS	*Pseudobarbus asper*	Smallscale redfin
HAD	*Melanorgammus aeglefinus*	Haddock
HKE	*Merluccius merluccius*	European hake
MON	*Lophius piscatorius*	Angler (=Monk)
MUS	*Mytilus Edulis*	Blue mussel
MUT	*Mullus barbatus*	Red mullet
CSH	*Crangon crangon*	Common shrimp
CTC	*Sepia officinalis*	Common cuttlefish
OCC	*Octopus vulgaris*	Common octopus
TUR	*Psetta maxima*	Turbot
SHC	*Alosa pontica*	Pontic shad
BLU	*Pomatomus saltatrix*	Bluefish
HMM	*Trachurus mediterraneus*	Mediterranean horse mackerel
BLL	*Scophthalmus rhombus*	Brill
SAL	*Salmon salar*	Atlantic salmon
RPW	*Rapana venosa*	Thomas'rapa whelk
OYF	*Ostrea Edulis*	European flat oyster
SCE	*Pecten maximus*	Great Atlantic scallop

Supplementary information table 2. Full penetration depth review

Gear	Gear component	Area	Target species	Sediment	Penetration depth	Sediment mobilisation	Sediment displacement	Reference
DRB	Whole-gear	West Scotland	Scallop	Sand	1 cm	1 mm (1.04 kg/m^2)	Flattening of ripples	O'Neill et al. 2008, 2013
OTB	Trawl doors	Mediterranean	Deep water shrimp and *Nephrops*	Mud	25 – 35 cm		Irregular furrows of approx. 35 to 45 cm width	Luchetti et al. 2012
OTB	Trawl doors	Mediterranean	Mixed demersal: Hake, mullet, monk	Mud	15 – 25 cm		Irregular furrows of approx. 25 to 35 cm width	Luchetti et al. 2012
H-DRB	Whole-gear	Adriatic Sea	Infauna bivalve: *Chamelea gallina*	Sand	5 – 15 cm		Regular furrows corresponding to gear width (3 m)	Luchetti et al. 2012
TBB	Whole-gear	Adriatic Sea	Flatfish: Sole, turbot, brill	Mud	5 – 15 cm		Regular furrows corresponding to gear width (4 m)	Luchetti et al. 2012
OTB	Trawl doors	Irish Sea (ICES div. VIIa)	*Nephrops*	Mud	≤ 15 cm		Pull at an oblique angle thus furrows ≤ width of gear	Kaiser et al. 1996 (ref to Krost et al. 1990)
OTB	Bobbins	Irish Sea	*Nephrops*	Mud	0 cm		Displace/damage boulders/epifauna	Kaiser et al. 1996
OTB	Net	Irish Sea	*Nephrops*	Mud	0 cm		Scour the surface of the sediment	Kaiser et al. 1996
OTB	Tickler chains (1-3)	Irish Sea	Flatfish	Soft-rough sediments	2-5 cm		Penetrate the upper few cm of the substrate	Kaiser et al. 1996
TBB	Shoes	Irish Sea (ICES div.	Flatfish, some by-catch	Soft-rough	≤ 5-10 cm		Penetrate the upper few cm of the	Kaiser et al. 1996 (ref to Anon. 1991

		VIIa)	species	sediment			substrate	table 1, de Groot & Lindeboom 1994)
TBB	Tickler chains	Irish Sea	Flatfish, some by-catch species	Soft sediment s	≤ 10 cm			Kaiser et al. 1996 (ref to Bridger 1972, de Groot & Lindeboom 1994)
TBB	Ticklers, longitudina l chains	Irish Sea	Flatfish,	Rough sediment s	≤ 3 cm		Displace boulders (prevent them from entering the net)	Kaiser et al. 1996 (ref to Bridger 1972, de Groot & Lindeboom 1994)
TBB	Net, groundrop e	Irish Sea	Flatfish	Soft-firm sediment	0 cm		Scour the surface of the sediment	Kaiser et al. 1996
DRB	Tooth bar, belly rings	(Irish Sea)	Scallops	Rough grounds	≤ 10 cm		Teeth rake through the sediment and disturb the partly burried scallops lifting them into the bag	Kaiser et al. 1996
TBB	Tickler chains & chain matrix	UK coastal waters	Flatfish (*Solea solea*, *Pleuronectes platessa*)	Sandy-firm sediment	< 5-10 cm		Penetrate the upper few cm of the seabed, displace rocks and damage/dug out some components of infauna and epifauna	Kaiser & Spencer 1996, Kaiser et al. 1998 ref to Cruetzberg et al. 1987, Bergman & Hup 1992, Kaiser & Spencer 1994, 1995)
OTB	Trawl doors	Scottish waters	Whitefish	Muddy sand	5-6 cm		Dug in about 5-6 cm, and displaced sediment deposited at the door heel in a 6-8 cm mount	Ivanovic et al. 2011
OTB	Roller clump of a twin trawl (300 hp	Scottish waters	Whitefish	Muddy sand	10-15 cm			Ivanovic et al. 2011

	Jackson trawl with rock-hopper ground gear)							
OTB	Roller clump of a twin trawl (300 hp Jackson trawl with rock-hopper ground gear)	Scottish waters	Whitefish	Sand	3-4 cm		Flattened ripples and smoothed the seabed	Ivanovic et al. 2011
OTB	Roller clump of a twin trawl (300 hp Jackson trawl with rock-hopper ground gear)	Scottish waters	Whitefish	Sand	~0 cm		Rolled and compacted ripples of a 4-5 cm amplitude.	Ivanovic et al. 2011
OTB	Trawl door	Simulated northeastern Grand Bank of Newfoundland		Sand	2 cm (0-5 cm)		Model experiment	Gilkinson et al. 1998 (ref to Krost et al. 1990)
OTB	Trawl path (trawl with bobbins &	Gulf of Alaska	Commercial rock fish	Hard bottom (pebble,	1-8 cm		Boulders displaced, density decreased of some epifauna	Freese et al. 1999

	rock hopper gear)			cobble, boulders)			(anthozoans, vase-shaped and morel-shaped sponges)	
DRB	Rapido trawl/dredge	Adriatic Sea	Scallops (offshore), fish (inshore)	Sand (offshore), mud (inshore)	6 cm		Tracks visible on side-scan sonar images after at least one week.	Pranovi et al. 2000
OTB	Trawl doors (demersal trawl with bobbin 6 rock hopper gear)	Gulf of Lion	Demersal fish	Mud	30 cm (trawl doors)	1 mm		Durrieu de Madron et al. 2005
OTB	Trawl doors (demersal trawl without bobbin but with twicklers)	Gulf of Lion	Demersal fish	Mud	30 cm (trawl doors)	1 mm		Durrieu de Madron et al. 2005
OTB	Near-bottom pelagic trawl	Gulf of Lion	Demersal fish	Mud	~0 cm	1 mm		Durrieu de Madron et al. 2005 (ref to Jones 1992)
OTB	Trawl doors	Barents Sea		Hard packed sand/mud, sand & gravel	10 cm		Increased roughness (increase in surface relief), decreased sediment hardness	Humborstad et al. 2004
OTB	Ground gear (rock hopper)	Barents Sea			Tracks visible on sidescan		Depressions from rock hopper gear was visible on sidescan	Humborstad et al. 2004

					sonar images, but depth uncertain		sonar images	
OTB	Trawl ground gear	North Tyrrhenian Sea	Demersal fish at depth < 150 m		Not visible			De Biasi 2004
OTB	Trawl roller clump	Inshore Scottish waters		Muddy sand	~ 12 cm			O'Neill et al. 2009
OTB	Trawl door	Inshore Scottish waters		Gravel	5-6 cm		Deposit 4-5 cm mound at door heel	O'Neill et al. 2009
DRB	Scallop dredge	Inshore Scottish waters		Fine – medium sand	2-4 cm		Reduced amplitude of sand ripples from 1.5-2 cm to ≤ 1 cm.	O'Neill et al. 2009, Dale et al. 2011
OTB	Trawl doors	Varangerfjorden, Norway		Mud	10-20 cm		10 cm in Scottish waters	Buhl-Mortensen et al. 2013 (ref to DEGREE 2010)
OTB	Sweeps			Sand	0-2 cm		Impact limited to top of ripples	Buhl-Mortensen et al. 2013
OTB	Sweeps			Mud	0 cm			Buhl-Mortensen et al. 2013
OTB	Sweep chains			Mud	2-5 cm			Buhl-Mortensen et al. 2013
OTB	Ground gear (rock hopper trawl)			Mud	5-10 cm			Buhl-Mortensen et al. 2013
OTB	Trawl doors			Sand	2-5 cm			Buhl-Mortensen et al. 2013
OTB	Sweep chains			Sand	0-2 cm			Buhl-Mortensen et al. 2013
OTB	Ground gear (rock			Sand	0-2 cm			Buhl-Mortensen et al. 2013

	hopper trawl)							
OTB	Trawl doors	Bay of Fundy, Canada	Flounder		1-5 cm			Løkkeborg 2005 (ref to Brylinsky et al. 1994)
TBB	Beam trawl ground gear	North Sea	Flatfish	Sand	1-8 cm			Valdemarsen et al. 2007 (ref to Paschen et al. 2000)

Gear types: Demersal otter trawl (OTB), Beam trawl (TBB), Dredge (DRB) and Hydro-dredge (H-DRB)

Gear components-OTB: whole-gear, Sweeps and bridles, trawl doors, ground gear, clump

Gear components-TBB: whole-gear, beam shoes, tickler chains/mats, ground gear

Gear components-DRB: whole-gear

Area information: ICES Area level

Sediment type: coarse, sand, mud

Penetration depth: Quantitative (e.g. depth average or range in cm)

Sediment displacement: Optional

Sediment mobilisation: Preferably quantitative (e.g. kg sediment per m^2 impacted)

Reference: Authors and Year (full reference in list below)

Supplementary material Table 3. Proportion of ground gear path width with impact at the surface and the sub-surface level, respectively, based on a combination of questionnaire information, available (sparse) scientific literature and expert opinions (BENTHIS gear technologists).

Metier	Typical target species	Typical ground gear	Surface impact (%)	Surface & Subsurface impact (%)
OT_SPF	Sprat or sandeel	Cookie	100	0
OT_MIX_DMF_PEL	Bentho-pelagic fish	Cookie or discs	50	50
OT_CRU	Nephrops or shrimps	Cookie or discs	0	100
OT_MIX_CRU_DMF	Nephrops and mixed demersal	Bobbins, Discs, Rollers	25	75
OT_MIX_CRU	Shrimp	Chain bightings	0	100
OT_DMF	Cod or plaice or Norway pout	Bobbins or cookie	50	50
OT_MIX_DMF_BEN	Benthic fish	Rockhopper, Bobbins	50	50
OT_MIX	Individual species not informed	as "OT_MIX_CRU_DMF"	50	50
TBB_CRG	Crangon	Bobbins	46	54
TBB_DMF	Sole and plaice	Chains	0	100
TBB_MOL	Thomas' Rapa whelk	Chains	0	100
DRB_MOL	Scallops, mussels	Sheering edge	0	100
SDN_DMF	Plaice, cod	Cookie	50	50
SSC_DMF	Cod, Haddock, flatfish	Chain bightings	50	50

Supplementary material Figure 1. Industry questionnaire (demersal otter trawl).

Country:			
Fishing area:			**Bottom trawls**
Date:			*BENTHIS-2013*
vessel:			(partner)
Trawl	type and name		
Trawling mode*	one or two vessels (single or pair trawling)		
Rigging	number of trawls per vessel		
Net maker	company name		
Codend	stretched mesh size (mm)		
Target species[1] (single)	only single species fisheries		
Primary species[1]	only mixed/multi-species fisheries		
Secondary species[1]	only mixed/multi-species fisheries		
Third species[1]	only mixed/multi-species fisheries		
Bottom type	bedrock, hard bottom, sand, hard clay, mud		
Vessel	engine power in kW		
	tonnage in GRT		
	Loa: overall length in metres		
Trawl circumference	number of meshes		
	stretched mesh size (mm)		
Trawl	Trawl height (metres)		
	Wing spread (metres)		
Doors	pelagic or bottom		
	number		
	producer and model		
	length (m)		
	height (m)		
	weight (kg)		
Door spread	door spread (metres)		
Sweeps	sweep length (metres)		
Bridles	number and length (metres)		
Tickler chains/lines	number		
	total weight of each chain or line (kg)		
Groundgear	length of groundgear (metres)		
	type, e.g. rockhopper, bobbins, discs, etc.		
	diameter of ground-gear (mm)		
	total weight of ground gear (kg)		
Clump	type (e.g. chain or roller)		
	weight of clump (kg)		
Other chains in gear	number and location in gear		
	total weight of each (kg)		

[1] please inform both common name and FAO 3-Alpha Species Codes (ASFIS)

Trawling speed (knots):		
Steaming speed (knots):		
Fuel consumption trawling (litres/hour):		
Fuel consumption steaming (litres/hour):		
Consumption other activities (litres/hour and activity):		

Supplementary material Figure 2. Industry questionnaire (beam trawls)

Country:			
Fishing area:			**Beam trawls**
Date:			*BENTHIS-2013*
vessel:			(partner)
Trawl type	conventional beam trawl, pulse-trawl, sum-wing, hydrorig, etc.)		
Total trawl number	number of trawls per vessel		
Net maker	company name		
Codend	stretched mesh size (mm)		
Target species[1] (single)	only single species fisheries		
Primary species[1]	only mixed/multi-species fisheries		
Secondary species[1]	only mixed/multi-species fisheries		
Third species[1]	only mixed/multi-species fisheries		
Bottom type	bedrock, hard bottom, sand, hard clay, mud		
Vessel	engine power (kW)		
	tonnage (GT)		
	overall length (m)		
Warp/depth ratio	(1 / x)		
Warp	warp diameter (mm)		
Beam	beam width (m)		
	complete beam weight in air (kg)		
Beam shoes	number		
	width (mm)		
	length (mm)		
Sumwing	width (m)		
	corde length (mm)		
	complete wing with nose weight in air (kg)		
Sumwing nose	width (mm)		
	total length (mm)		
	contact plate length (mm)		
Tickler chains	number		
	total weight of each (kg)		
Chain mat	total weight (kg)		
Groundgear	length of groundgear (m)		
	type, e.g. bobbins, rubber discs, chain, etc.		
	diameter of ground gear (mm)		
	total weight of ground gear (kg)		
Electrodes	number		
	electrode length (m)		
	electrode diameter (mm)		
	electrode type		

[1] please inform both common name and FAO 3-Alpha Species Codes (ASFIS)

Trawling speed (knots):	
Steaming speed (knots):	
Fuel consumption trawling (litres/hour):	
Fuel consumption steaming (litres/hour):	
Consumption other activities (litres/hour and activity):	

.

Supplementary material Figure 3. Industry questionnaire (demersal seines)

Country:			
Fishing area:			**Demersal seines**
Date:			*BENTHIS-2013*
vessel:			(partner)
Seine type	flyshooter/Scottish seine or anchored/ Danish seine		
Net maker	company name		
Codend	stretched mesh size (mm)		
Target species[1] (single)	only single species fisheries		
Primary species[1]	only mixed/multi-species fisheries		
Secondary species[1]	only mixed/multi-species fisheries		
Third species[1]	only mixed/multi-species fisheries		
Bottom type	bedrock, hard bottom, sand, hard clay, mud		
Vessel	engine power (kW)		
	tonnage (GT)		
	overall length (m)		
Seine circumference	number of meshes in circumference		
	stretched mesh size (mm)		
Seine height	height of seine (metres)		
Seine rope	total rope capacity (total length in metres)		
	rope diameter in (mm or inches)		
	rope weight (kg per meter rope)		
Groundgear	length of groundgear (metres)		
	type, e.g. bobbins, rubber discs, chain, etc.		
	diameter of groundgear (mm)		
	total weight of ground gear (kg)		

[1] please inform both common name and FAO 3-Alpha Species Codes (ASFIS)

Steaming speed (knots):	
Fuel consumption steaming (litres/hour):	
Fuel consumption fishing (litres/hour):	
Duration of haul/fishing operation (hours):	
Consumption other activities (litres/hour and activity):	

Supplementary material Figure 4. Industry questionnaire (dredges)

Country:			
Fishing area:			**Dredges**
Date:			*BENTHIS-2013*
vessel:			(partner)

Dredge	type and name		
Total dredge number	number of dredges per vessel		
Net maker	company name		
Codend	stretched mesh size (mm)		
Target species[1] (single)	only single species fisheries		
Primary species[1]	only mixed/multi-species fisheries		
Secondary species[1]	only mixed/multi-species fisheries		
Third species[1]	only mixed/multi-species fisheries		
Bottom type	bedrock, hard bottom, sand, hard clay, mud		
Vessel	engine power (kW)		
	tonnage (GT)		
	overall length (m)		
Warp/depth ratio	ratio of warp length and fishing depth (1 /x)		
Warp	warp diameter (mm)		
Dredge	total width (m)		
	total weight (kg)		

[1] please inform both common name and FAO 3-Alpha Species Codes (ASFIS)

Trawling speed (knots):

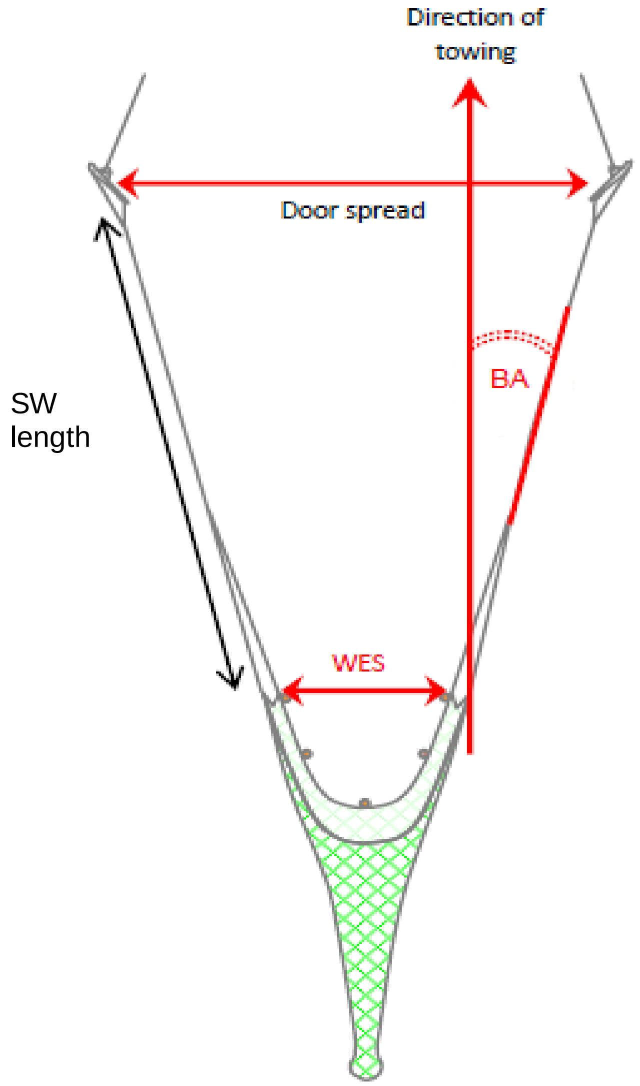
Steaming speed (knots):

Fuel consumption trawling (litres/hour):

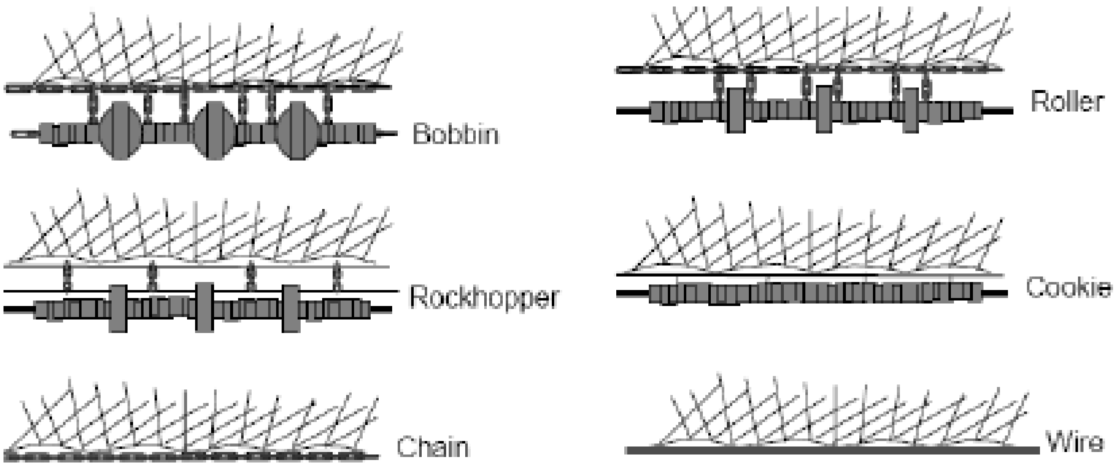
Fuel consumption steaming (litres/hour):

Consumption other activities (litres/hour and activity):

Supplementary material Figure 5. Otter trawl geometry theory used for estimating path widths for the main gear components (sweeps/bridles, ground gear and doors). Abbreviations: WES = wingend spread, BA = bridle/sweep angle, PW = path width, GG = ground gear, SW= sweeps+bridles, DO = doors. Assumptions: PW_GG = 0.4 * GG_Length, PW_ SW = sinus (13°) * SW_length, PW_DO = 0.4 * DO_length. The assumptions are based on Valdemarsen et al. 2007 and SEAFISH 2010.



Supplementary material Figure 6. Examples of ground gear designs for bottom trawling. (Illustration from Buhl-Mortensen et al. 2013).



Supplementary material Reference list

Anonymous 1991. Report of the study group on ecosystem effects of fishing activities. International Council for the Exploration of the Sea. C.M. 1991/G:7 (see table 1)

Bergman, M.J.N., and Hup, M.1992. Direct effects of beam trawling on macrofauna in a sandy sediment in the southern North Sea. ICES Journal of Marine Science 49:5-13

Bridger, J.P. 1972. Some observations on the penetrations into the sea bed of tickler chains on a beam trawl. International Council for the Exploration of the Sea. C.M. 1972/B:7, 9pp

Brylinsky, M., Gibson, J., and Gordon, D.C. Jr. 1994. Impact of flounder trawls on the intertidal habitat and community of the Minas Basin, Bay of Fundy. Canadian Journal of Fisheries and Aquatic Science 51:650-661

Buhl-Mortensen, L., Aglen, A., Breen, M., Buhl-Mortensen, P., Ervik, A., Husa, V., Løkkeborg, S., et al. 2013. Impacts of fisheries and aquaculutre on sediments and benthic fauna: suggestions for new management approaches. The Institute of Marine Research's internal committee on the effects of fishing and aquaculture on sediments and seabed habitats. Havforskninginstituttet, Bergen, 75 pp.

Creutzberg, F., Duineveld, G.C.A., and van Noort, J.G. 1987. The effect of different numbers of tickler chains on beam trawl catches. Journal du Conseil International pour l'Exploration de la Mer 43:159-168

Dale, A.C., Boulcott, P., and Sherwin, T.J. 2011. Sedimentation patterns caused by scallop dredging in a physically dynamic environment. Marine Pollution Bulletin 62:2433-2441

De Biasi, A.M. (2004). Impact of experimental trawling on the benthic assemblage along the Tuscany coast (north Tyrrhenian Sea, Italy). ICES Journal of Marine Science 61:1260-1266

DEGREE 2010. Development of fishing gears with reduced effects on the environment. DEGREE EU Contract 022576 Final Publishable Activity Report

Durrieu de Madron, X., Ferre, B., Le Corre, G., Grenz, C., Conan, P., Pujo-Pay, M., Buscail, B., et al. 2005. Trawling-induced resuspension and dispersal of muddy sediments and dissolved elements in the Gulf of Lion (NW Mediterranean). Continental Shelf Research 25:2387-2409

Freese, L., Auster, P.J., Heifetz, J., and Wing, B.L. 1999. Effects of trawling on seafloor habitat and associated invertebrate taxa in the Gulf of Alaska. Marine ecology Progress Series 182:119_126.

Gilkinson, K., Paulin, M., Hurley, S., and Schwinghamer, P. 1998. Impacts of trawl doors scouring on infaunal bivalves: results of a physical door model/dense sand interaction. Journal of Experimental marine Biology and Ecology 224:291-312

de Groot, S.J., and Lindeboom, H.J. 1994.Environmental impact of bottom gears and benthic fauna relation to natural resources management and protection of the North Sea. Netherlands Institute for Fisheries Research Report No. 1994-11, Texel, The Netherlands, 257 pp

Humborstad, O.B., Nøttestad, L., Løkkeborg, S., and Rapp, H.T. 2004. RoxAnn bottom classification system, sidescan sonar and video-sledge: spatial resolution and their use in assessing trawling impacts. ICES Journal of Marine Science 61:53-63

Ivanovic, A., Neilson, R.D., and O'Neill, F.G. 2011. Modelling the physical impact of trawl components on the seabed and comparison with sea trials. Ocean Engineering 38:925-933

Jones, J.B. 1992. Environmental impact of trawling on the seabed: a review. New Zealand Journal of Marine and Freshwater Research 26:59-67

Kaiser, M.J., and Spencer, B.E. 1994. Fish scavenging behaviour in recently trawled areas. Marine Ecology Progress Series 112:41-49

Kaiser, M.J., and Spencer, B.E. 1995. Survival of by-catch from a beam-trawl. Marine Ecology Progress Series 126:31-38

Kaiser, M.J., and Spencer, B.E. 1996. The effects of beam-trawl disturbance on infaunal communities in different habitats. Journal of Animal Ecology 65:348-358

Kaiser, M.J., Hill, A.S., Ramsay, K., Spencer, B.E., Brand, A.P., Veale, L.O., Prudden, K., et al. 1996. Benthic disturbance by fishing gear in the Irish Sea: a comparison of beam trawling and scallop dredging. Aquatic Conservation: Marine and Freshwater Ecosystems 6:269-285

Kaiser, M.J., Edwards, D.B., Armstrong, P.J., Radford, K., lough, N.E.L., Flatt, R.P., and Jones, H.D. 1998. Changes in megafaunal benthic communities in different habitats after trawling disturbance. ICES Journal of Marine Science 55:353-361

Krost, P., Bernhard, M., Werner, F., and Hukriede, W. 1990. Otter trawl tracks in Kiel Bay (Western Baltic) mapped by side-scan sonar. Helgolander Meeresuntersuchungen 32:344-353

Lucchetti, A., and Sala, A. 2012. Impact and performance of Mediterranean fishing gear by side-scan sonar technology. Canadian Journal of Fishery and Aquatic Sciences 69: 1–11

Løkkeborg, S. 2005. Impacts of trawling and scallop dredging on benthic habitats and communities. FAO Fisheries Technical Paper 472:1-58

O’Neill, F.G., Summerbell, K., and Breen, M. 2008. The suspension of sediment by scallop dredges. Fisheries Research Service Internal Report.

O’Neill, F.G., Summerbell, K., and Breen, M. 2009. An underwater laser stripe seabed profiler to measure physical impact of towed gear components on the seabed. Fisheries Research 99:234-238

O’Neill, F.G., Robertson, M., Summerbell, K., Breen, M., and Robinson, L.A. 2013. The mobilisation of sediment and benthic infauna by scallop dredges. Marine Environmental Research 90:104-112

Paschen, M., Richter, U., and Köpnick, W. 2000. TRAPESE – Trawl penetration in the seabed. Final Report EI Contract 96-006, University of Rostock, ASBN 3-86009-185-9

Pravoni, F., Raicevich, S., Franceschini, G., Farrace, M.G., and Giovanardi, O. 2000. Rapido trawling in the northern Adriatic Sea: effects on benthic communities in an experimental area. ICES Journal of Marine Science 57:517-524

SEAFISH 2010. Bridle angle and wing end spread calculations. SEAFISH Research & Development Catching sector Fact Sheet January 2010, 6 pp.

Valdemarsen, J.W., Jørgensen, T., and Engås, A. 2007. Options to mitigate bottom habitat impact of dragged gears. FAO Fisheries Technical Paper 506:1-29