Fisheries Innovation Scotland

FIS003 - Modelling the whole-ecosystem impacts of trawling

A REPORT COMMISSIONED BY FIS
AND PREPARED BY

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Published by: Fisheries Innovation Scotland (FIS)

This report is available at: http://www.fiscot.org.

Suggested Citation:
Heath, M., Wilson, R., Speirs, D. 2015. Modelling the whole-ecosystem impacts of trawling. A study commissioned by Fisheries Innovation Scotland (FIS) http://www.fiscot.org/

Title: Modelling the whole-ecosystem impacts of trawling

ISBN: 978-1-911123-02-6

First published: October 2015

Final Report

Modelling the whole-ecosystem impacts of trawling

Fisheries Innovation Scotland contract FIS03

with co-funding from the Natural Environment Research Council (NERC) and Department for Environment Food and Rural Affairs (Defra) Marine Ecosystems Research Programme

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FIS03: Modelling the whole-ecosystem impacts of trawling

Final report

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Executive summary

Trawling has been controversial since its introduction in the 17th century. In 1882 the Fishery Board for Scotland was established and assigned powers to ban beam and otter trawling where necessary to protect traditional static gear fisheries. Under these powers, large parts of the inshore waters off the east and west coasts of Scotland were closed to trawling. The Firth of Clyde remained closed until 1962.

More recently, in April 2015 solicitors acting for Greenpeace obtained High Court permission for a judicial review of Defra's alleged failure to adjust its policy on allocating annual landing quotas to reflect reforms to the CFP. It is claimed the reforms stipulate that greater preference should be given to sustainable low impact fishing methods at the expense of high-impact methods such as trawling. In Scotland, the exclusion of trawling activity from a network of marine protected areas established in July 2015 has also been highly controversial.

There is no doubt that some trawl gears can be extremely destructive of fragile habitats and slowly regenerating fauna such as coral. Over expanses of mud or sand, however, it has been claimed that trawling may be a positive factor, akin to ploughing the fields in terrestrial agriculture, and enhancing the productivity of the ecosystem.

There have been many scientific studies, both in the field and using mathematical modelling, of the impact of trawling on the seabed. Similarly, we know very well that harvesting of fish and shellfish, whether using trawling or static gear, has consequences for marine food webs. However, there have been few, if any, scientific studies which have put these two aspects of trawling together and then compared the seabed impacts of trawling with the consequences of harvesting.

In this project we used a mathematical model to compare and contrast the whole ecosystem effects of harvesting fish and shellfish with the consequences of other aspects of trawling activity, especially the ploughing of seabed habitats. The model is not detailed to the level of individual species or exact locations. Rather it gives results at the level of a whole regional sea area, such as the North Sea or the whole of the west of Scotland.

The project had three main components. First, was the extension of an existing mathematical model of a marine ecosystem to include explicit representation of the ploughing effects that different gears have on seabed habitats. Second, an analysis of a large international data set on activity, landings and catches by different fishing gears in northwest European waters, and the mapping of these onto different seabed habitats to generate inputs to the model. Finally, we carried out a series of sensitivity experiments with the model. These experiments investigated the whole ecosystem effects of seabed ploughing by different gears, using food web indicators relevant to the EU Marine Strategy Framework Directive, and compared them with the impact of one scenario for implementing a landing obligation, and the potential impacts of a reduction in overall fishing activity.

For the North Sea, the results show that even if all ploughing effects were eliminated, the effects on the whole ecosystem would be equivalent to only a 1% or less change in overall harvesting rate of fish and shellfish. This is a very small effect compared to the changes in effective harvesting rate implied by the improvements in gear selectivity required to achieve the landing obligation.

For the west of Scotland region, the model showed that the food web was more sensitive to the effects of ploughing by fishing gears than in the North Sea, but the effect was still small compared to the consequences of activity reduction overall. The greater sensitivity of the west of Scotland to seabed ploughing arose because the disturbance rate of muddy sediments was around 5-times higher than in the North Sea, almost entirely due to the activities of TR2 Nephrops trawling.

Despite our conclusion that the regional scale food web effects of seabed ploughing are small compared to the primary consequences of harvesting fish, this is not to say that there are no effects on regional biodiversity, or significant effects at local scales on specific habitats or vulnerable species. In particular the study identifies the TR2 gear fleet as being responsible for the majority of ecosystem-wide consequences of seabed ploughing. This gear has a particularly high ploughing rate and its activity is focussed on muddy sediments where the nutrient chemistry processes are more vulnerable to ploughing than in sandy and coarser sediments.

Recommendation from the project

Without denying the damaging effects that ploughing of the seabed by trawl gears can have on biodiversity, and local scale seabed integrity and fragile fauna, the key message from the project is that effects on food web indicators at a regional scale are small compared to the effects of harvesting and landing biomass. By region scale, we mean the whole North Sea, or the west of Scotland shelf.

At the regional scale the main benefits for ecosystem food web status are likely to come for managing the overall levels of activity, or the selectivity (power) of fishing gears, rather than focussing on specific gears which are perceived to be particularly damaging to the seabed.

Notwithstanding the above, a key action point to come out of the project concerns the high ploughing impact of the TR2 gear, especially in the west of Scotland region. Anything that can be done to alleviate this feature of the gear will improve its image and the sustainability of the fishery that relies on it, will be a positive measure. The vast majority of the regional impacts of seabed ploughing arise from the activity of this gear alone.

Co-funding acknowledgement

Whilst the primary support for this project came from Fisheries Innovation Scotland, a significant element of the enabling model development was attributable to financial support from the Natural Environment Research Council and Department for Environment, Food and Rural Affairs [grant number NE/L003279/1, Marine Ecosystems Research Programme].

MH was supported by the Marine Science and Technology Scotland (MASTS) pooling scheme (Scottish Funding Council grant reference HR09011)

Contents

Introduction

The impact of trawling on marine ecosystems has long been a matter of social, economic, conservation and scientific concern. Towed beam and otter trawls were initially deployed from sailing vessels in the 17th century, and later from steam-driven vessels in the mid-19th century. In response to widespread concerns about damage to herring spawning beds and the destruction of traditional static gears that might be caused by these fishing methods, the Fishery Board for Scotland was established in 1882, and assigned powers to ban trawling in inshore waters. The Lord Privy Seal is quoted in a debate on 20th May 1895 as stating:

> *"The Government thought it necessary that some further restriction should be adopted with respect to trawling in Scottish waters, and for three reasons—first, because, however doubtful the destruction done to fish generally by trawling, it was undoubtedly possible that in limited areas, especially in waters near the shore, great damage could be done, and these areas rendered for the time useless; secondly, because great damage was also done to the gear of the line and net fishermen, especially in inshore waters; and, thirdly, because a very excited state of feeling existed between 44–45ths of the fishermen of Scotland and the remaining 1–45th, who were trawlers—a state of feeling which the Government thought they ought to attempt to allay by giving power to the Scottish Fishery Board to allocate particular fishing-grounds to these particular classes of fishermen."* (Hansard 1895).

Under these powers, large parts of the inshore waters off the east coast of Scotland and the entire Firth of Clyde were closed to trawling (Hansard 1889). The Firth of Clyde was not re-opened to trawling until 1962.

Concern about the possible and demonstrable impacts of trawling have not diminished in the intervening years, and continue to the present day. In April 2015, the High Court gave approval for a judicial review of the UK government's approach to allocating fishing quota in England and Wales in a case brought by Greenpeace (Harrison Grant Solicitors 2015, Monkton Chambers 2015). The argument put forward by the plaintiffs was that under the revised Common Fisheries Policy (CFP), vessels using low impact gears should receive an increased share of quota at the expense of those using trawls which are shown to be more damaging to the environment. The claim was that Defra's adherence to long standing criteria for quota allocation is in contravention of the CFP. More recently still, the Scottish Government's announcement of a network of Marine Protected Areas from which trawling activity will be excluded (Scottish Government 2015) has caused consternation in some sectors of the Scottish Fishing Industry (Scottish Fishermen's Federation 2015). In view of the history and recent developments in our understanding of the seabed impacts of towed fishing gears, a modelling study on the whole-ecosystem impacts of trawling is both timely and necessary.

The impact of trawling on the seabed has been a topic of scientific research since the 1880's, but the investigation rate has escalated since around 1990 (Lengkeek and Bouma 2010), addressing a range of ecological issues (Jones 1992, Jennings and Kaiser 1998, Kaiser et al. 2002) and conservation concerns (Auster et al. 1996, Bellman et al. 1996). A recent systematic review (Eigaard et al. 2015) showed large variations in the seabed impact of fishing activity for different fishing gears. Patterns of seabed disturbance by trawling have been shown to affect the biodiversity (species richness and evenness) and abundance and productivity of benthic fauna (Hiddink et al. 2006, Van Denderen et al. 2014). Consequently there is much debate about which fishing methods are most sustainable from an environmental and economic point of view. Historically, changes in fishing gears and practices have been driven by economics and the catching efficiency ("power") of alternative gears, and rarely if at all by concerns about damage to the environment.

The direct physical impacts of trawling on the seabed are well known and have been studied for many years (Hall 1999, Thrush & Dayton 2000). These include the destruction of habitat features such as biogenic reefs and removal of geological features such as boulders (Althaus et al. 2009), ploughing effects leading to re-structuring of seabed morphology, re-suspension and re-distribution of sediment, exposure of buried organic material, oxygenation of sediments and release of nutrient from the pore-waters (Churchill, 1989, Martin et al. 2014, Pilskaln et al. 1998, Pusceddu et al. 2014). Many of these physical impacts may have indirect ecological consequences. For example, benthic fauna and organic matter excavated by ploughing may become more accessible to consumers in the food web. Similarly, the release of nutrient from sediment pore-waters has been hypothesised to impact ecosystem function by stimulating primary production, whilst the re-suspension of fine sediment may have the opposite effect by increasing turbidity and reducing light penetration into the water column (Bradshaw et al. 2000, Colie et al. 1997, Hiddink et al. 2006, Kaiser & de Groot 2000, Kaiser et al. 1998, 2006, Watling & Norse 1998).

In addition to the above physical impacts and associated indirect ecological consequences, there are a range of direct biological effects. Principal among these is, of course, the removal of targeted fish and benthic fauna (demersal fish and invertebrates – e.g. *Nephrops* and scallops), removal of non-target by-catch which may be subsequently discarded, and direct mortality due to physical damage (Schratzberger & Jennings 2000, Jennings et al. 2001). Inevitably, these direct effects precipitate other indirect effects as the ecosystem re-adjusts to the changes which have occurred – scavenging species take advantage of the corpses arising from mortalities and discards of unwanted by-catch which settle back to the seabed; other surviving benthic species flourish as a result of the relaxation of predation pressure from demersal fish which have been captured and removed (Van Denderen et al. 2013).

The individual processes and feedbacks outlined above act on a wide range of time scales, from the very short (immediate impacts of the passage of a trawl) to the very long (months to years for habitat re-structuring and re-adjustment to changes in predation pressure from fish). Many of the processes have been studied experimentally in isolation (Tuck et al. 1998), but the challenge is to determine the integrated effects of all the varied processes together. This will be very difficult to achieve by direct field observation since the number of replicates required to factor out un-controllable natural variation due to factors other than trawling seems likely to be unfeasibly high. The alternative, which we propose here, is to use simulation modelling based on mathematical representations of the main processes.

Impacts of fishing gear on seabed sediments

One of the main perceived impacts of demersal trawling gear is the ploughing effect on seabed habitats. *S*ediment is lifted into suspension in the wake of gear components, such as trawl-doors and ground-lines, which are in contact with the seabed (Davis 2003, Thrush & Dayton 2002, Churchill 1989, Mayer et al. 1991, Martin et al. 2014, Pilskaln,et al. 1998, Pusceddu et al. 2014, Palanques et al. 2001, National Academy of Sciences 2002). Field studies show that this results in a pulse release of nutrients into the water column because the pore waters, especially in soft muddy sediments, are enriched in nutrients (Dounas 2006, Dounas et al. 2005, 2007, Warken et al. 2003).

The chemistry of seabed sediments is a complex area (Lohse et al. 1993, Christensen et al. 1987, Pilskaln et al. 1996, Seitzinger 1988, Vermaat et al. 2009). Very briefly, organic matter settling out of the overlying water column is incorporated into the sediments where it represents a rich substrate for bacteria. These consume the material, respiring part of the carbon content as carbon dioxide, converting the nitrogen content to ammonia, the phosphorus content to phosphate, and allowing any silica content to dissolve. Other things being equal, these dissolved inorganic components will diffuse out of the sediment back into the water column. However, in the process of degrading the organic matter, microbes consume oxygen from the sediment pore waters, and if the supply of organic matter exceeds the rate at which oxygen can diffuse into the sediment from the overlying water, then the sediments become anoxic. Under these circumstances, a complex set of processes take effect – in the first instance the microbes begin to break down sulphate ions to scavenge the oxygen content, leading to the production of hydrogen sulphide (Christensen 1989). The chemistry of phosphate under anoxic conditions is also complicated – phosphorus can become adsorbed onto sediment particles and unable to diffuse back into the water column. In the case of nitrogen, ammonia is oxidised to nitrate under oxic conditions, whilst nitrate is de-nitrified to nitrogen gas in low oxygen conditions (Christensen et al. 1987, Seitzinger 1988). The latter is especially important for the ecosystem since it represents a sink, or loss, of nutrient element from the system. In the North Sea, denitrification has been estimate to account for a similar flux of nutrient out of the system to the quantities discharged from all European rivers (Vermaat, et al. 2009).

At least two previous mathematical modelling studies of the ecological impacts of trawling have focussed on the biogeochemical impact using the European Regional Seas Ecosystem Model (ERSEM; Allen et al. 2001, Baretta et al. 1995, Blackford 1997) – one applied to the North Sea (Allen & Clarke 2007) and the other to the north-Cretian shelf in the eastern Mediterranean (Dounas et al. 2007). The ERSEM model includes a detailed representation of geochemistry in vertical layers of the sediment (Allen et al. 2001, Baretta et al. 1995, Blackford 1997), and may be configured to provide highly spatially resolved results. The passage of trawl gears was represented as the intermittent removal of the surface oxygenated layer of sediment at random locations in space and time, and the release of its associated pore water nutrient (Allen & Clarke 2007, Dounas et al.. 2007, Duplisea et al. 2001). The volume of pore-water (porosity) depends on the sediment grain size at each model location – fine-grained cohesive sediments have a higher porosity than coarse grained permeable sediments. The exposed low-oxygen 'redox' layer is then allowed to equilibrate with the overlying water. Results have shown increased rates of primary production with increased disturbance events. Additionally, the North Sea study represented the effects of collateral mortality on benthic fauna, and simulated expected recovery rates following the cessation of trawling.

Despite a sophisticated representation of biogeochemistry, the ERSEM model does not include the fish populations which are the target of most trawl fisheries, and form the food web which generates the natural predation pressure on benthic communities. Hence, simulations of trawling impacts using ERSEM may be highly detailed with regard to some aspects of the problem, but they only provide a partial perspective of the overall impacts. Similarly, other studies have tackled the problem with models which only represent parts of the ecosystem. For example, Van Denderen et al. (2013, 2014) developed a simple model of only the benthos fauna and a fish predator, and concluded that depending on the dynamics of the benthos, trawling disturbance could result in increased production of fish. There is a clear need for modelling which spans the entire marine food web so that the full range of direct and indirect effects can be accomodated.

In this report, we describe the use of StrathE2E – an end-to-end ecosystem model developed at the University of Strathclyde (Heath 2012, Heath et al. 2014a, b, Morris et al. 2014) to address the question of ecosystem impacts of trawling in a holistic way. StrathE2E provides a cruder representation of biological and chemical processes in the sea than ERSEM, but spans the entire food web from microbes to birds and mammals.

Brief summary of the StrathE2E model

Technically, the StrathE2E model consists of a network of coupled ordinary differential equations (Heath 2012). Conceptually, the model incorporates all of the living organisms in the ecosystem from plankton through fish and benthos to birds and mammals (Figure 1), as well as anthropogenic and natural external driving factors such as fishing, river inflows and ocean currents. This living food web is underpinned by a representation of the biogeochemical processes that hold the system together by recycling nutrient from dead organic matter into inorganic elements which are absorbed by primary producers.

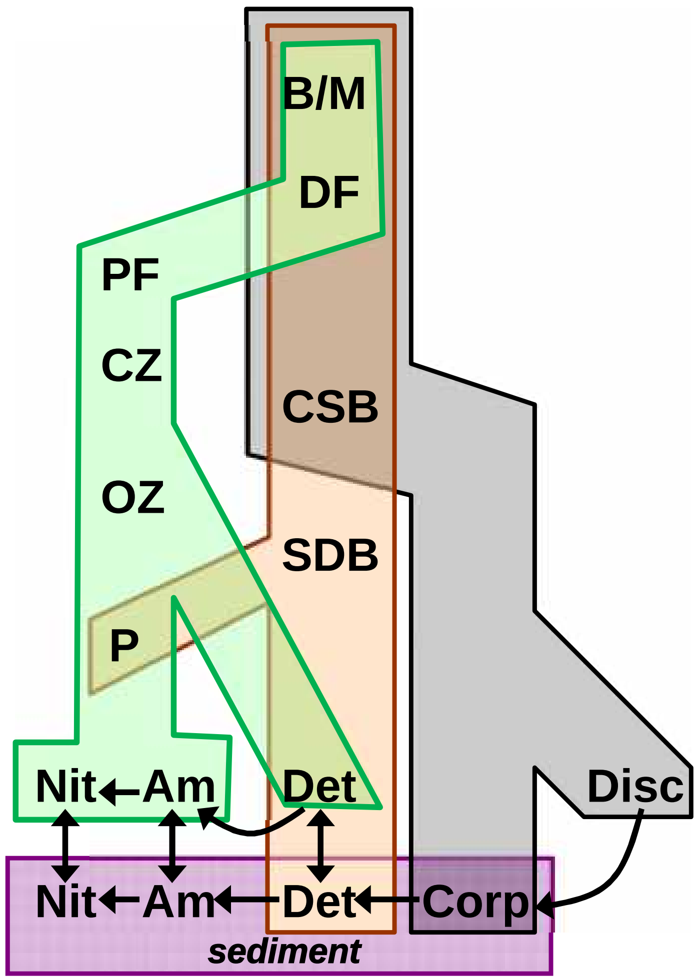

Figure 1. *Schematic of the food web compartments of the StrathE2E model. Taxa and non-living resources in the model form three interlinked food chain compartments: grey - scavenging; orange - benthic; green - pelagic. The purple compartment represents seabed sediment geochemistry. B/M - seabirds and marine mammals; DF - demersal fish (e.g. cod, haddock and plaice which feed mainly on other fish and benthos); PF - pelagic fish (e.g. herring, sprat and sandeel which feed mainly on plankton); CZ - carnivorous zooplankton; OZ - omnivorous zooplankton; P- phytoplankton; CSB - carnivorous/scavenging benthos;*

SDB - suspension/deposit feeding benthos; Nit - nitrate, Am- ammonia; Corp- corpses; Disc- fishery discards. Omnivory occurs within each compartment e.g. PF feed on both CZ and OZ; DF and PF are subdivided into larvae and adults; Nit, Am, Det and P in the water column are subdivided into surface and deep layers. Transformations between Disc, Corp, Det, Am and Nit are due to microbial degradation, mineralisation and nitrification processes. Fishery landings and denitrification represent export fluxes from the model, Water column classes of P, Nit, Am and Det are subject to hydrodynamic exchanges which generate net imports and exports depending on simulated concentration gradients. The model also includes fluxes from living components to Am, Det, Corp and Disc due to excretion, defecation, death.

Obviously, in order to accommodate such an extensive and complex system and still be simple enough to analyse and understand, the model involves a number of major assumptions. However, these are compensated to some extent by the use of state-of-the-art statistical methods to fit the parameters of the model so that it conforms as closely as possible to as wide a range of observed data on the state of the ecosystem. Nevertheless, the assumptions place some limitations on the range of questions that the model can be used to address. For example it does not resolve individual species, so it cannot be used to answer questions about cod as opposed to whiting. Instead, it regards all demersal fish as being a single aggregated group. Similarly, all pelagic fish are treated as a single group. The model does not resolve spatial distributions – it simulates the total abundances in the region represented by the model. However, the essential property that the model is designed to represent is the inter-connectivity of nutrients, plankton, benthos, fish, birds and mammals. This means that changes in any of the climatic factors or human activities that are included as driving forces in the model cause the entire system to readjust, not just the components that are directly affected. We refer to this propagation or 'rippling effect' of external changes through the entire system as a 'trophic cascade' (Pace et al. 1999, Heath et al. 2014a). Cascades are widely observed in nature, especially in marine systems (Baum & Worm 2009), but are poorly represented in results from most ecosystem models which are usually only a partial representation of the system.

Another key sacrifice of detail in the StrathE2E model is to represent the biomass of living organisms solely in terms of their nitrogen content, ignoring the effect that variations in carbon, phosphorus and silicon content may have on their productivity. In temperate open shelf seas this is justified because nitrogen is usually the main nutrient limiting annual primary production. Nevertheless, the representation of biogeochemistry in sediments and the water column is still relatively complex. Dead organic matter in the model its mineralisation to ammonia, then to nitrate by the process of nitrification. Some of this inorganic nitrogen may be lost from the system by a representation of denitrification. The rates of these processes in the sediment and water column are each controlled by a temperature dependent parameter. Exchange fluxes of ammonia and nitrate between sediment pore waters and the overlying water column depend on the concentration gradient between the two and a diffusion coefficient which is related to the grain size composition of sediments.

StrathE2E does not resolve spatial locations – processes are represented as if they were averaged over the domain of the geographic region represented by the model. In the original model, sediment properties such as porosity are parameterised as a spatial average over the region. This means that we have to take a different approach to representing trawling events from that used in the ERSEM models. At the spatial scales represented by StrathE2E, trawling is not an intermittent process – rather it is a continuous process which is occurring over a small fraction of the seabed area at any point in time. This required us to develop some new modelling approaches which were incorporated into the StrathE2E system.

The StrathE2E model needed some other adaptations to enable it to address the impacts of trawling, in particular a representation of different seabed sediment types, and their natural disturbance by waves and tides and benthic fauna. The balance between natural and anthropogenic disturbance is a key issue for the assessment of trawling impacts. If we base an assessment on a model which does not take account of natural disturbances, then we may form an erroneous view of the scale of anthropogenic impact. Few ecosystem models address this aspect in great detail. We made use of recent developments in estimating sediment resuspension due to bed shear stress arising from the combination of tidal flows and wave orbital velocities at the seabed, such as described by Deising et al. (2103).

Detailed project report

The project proposal detailed a programme of work under 4 objectives:

Objective 1. Representation of physical impacts of towed gear in the model
Objective 2. Representation of direct effects of towed gear on benthos
Objective 3. Sensitivity analysis and scenario experiments
Objective 4. Reporting and Knowledge Exchange

In the following sections we report on the work carried out on each of these objectives.

Objective 1. Representation of physical impacts of towed gear in the model

Description: "*In this part of the project we will conduct an analysis of the association between seabed sediment types and fishing effort by towed gears in the North Sea and West of Scotland regions. We will use this, together with existing data on the porosity and permeability of sediments in relation to grain sizes, to parameterise an increase in sediment water diffusion rate in the StrathE2E model as a caricature of the physical impacts of trawling."*

The work in support of this objective comprised three parts

i) Adaptations of the existing StrathE2E model to incorporate representation of different seabed habitats and the processes involved in the disturbances of these caused by natural events and the ploughing effects of different fishing gears. Some of the work associated with this task (habitat discrimination and natural disturbance processes) was supported by a parallel-running grant from the Natural Environment Research Council Marine Ecosystem Research Programme (MERP), and our FIS project was able to benefit from this. The additional model development work specifically for FIS was in relation to incorporating the ploughing effects of fishing gears in different sediment types.

ii) Analysis of datasets on seabed sediments, bathymetry, and tidal current properties in order to derive the region-specific hydrodynamic and seabed habitat parameters needed for the extended StrathE2E model. This work was also supported by the parallel-running grant from the Natural Environment Research Council Marine Ecosystem research Programme (MERP), but was nevertheless essential our FIS project.

iii) Analysis of international databases of fishing activity, landings and discards, to derive statistics on the distributions of activity by different fishing gears in relation to seabed habitats, and fishing power, which were required as parameters for the newly extended StrathE2E model.

Adaptation of the existing StrathE2E model (developed with combined funding from NERC and FIS)

The original StrathE2E model as defined in Progress in Oceanography (Heath 2012), has been used to examine a range of issues based on a configuration for the North Sea: a) interactions between pelagic and demersal fisheries, b) trophic cascade dynamics, c) ecological implications of the landing obligation, d) ecosystem effects of ocean acidification, e) hindcasting MSFD indicators.

Configurations of the model have also been prepared for other shelf sea regions: West of Scotland, and Celtic Sea. These configurations force us to think more about the physical properties of a region that may dictate cascade properties and whole-ecosystem dynamics.

The properties of the original model which defined a region were primarily contained in the set of external, time-dependent driving data on irradiance, suspended silt, temperature, vertical mixing rates, volume fluxes into the model domain from the ocean and rivers, concentrations of state variables in the inflowing water, and atmospheric deposition rates of nutrients. The only static configuration parameters were the depth horizon separating the water column layers (referred to as shallow and deep), thicknesses of these layers, and the thickness, porosity and permeability of the sediment layer.

The original model assumed that only the deep layer of the water column had any contact with the seabed. Nutrient released from the sediment was returned to the euphotic shallow layer solely through mixing with the deep layer. Of course, this is not entirely the case in reality, but the model was intended to be a ‘bare essentials’ representation of the real world. However, comparing the North Sea, West of Scotland and Celtic Sea, it is immediately clear that if we define the shallow layer as being 0-30m, then the proportion of seabed in direct contact with the shallow layer is a distinctive structural property of these regions. Around 26% of the seabed in the North Sea is shallower than 30m, whilst this fraction is <10% in the Celtic Sea (17% for West of Scotland). If the recycling of nutrient from the sediments directly into the shallow layer, and the deposition of settling material from the shallow layer directly onto the seabed, are likely to lead to relevant differences in trophic dynamics, this seems to be an important structural property to include in a new version of the model.

Once we consider the introduction of new structure to enable seabed contact with the surface layer, we also need to think about what this implies for state variables. A starting point might be to simply assume that a fixed fraction of the sediment water nutrient flux goes directly to the shallow layer rather than all to the deep, and that a proportion of settling shallow material goes directly to the sediment, by-passing the deep layer. But, a consequence of this is that we must assume the sediment layer is well mixed horizontally between shallow and deep waters. This is plainly not a viable simplification. Hence, as a minimum we need to separately resolve the detritus and pore-water nutrients in shallow and deep sediments. Then, since presumably these sediments have different properties of porosity and permeability, we have to consider in more detail how sediment properties are represented in the model.

Resolving different types of sediments

Porosity is the proportion by volume of the sediment which is fluid-filled void space. In the model this is simply a scaling factor to enable the estimation of pore-water nutrient concentrations, and hence it is reasonable to expect that regional porosity can be represented by the arithmetic mean. However, the same is not true for permeability, which is a measure of the connectedness of the fluid filled void spaces between the particle grains in the sediment. In the model the exchange rate of dissolved nutrient between pore waters and the overlying water column is dependent on the product of the difference in concentration and the hydraulic conductivity of the sediment. Hydraulic conductivity is a measure of the ease with which fluids flow through the matrix, and hence is related to permeability but is a function of both the sediment and the permeating fluid, in particular the fluid viscosity and density. A simple analytical model shows that under constant production and consumption rates, the steady state nutrient concentration in sediment pore waters varies non-linearly with hydraulic conductivity. Hence, low conductivity sediments act as a nutrient store in the model, and the validity of expressing regional sediment permeability by an arithmetic mean is suspect.

Both porosity and permeability of marine sediments vary in a relatively orderly manner with median grain size. Fine grained muddy sediments have lower permeability and higher porosity than sands, mixed and coarse sediments. However, the relationships are strongly non-linear, and there is a clear distinction between muddy sediments and others. As a first order approximation, we can divide seabed sediments into those with a high and low mud content, and assign representative porosities and permeabilities to each of these. Hence, in the revised StrathE2E model we explicitly resolve patches of high and low mud content sediments in direct contact with both the shallow and deep water column layers. In addition, since these two broad classes of sediment do not account for 100% of the seafloor, we also include regions of rock or otherwise inactive sediment on which there is no deposition of settling detritus and from which there is no release of nutrient (Figure 2).

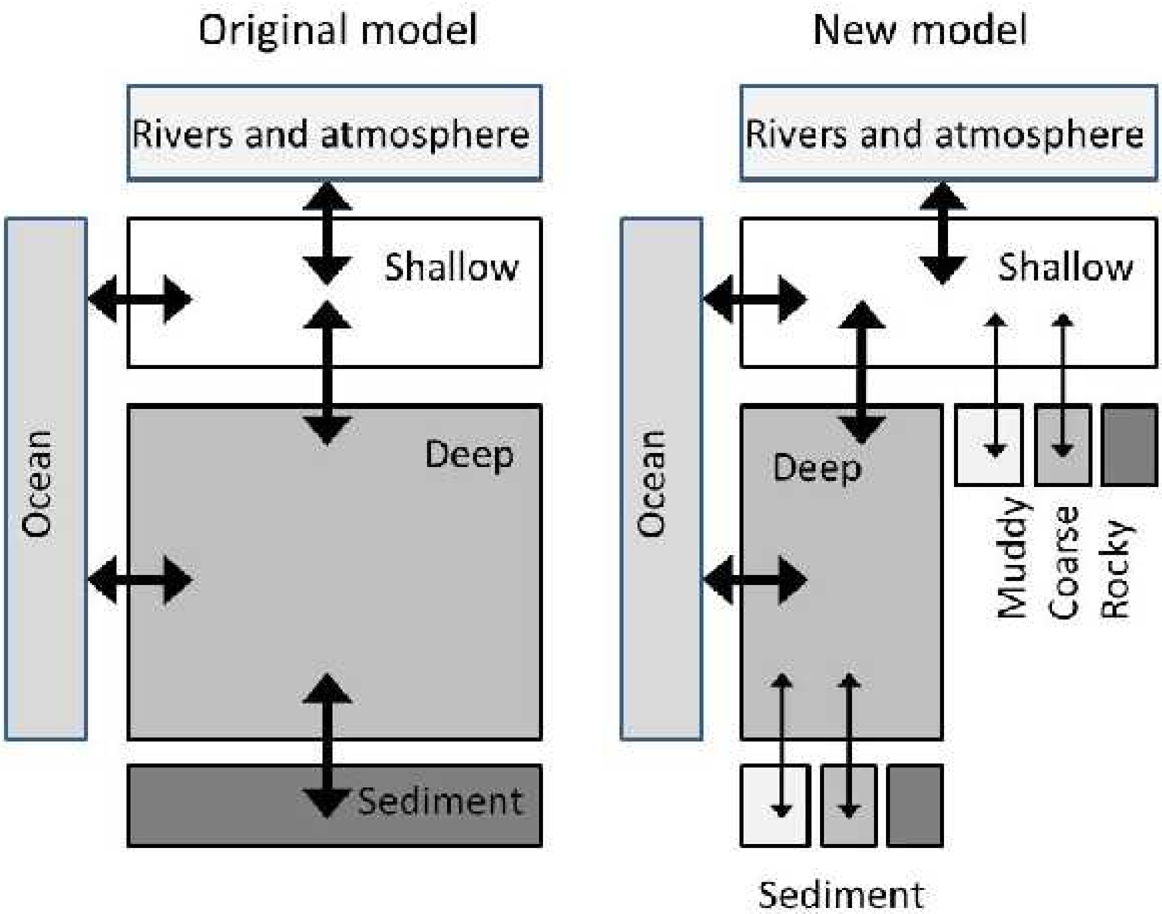

Figure 2. *Schematic showing the boundary, layer and seabed configurations of the original StrathE2E model (left) and the new extended model (right). Seabed sediments are divided into three classes in each depth zone representing low, high, and zero permeability (muddy, coarse and rocky sediments).*

The static configuration parameters required for the model now become as follows:

- Depth of the horizon between shallow and deep water column layers
- Mean thickness of the shallow water column layer
- Mean thickness of the deep water column layer
- Thickness of the seabed sediment layer
- Proportion of sea surface area above:
  - Shallow muddy sediment
  - Shallow coarse sediment
  - Shallow rocky seabed
  - Deep muddy sediment
  - Deep coarse sediment
  - Deep rocky seabed
- Porosity and permeability of:
  - Shallow muddy sediment
  - Shallow coarse sediment
  - Deep muddy sediment
  - Deep coarse sediment

Representing natural and anthropogenic disturbance of sediment

In the original StrathE2E model the sinking rate of suspended detritus in the deep water column layer was attenuated in indirect relation to the vertical mixing rate between the surface and deep layers, to represent the action of large scale turbulence in the water column on deposition rates of suspended detritus. However, this representation does not reflect the re-suspension of material already attached to the seabed, or the release of pore-water nutrients associated with such events. In addition, the introduction of a direct connection between the shallow water column layer and the seabed in the revised model requires us to adopt a new approach.

In the revised model, we abandon the parameterised relationship between deep suspended detritus sinking rate and vertical mixing, and instead consider an explicit representation of natural and anthropogenic processes which disturb the seabed and lead to re-suspension of sediment detritus into the suspended pool. In addition, we include the modification of sediment-water fluxes of dissolved nutrients that such processes cause.

The background flushing and diffusion exchange of dissolved nutrient between the sediment pore waters and the overlying water column is already represented in the model by the product of hydraulic conductivity and the concentration gradient as follows.

The flux (F; kg.m^{-2}.d^{-1}) of a dissolved nutrient between the sediment and the water column due to diffusion and flow through the sediment is given by:

$$F = (H).(n/(\varphi.\delta) - N/\Delta) \qquad (1)$$

where, for unit sea surface area (1 m^2), Δ and δ (m) are the thicknesses of the overlying water column and sediment layers respectively, N and n are the masses (kg) of nutrient in the water column and in the sediment pore waters respectively, φ is the sediment porosity, and H is a whole-sediment hydraulic conductivity (m.d^{-1}).

Now, we introduce a hydrodynamic process which erodes a uniform surface skin of sediment representing a proportion α of the seabed sediment layer thickness per day. This might entail the wholesale re-suspension of the skin, or bedload transport such as in the formation ripples and waves. In either case, it is assumed that all the organic detritus in the eroded skin is released into suspension. In addition, pore water in the eroded skin, of volume $\alpha.\varphi,A.\delta,$ is replaced with water from the overlying water column. Assuming that the water column and pore waters are well mixed, and that the lower bound of the sediment layer is impervious to nutrient, we can represent this process in terms of differential equations as follows:

$$dn/dt = (q - u.n) - F - \alpha.n + \alpha.\varphi,\delta,N/\Delta \qquad (2)$$

where q is a production rate of nutrient in the sediment (kg.m^{-2}.d^{-1}), and u is a proportion of pore-water nutrient mass consumed per unit time (d^{-1})).

Similarly, in the water column,

$$dN/dt = (Q - U.N) + F + \alpha.n - \alpha.\varphi,\delta,N/\Delta \qquad (3)$$

where Q is a production rate of nutrient in the water column ($kg.m^{-2}.d^{-1}$), and U is a proportion of water column nutrient mass consumed per unit time (d^{-1})).

Here, the terms *Q, q, U* and *u* caricature the integrated effects of the many food web and microbial processes represented in the StrathE2E model.

With respect to organic detritus re-suspended from the seabed along with the mineral material, the flux to the water column is simply *α.d,* where *d* is the mass of detritus in the sediment. If *D* is the mass of detritus in the overlying water column, then the corresponding differential equations for the rates of change are:

$$dd/dt = (r - m.d) - \alpha.d + s.D \qquad (4)$$

where *r* and *m* are the production and consumption rates of organic detritus respectively in the sediment, and *s* is the sinking rate of detritus in the water column (proportion transferred to the sediment per day). As before, the term *(r – m.d)* encapsulates the range of detrital microbiology processes represented in the full StrathE2E model.

Similarly, in the water column:

$$dD/dt = (R - M.D) + \alpha.d - s.D \qquad (5)$$

where *R* and *M* are the production and consumption rates of organic detritus respectively in the water column.

We seek to represent three natural re-suspension or irrigation processes in the model: tidal current erosion, wave orbital velocity erosion, and bioturbation by benthic fauna. In each case, we need to estimate a value for *α* in each sediment type due to the action of the process concerned. In addition, we seek to represent the anthropogenic disturbance of sediment, for example by trawling.

Tidal current erosion

With increasing water flow over the seabed, particle movement will occur when the instantaneous fluid force on a particle is just larger than the instantaneous resisting force. The latter is related to the submerged particle size or weight and the friction coefficient. Cohesive forces are also important when the bed consists of appreciable amounts of clay and silt particles. The shear stress to which a particle is subjected is a function of its size, the flow speed, and the densities of the fluid and particles. The critical value of shear stress required to initiate motion is often estimated from the empirically based 'Shield diagram', which relates a dimensionless measure of critical shear stress to the Reynolds viscosity of a particle in a given flow (Shields 1036).

Seabed shear-stress (τ_b, $N.m^{-2}$) can be estimated from the vertically averaged current speed throughout the water column using the "law-of-the-wall" method (Soulsby and Clarke 2005):

If $\overline{U}$ is the vertically averaged current speed, h is the water column depth, ν is the kinematic viscosity ($m^2.s^{-1}$) of the fluid, ρ is the fluid density ($kg.m^{-3}$), and d_{50} is the median particle size on the seabed, then the current Reynolds number (R_e) is given by:

$$R_e = \frac{\overline{U}h}{\nu} \qquad ‘ \qquad (6)$$

Then,

If $\overline{U}$ = 0, τ_b = 0

If $\overline{U}$ > 0,

If $R_e \leq 2000$ then laminar flow and $\tau_b = \frac{3\rho v \overline{U}}{h}$

If $R_e > 2000$ then turbulent flow and

$$\tau_{bs} = (0.0001615.\exp\ 6(R_e)^{-0.08}\ .\rho\overline{U}^2 \text{ (smooth bed surface)} \quad (7)$$

$$\tau_{br} = \left(\frac{0.40}{\ln\frac{h}{z_0} - 1}\right)^2 .\rho\overline{U}^2 \text{ (rough bed surface; } z_0 \text{ = bed roughness length = } d_{50}/12) \quad (8)$$

$$\tau_b = \max(\tau_{bs}, \tau_{br}) \quad (9)$$

The shear velocity (u_*, $m.s^{-1}$) is then given by:

$$u_* = \sqrt{(\tau_b / \rho)} \quad (10)$$

The dimensionless particle Reynolds viscosity (R_p) is given by :

$$R_p = (u_*.d)/v \quad (11)$$

where d is the diameter of a particle on the seabed (m).

The dimensionless Shield number or Shield stress (τ^*) is then given by:

$$\tau^* = \tau_b / ((\rho_s - \rho).g.d) \quad (12)$$

where ρ_s is the density of sediment grains ($kg.m^{-3}$), and g is the acceleration due to gravity ($m.s^{-2}$).

The critical value of Shield stress for the initiation of particle motion (τ_c^*) is given from an empirical relationship between τ_c^* and R_p parameterised from the Shield diagram (Wilcock et al. 2009):

$$\tau_c^* = 0.105 * R_p^{-0.3} + 0.045.\exp(-35 * R_p^{-0.59}) \quad (13)$$

Movement of particles is assumed to be initiated when $\tau^* > \tau_c^*$

The Shield relationship $\tau_c^* = f(R_p)$ indicates that sand grain sized particles have the lowest critical Reynolds number for initiation of movement. Muddy sediment have higher critical Reynolds numbers due to cohesive forces, whilst coarser sediments have higher critical Reynolds numbers to do greater mass of individual particles.

For each sediment sub-region of the model seabed, we are required to estimate the proportion of seabed area $p_{\tau^*>\tau c^*}$ in which the Shield number exceeds the critical value during a tidal cycle, and the sediment depth (x_{Te}) to which the resulting erosion occurs. Then the value of *α* for tidal erosion is given by:

$$\alpha_{tidal} = p_{\tau^*>\tau c^*} * x_{Te} \qquad (14)$$

Wave and wind driven erosion

Wave and wind driven turbulent velocities have the potential to re-suspend seabed sediments and release pore water nutrients, when the bed shear due to orbital velocities exceeds the critical shear for initial movement. We parameterise the proportion of sediment layer thickness disturbed per day from the time series of log-vertical mixing rate driving data already available in the model, together with an exponential decay rate for the rate of disturbance with depth.

The daily fraction of seabed sediment layer thickness which is eroded is given by:

$$\alpha\ (wave)_{z,x} = \beta_{wave(x)}\ .\ \log_{10}(Vmixing)\ .\ exp(\ -\beta_{wave\_depth}.(depth)) \qquad (15)$$

where $\beta_{wave(x)}$ is a proportionality scaling factor, and β_{wave_depth} is the decay rate of disturbance with depth (z). As with tidal erosion, we expect that the orbital velocities required to disturb muddy sediments will be greater than for sands, so we expect different values of β_{wave} for muddy and non-muddy sediments.

Bioturbation

Burrowing and filter feeding benthic in-fauna create ventilation shafts into the interior of the sediment layer on the seabed and over-turning of the sediment structure. In effect, this process leads to an increased whole-sediment permeability and causes changes in nutrient fluxes (Olsgard et al. 2008), but we assume it does not lead to resuspension of organic detritus. In the model we represent this phenomenon by linking the proportion of sediment disturbed per day to the daily proportion of sediment detritus consumed per day by the filter and deposit feeding benthos group, with a scaling coefficient:

$$\alpha(bioturb)_{z,x} = \beta_{bioturb}\ .\ (Uptake(xd - bsdf)_{z,x})\ /\ (xd_{z,x})) \qquad (16)$$

where $\beta_{bioturb}$ is a proportionality scaling factor, $xd_{z,x}$ denotes the mass of sediment detritus in sediment depth layer *z* and class *x*, $Uptake(xd - bsdf)_{z,x}$ denotes the daily uptake of sediment detritus by suspension and deposit feeding benthos in sediment depth layer *z* and class *x*.

The proportion of sediment disturbed by bioturbation, *α(bioturb),* is applied only to the flux of dissolved nutrients between pore water and the water column, not to the resuspension flux of organic detritus.

Anthropogenic disturbance

We consider anthropogenic disturbances of the seabed, such as the ploughing effects of trawling, to act differently from natural disturbance in that they are typically focussed on a local patch rather than being continuously distributed. In the model we consider these as mining out the entire thickness of the sediment layer in a spatial sub-patch, rather than eroding a surface skim off the whole area. Hence, in the mined sub-patch, the background diffusion and flushing process is completely eliminated (Figure 3).

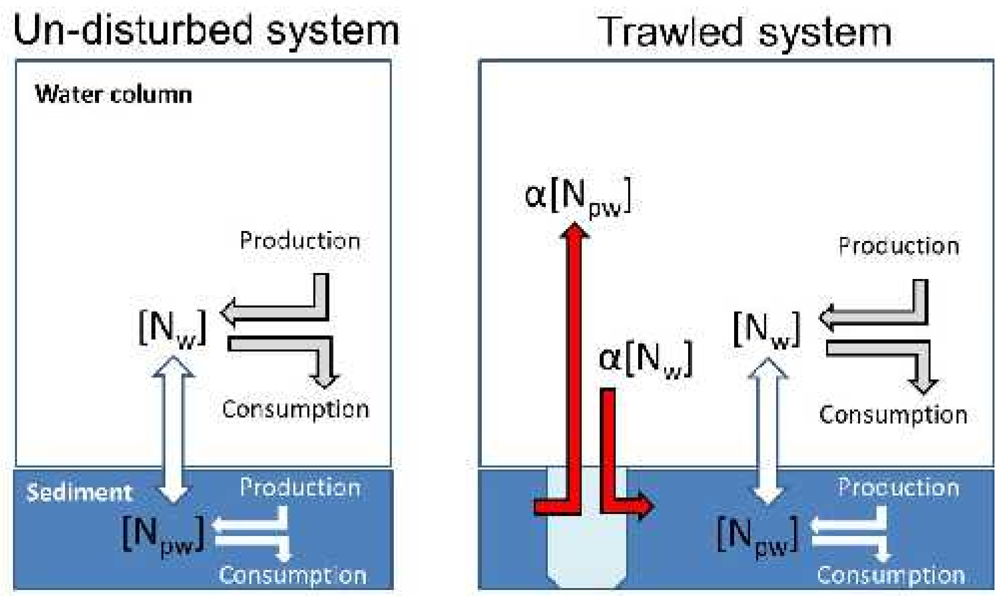

Figure 3. *Schematic of the representation of seabed ploughing by trawling in the extended StrathE2E model.*

We define a fraction of the sediment layer disturbed *α(anthrop),* equivalent to the fractions *α(tidal), α(wave),* and *α(bioturb)* of seabed disturbed in our representation of natural disturbance, but in this case there is a fraction (1 - *α(anthrop))* which remains undisturbed. So, the corresponding differential equation for the rate of change of nutrient in the sediment pore-waters and water column becomes:

$$dn/dt = (q - u.n) - (1 - \alpha(anthrop)).F - \alpha(anthrop).n + \alpha(anthrop).\varphi,\delta,N/\Delta \qquad (17)$$

and in the water column,

$$dN/dt = (Q - U.N) + (1 - \alpha(anthrop)).F + \alpha(anthrop).n - \alpha(anthrop).\varphi,\delta,N/\Delta \ (18)$$

Combined effects of natural and anthropogenic sediment disturbance:

If we let

$$A = \alpha(tidal) + \alpha(wave) + \alpha(bioturb) + \alpha(anthrop) \qquad ‘ \qquad (19)$$

Then our differential equations describing the rate of change of nutrient dissolved in porewaters and the overlying water column become:

$$dn/dt = (q - u.n) - (1 - \alpha(anthrop)).F - A.n + A.\varphi,\delta,N/\Delta \qquad (20)$$

and in the water column,

$$dN/dt = (Q - U.N) + (1 - \alpha(anthrop)).F + A.n - A.\varphi,\delta,N/\Delta \qquad (21)$$

With respect to organic detritus in the sediment:

$$dd/dt = (r - m.d) - (A - \alpha(bioturb)).d + s.D \quad (22)$$

and in the water column:

$$dD/dt = (R - M.D) + (A - \alpha(bioturb)).d - s.D \quad (23)$$

Defining fishing in terms of activity and power

Fishing harvest ratio (proportion of stock biomass captured per day) is an external driving variable in the existing StrathE2E model, which is applied as a time series for each of four groups of resource taxa in the model: pelagic fish, demersal finfish, filter and deposit feeding benthos (archetype: scallops), and carnivore/scavenge feeding benthos (archetype: Norway lobster). Each time increment in the model run, these proportions of the nutrient content of the standing stock biomass is removed to represent harvesting. Simultaneously, fish and benthos nutrient is transferred to predator groups in the model to represent predation, fractions are transferred to dissolved nutrients and detritus to represent metabolism, and nutrient is added the groups from others in the model to represent food ingestion. The balance of these additions and subtractions represents the change in stock biomass which occurs before the next time step.

Of the nutrient mass which is considered to have been captured in a given time step, a fraction may be returned to the model by an addition to a category of detritus which represents discards. This material goes through a series of decay processes in subsequent time steps to represent its consumption by scavengers and its eventual decay into dissolved nutrients. The remainder of the catch in the model is regarded as an export, i.e. a loss of nutrient from the model as a whole, to represent landings.

We can assume that harvest ratio is proportional to fishing effort, where the effort is composed of two components – fishing activity and fishing power. The latter (fishing power) is a measure of the effectiveness of the gear at catching fish and might reflect engine power of vessels and/or area sweeping rate of the gear ($m^2.h^{-1}$). Hence, in the revised StrathE2E, we drive the model with two time series for each fishing gear - annual hours fished per unit sea surface area of the model domain (activity density), and fishing power.

$$HR_i = A_i \,.\, P_i \quad (24)$$

where A_i is the activity density ($sec.m^{-2}.d^{-1}$) and P_i is the power ($m^2.s^{-1}$) for gear type i and the total harvest ratio for the given resource group $HR_T = \sum_i HR_i$

The power of a gear is given by:

$$P_i = \Psi_i \,.\, \beta \quad (25)$$

where Ψ_i is the relative power ($kg.s^{-1}$) for gear type *i*, and β is a constant which is effectively 1/(stock density) during a data calibration period with appropriate scaling to take account of conversion between the units used to quantify stock in the calibration data and the model.

The relative power term Ψ_i for each gear and the constant β are estimated from activity, landings and discards data for a calibration period where the overall harvest rate on a model resource group is known:

$$\Psi_i = (\text{landings}_i + \text{discards}_i)/A_i \text{ and } \beta = HR_T / \sum_i A_i \cdot \Psi_i \quad (26)$$

Seabed ploughing rate by fishing gears

In the new StrathE2E model we wish to be able to relate the rate of fishing to the proportion of seabed area ploughed by different fishing gears per unit time. Logically, this is not related to the harvest ratio, but to the activity of gears which may have very different seabed ploughing characteristics. So, we need a relationship between harvest ratio and fishing activity. For each fishing gear, we require an additional parameter - the gear-specific area ploughing rate (ε, $m^2.s^{-1}$). Then, the regional scale daily proportion of seabed ploughed by a trawl pass $\alpha(anthrop)_{regional}$ *is given by*

$$\alpha(anthrop)_{i,regional} = A_i \, . \, \varepsilon_i \quad (27)$$

Damage mortality inflicted on benthos by fishing gears

Gears which are in contact with the seabed may cause fatal injury to various benthos taxa without actually catching them (Collie et al. 1997, 2000, Hiddink et al. 2006, Kaiser & De Groot 2000). We refer to this as damage mortality. In the extended StrathE2E model we link the damage mortality to the ploughing rate.

If ξ_j is the proportion of biomass of a benthos group j killed per trawl pass per year, then the daily proportion of biomass killed is given by:

$$\alpha(anthrop)_{i,regional} \cdot \xi_j / 365 \quad (28)$$

Distribution of fishing across sediment types and the rate of seabed disturbance

In order to distribute the regional average seabed ploughing effect of each fishery across the four seabed sediment classes in the model (shallow and deep, mud, non-mud; not rock), we require information on the proportion of regional effort expended on each sediment. We assume that fishing power is uniformly distributed, and hence that the spatial distribution of effort is accounted for entirely by the distribution of activity.

For each gear category (i) and seabed class (k), the proportion of sediment ploughed per unit time is given by:

$$\alpha(anthrop)_{i,k} = \alpha(anthrop)_{i,regional} \, . \, p_{i,k} / p_k \quad (29)$$

where $p_{i,k}$= proportion of regional fishing activity by gear i on seabed class k, and p_k = the proportion of regional area accounted for by seabed class k.

Spatial distribution of seabed corpses arising from fishery discards

A consequence of having dis-aggregated the seabed in the model into shallow and deep regions, and areas of muddy, non-muddy and rocky sediments, is that we have to properly account for the inputs of particulate detritus material to each of these seabed classes. These inputs comprise two sources – settling suspended detritus from the water column, and corpses produced as a result of density dependent mortality rates applied to various living categories in the model, and fishery discards which sink to the seabed. In the revised model, we apportion settling detritus and corpses arising from density dependent mortality between seabed classes simply on an area proportional basis. However in the case of corpses arising from fishery discards, we are explicitly representing the spatial distribution of fishing activity in the model, so we can partition the flux from discards to seabed corpses on the basis of the proportion of fishing activity over each seabed class.

Whilst detritus sinking from the water column is not permitted to settle on rocky seabed areas in the model, we do permit corpses arising from discards to settle onto rock. However, detritus arising from their time-dependent disintegration is released to the water column, rather than being incorporated into the seabed as in muddy and non-muddy areas.

The fate of corpses arising from density dependent mortality

In the original model, density dependent mortality is applied to birds & mammals, adult and larvae of pelagic and demersal fish, carnivorous zooplankton, and carnivorous/scavenge feeding benthos. The flux of nutrient generated by these mortality rates was directed to seabed corpses (along with the settling flux of fishery discards). In effect, seabed corpses represent large lumps of detritus.

In revising the model, it makes sense to consider whether it is appropriate to include the corpses from density dependent mortality of carnivorous zooplankton and fish larvae in the flux to seabed corpses. More likely, the majority of this material will disintegrate or be preyed on in the water column rather than on the seabed, though there are accounts of, for example, mass mortalities of jellyfish forming a carpet on the seabed. This is a difficult judgement, but in the revised model we have diverted the mortality flux from carnivorous zooplankton and fish larvae to deep suspended detritus.

Analysis of bathymetry, sediment habitat, and tidal current data to derive model configuration parameters (developed with combined funding from NERC and FIS)

Data on the area proportions of depth and sediment classes

We extracted a sub-set of the ETOPO5 1/12 degree gridded elevation data points (National Geophysical Data Centre, www.ngdc.noaa.gov/mgg/global/global.htm), falling within a polygon delineating the model domain and having an elevation below mean sea level. These points are on a polar coordinate grid, so we calculated the sea surface area represented by each point, which decreases with latitude. Then we calculated the total sea surface area in the domain, the wet-area at 30m depth, the mean thickness of the 0-30m layer (taking account of areas shallower than 30m), and the mean thickness of the 30m-seabed layer.

Seabed sediment compositions are typically classified according to the Folk triangle (Folk 1954) which expresses the proportions of mud, sand and gravel in a given sediment sample (Figure 1). For the new StrathE2E model, we required a simpler sediment classification which separated muddy sediments from the coarser, more permeable sediments. The European Nature Information System (EUNIS) level 3 sediment classification (coarse, mixed, sand and muddy sand, mud and sandy mud) is a widely accepted aggregation of the Folk scheme (Connor et al. 2004, Davies & Moss 2004; Figure 4).

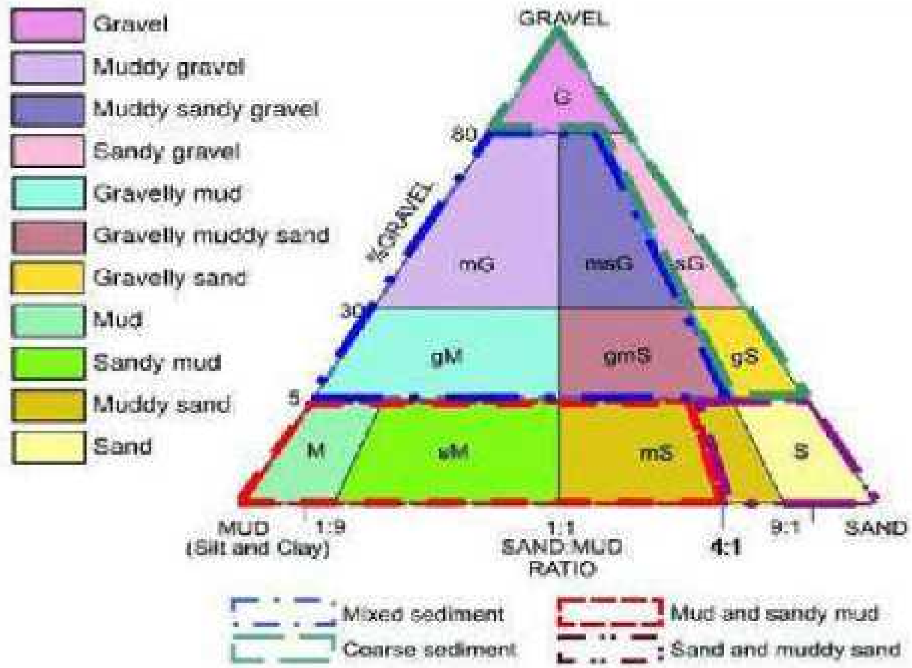

Figure 4. *Folk sediment trigon, overlaid with the aggregation into the European Nature Information System (EUNIS) level 3 sediment classes (coarse, mixed, sand and muddy sand, mud and sandy mud) (from McBreen and Askey 2011).*

Spatial distributions of the percentage of EUNIS level 3 sediment classes in 1° longitude x 30' latitude rectangles for the northwest European shelf in the range 48°-62°N, seabed depths <500m, were derived by the British Geological Survey (Cooper et al. 2006; Figure 5).

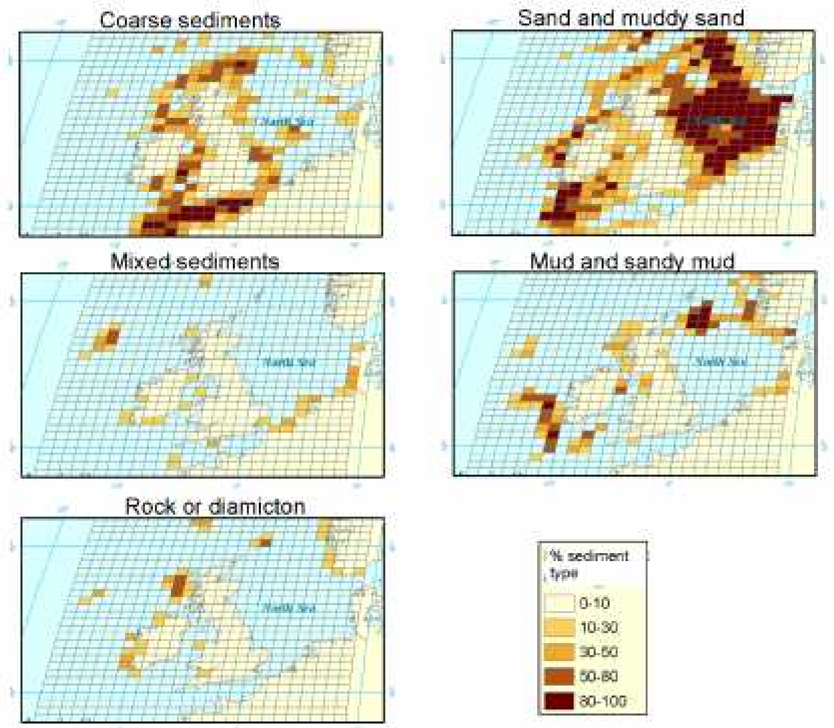

Figure 5*. Percentage of EUNIS level 3 sediment classes in 1° longitude x 30' latitude rectangles for seabed depths <500m, from the British Geological Survey.*

To calculate the areas of each EUNIS sediment class in the 0-30m and >30m depth ranges, we assigned the same percentage sediment composition to each ETOPO5 bathymetry point falling within each 1° longitude x 30' latitude rectangle. We then summed the areas of ETOPO5 grid points, weighted by the percentage composition of each sediment type. To configure the StrathE2E model, we combined the area proportions of coarse, mixed, and sand & muddy sand categories into a single 'coarse' sediment class, leaving the mud and sandy mud as representative of the 'muddy' sediments in a region. The area proportions of these seabed classes in the North Sea and west of Scotland regions are shown in Table 1.

Table 1*. Sea surface areas of the North Sea and West of Scotland regions for which the StrathE2E model was configured, together with the proportions of these areas in the 6 seabed habitat classes defined by depth and sediment type. Grey shaded cells indicate habitats in water deeper than 30m.*

Region	**Sea surface area km^2**	**Muddy seabed <30m**	**Coarse seabed <30m**	**Rocky seabed <30m**	**Muddy seabed >30m**	**Coarse seabed >30m**	**Rocky seabed >30m**
North Sea	514651	0.0165	0.2416	0.0062	0.1067	0.6111	0.0178
West of Scotland	116076	0.0349	0.1080	0.0255	0.0543	0.6836	0.0937

We took the percentage composition of each EUNIS sediment class in terms of the constituent elements mud, sand, and gravel from McBreen and Askew 2011, together with the typical grain size range for each of these three elements from the grain size ranges of Folk sediment classes (Table 2). Then, assuming that percentage composition of each EUNIS class, and grain size of each constituent were both log-normally distributed, we estimated the median grain size for the whole-sediment EUNIS classes (Table 3).

***Table 2**. 95% Confidence intervals for the median percentage mud sand and gravel for EUNIS Level 3 habitats, and estimated grain size range of each constituent based on particle size data, from McBreen and Askew 2011.*

EUNIS level 3 categories	***Mud (%)***	***Sand (%)***	***Gravel (%)***
Coarse sediment	3 – 8	90 - 96	0.2 – 0.5
Mixed sediment	8 – 13	59 - 71	9 – 18
Sand and muddy sand	1.6 - 2.2	96 - 98	0 - 0.1
Mud and sandy mud	52 – 64	33 - 42	*0*
Grain size range (mm)	0.002 - 0.063	0.063 - 2	2 – 63

***Table 3**. Estimated median grain size of EUNIS level 3 sediment classes*

EUNIS level 3 categories	***Median grain size (mm)***
Mixed sediment	0.399
Sand and muddy sand	0.333
Coarse sediment	0.297
Mud and sandy mud	0.044

Relationship between median grain size, porosity and permeability in marine sediments

Empirical data shows that coarse grained sediments generally have a lower porosity and higher permeability than muds and silts. However, data to parameterise the details of the relationship between porosity, permeability and grain size in European shelf sea sediments are extremely sparse. Porosity and grain size data are available from a few sources, but permeability measurements are rare since they are difficult to make at sea on a moving ship.

Ruardij & Van Raaphorst (1995) and Lohse et al. 1993, presented data on porosity and median grain size in muds from the southern North Sea. Wiesner et al. 1990, list data on grain size and water content (by weight) for a wide range of North Sea sediments. Serpetti (2012) measured grain size distributions, porosity and permeability in sediment cores from coarse, mixed and fine grained sediments at 8 sites off the northeast coast of Scotland, repeated at monthly interval over an annual cycle.

Porosity and grain size data from all these studies were combined to produce a North Sea-wide dataset spanning a range of sediment types. Data from Serpetti (2012) were averaged over the annual cycle of observations at each site. Water content data (by weight) from Wiesner et al. 1990 were converted to porosity assuming a solid material density of 2.65 g.cm^{-3} and a fluid density of 1.025 g.cm^{-3}. Log-transformed porosity showed a sigmoidal relationship with $\log_{10}$-grain size (mm), to which we fitted a relationship of the logistic form using Nelder Mead optimisation in the 'optim' package of R (Table 4, Figure 6):

$$\log_{10}\ porosity\ = p_1 + p_2\ \frac{1}{1+e^{\frac{-\log_{10}\ grainsize\ - p_3}{p_4}}} \qquad (30)$$

***Table 4**. Fitted values and their standard error, of the four parameters for the function relating sediment porosity to median grain size.*

Parameter	**Fitted value**	**Standard error**
p_1	-0.436	0.023
p_2	0.366	0.050
p_3	-1.227	0.063
p_4	-0.270	0.046

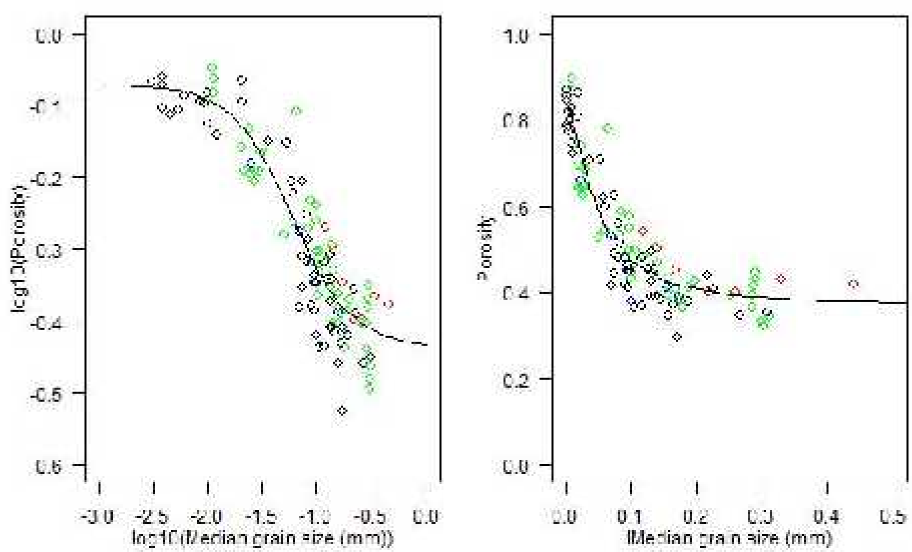

***Figure 6**. Assembled data on sediment porosity and median grain size, and the fitted relationship (solid line). Left panel, log-transformed data, right panel un-transformed data. Red symbols: Serpetti 2012; green: Ruardij and van Raaphorst 1995; blue: Lohse et al.1993; black: Weisner et al. 1990.*

The best available dataset on whole sediment permeability in relation to median grain size is that of Serpetti (2012). These data cover muddy sand, sand and mixed sediments sampled approximately monthly over an annual cycle at 7 sites off the east coast of Scotland. Permeability and median grain size were measured on cores from the upper 5cm and upper 10cm of the seabed at each site. A power function of median grain size (D, mm) was found to explain the differences in annual average permeability (m^{-2}) between sites (r^2 = 0.999 for 10cm cores, r^2 = 0.966 for 5 cm cores) (Figure 7):

Permeability = $10^{-8.675}.D^{4.958}$ (5 cm cores) (31)

Permeability = $10^{-9.213}.D^{4.615}$ (10 cm cores) (32)

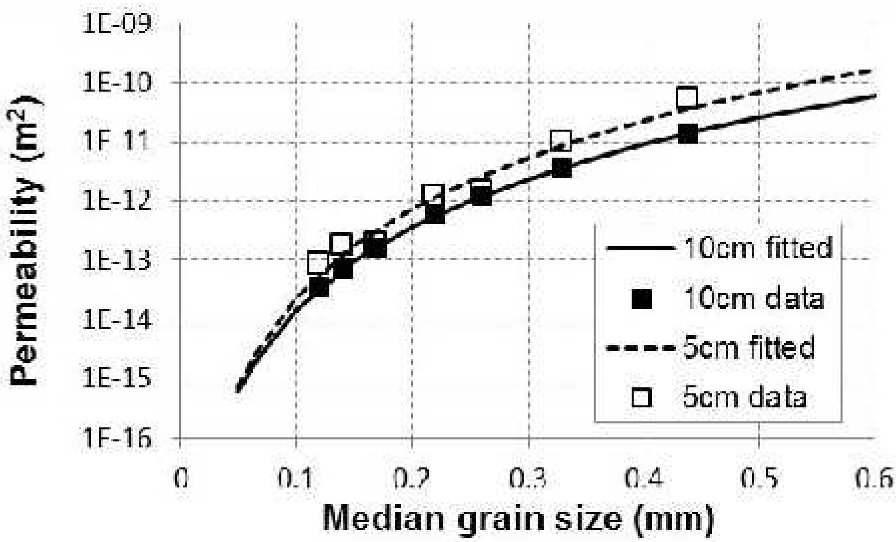

***Figure 7**. Annual average permeability (m^{-2}) of sediments from 7 sites off the north east coast of Scotland (data from Serpetti et al. 2012). Open symbols, permeability over the upper 5cm of sediment, filled symbols over the upper 10cm.*

Applying these results to the median grain sizes estimated for each of the EUNIS sediment classes, we can estimate their typical porosities and permeabilities (Table 5).

***Table 5**. Estimated median grain size of EUNIS level 3 sediment classes*

EUNIS level 3 categories	***Porosity***	***Permeability (m^{-2})***
Mixed sediment	0.380	8.798×10^{-12}
Sand and muddy sand	0.385	3.816×10^{-12}
Coarse sediment	0.388	2.241×10^{-12}
Mud and sandy mud	0.616	3.212×10^{-16}

The StrathE2E model requires data on hydraulic conductivity in order to compute nutrient fluxes between sediment pore waters and the overlying water column. Hydraulic conductivity ($m.s^{-1}$) is related to permeability by:

HC = Permeability · density · g/(dynamic viscosity) (33)

Where: seawater density = 1027 kg.m-3 at salinity 35 and temperature 10°C; seawater dynamic viscosity = 1.48 x 10^{-3} $kg.m^{-1}.s^{-1}$ at salinity 35 and temperature 10°C; g = acceleration due to gravity = 9.8 $m.s^{-1}$

Hence HC = Permeability · 6.8004 x 10^{6} (34)

Data on the natural disturbance of sediments.

The area-proportions of each seabed habitat type (except those where the seabed was rocky) where the peak depth averaged current speed during a mean tidal cycle was sufficient for the Shelds shear stress to exceed the critical value for particle motion were calculated from output of a M2 tidal run of the HAMSOM hydrodynamic model with ¼ degree longitude x 1/8 degree latitude spatial resolution (Hainbucher and Backhaus 1999) (Table 6).

Table 6*. Area proportions of each of the 6 seabed habitat classes defined by depth and sediment type, where the critical Shields stress is exceeded during an average tidal cycle . Grey shaded cells indicate habitats in water deeper than 30m.*

Region	Muddy	Coarse	Muddy	Coarse
North Sea	0.0813	0.3936	0.0019	0.0562
West of Scotland	0.0425	0.1924	0.0456	0.0952

Analysis of spatial datasets on fishing activity, landings and discards

In this section of the project we obtained and analysed the 2003-2013 STECF datasets on international fishing activity, landings and discards by fishing gear categories (Table 7), in order to assemble the fishery configuration data needed for the new StrathE2E model.

The long term goal is to extend the StrathE2E model to a number of geographical regions. We therefore created data sets of fishing activity, landings and discards for the following regions: Biscay Ocean, Biscay Shelf, Celtic Sea, Central North Sea, Clyde and Irish Sea, English Channel, Faroe Island, North Sea, Northern North Sea, Porcupine, Rockall, Rockall Trough and Faroe Islands, Southern North Sea, and West of Scotland. These regions are shown in the map in Figure 8.

The time period covered by the STECF data is 2003-2013. Our methodology and computer code was designed so that it can easily be modified to accommodate data updates by STECF. In this exercise we are only concerned with annual means over the period 2003-2013. However, our code was designed so that minor modifications will allow calculations of annual landings, discards and activity.

Data products

We created three data products:

- Aggregate fishing activity by each gear for each geographic region.
- Aggregate landings, by model guild, by each gear in each geographic region.
- Estimated discards, by model guild, by each gear in each geographic region.

In each case the data product is an annual mean for the period 2003-2013.

Table 7 *Definitions of raw STECF gear codes*

Code	Gear type
POTS	Pots and traps
BOTTOM TRAWLS	Bottom trawls
BEAM	Beam trawl
TR2	(demersal trawls and seines with mesh 70-99mm
TR1	demersal trawls/seines with larger mesh sizes > 100MM
BT2	Beam trawls of mesh equal to or larger than 80 mm and less than 120 mm.
DREDGE	Dredges.
GILL	Drift and fixed Nets except Trammel Nets
GN1	Gill nets, entangling nets.
LONGLINE	Longlines
LL1	Longlines
NONE	unidentified gears
OTTER	Bottom trawl
PELAGIC TRAWLS	Pelagic trawls
TRAMMEL	Trammel Nets
GT1	Trammel nets
PEL_TRAWL	Pelagic Trawl
BT1	Beam trawls of mesh equal to or larger than 120 mm
TR3	Bottom trawls and seines of mesh size equal to or larger than 16 mm and less than 32 mm.
3B	Gillnet ≥ 60 mm
3A	"Bottom trawler mesh size ≥ 32 mm)"
PEL_SEINE	Pelagic seine nets
DEM_SEINE	Danish and Scottish seiners

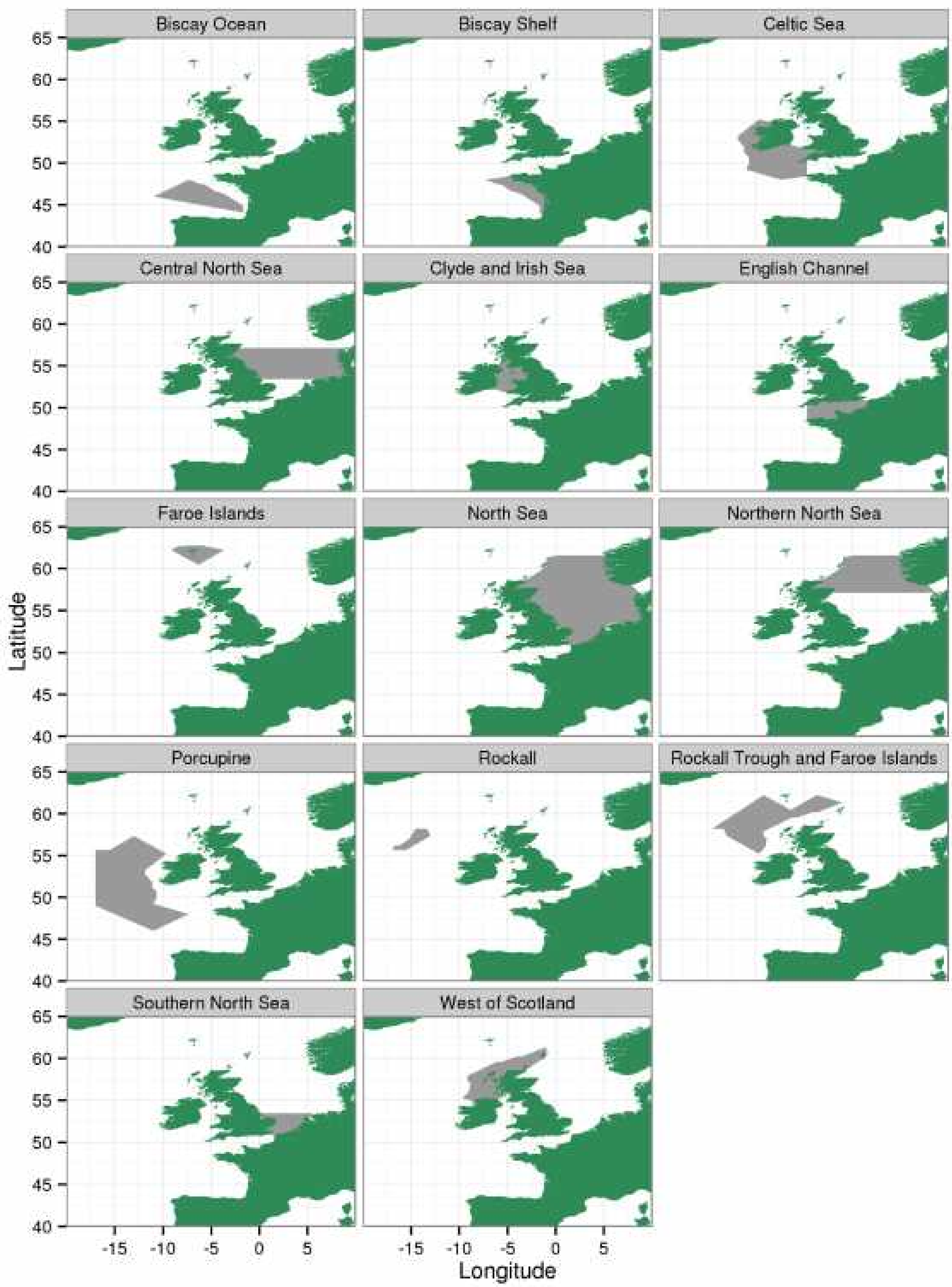

Figure 8*. Map of regions for which we estimated mean annual activity, landings and discards data between 2003 and 2013*

Data summary

All fishing data is taken from the Scientific, Technical and Economic Committee for Fisheries (STECF). We use three types of data: activity, landings and discards. This data (filename: '2014_STECF 14-20 - Fishing Effort Regimes data tables.zip') was downloaded from the STECF website (http://stecf.jrc.ec.europa.eu/data-reports). Data covers the period 2003-2013. STECF gear definitions are outlined in Table 7.

STECF landings data are estimated using national fisheries statistics which must be recorded as laid out by the control regulation (Council Regulation 1224/2009). This data, based on logbooks or sales slips, records total weight (in tonnes) of fish caught in each ICES rectangle. Data is reported at the level of gear, boat length, Annex, area, special condition, county and species.

STECF discard data is is estimated according to the provisions in the Data Collection Framework (DCF) (Council Regulation 199/2008). Member States are required to carry out at-sea estimates of discards using onboard observers.

Care must be taken with STECF data to ensure that double or multiple counting of activity, landings or discards does not occur. STECF data is principally reported at the level of Annexes, which reflect separate management regimes under the Common Fisheries Policy. The data for each Annex is in turn reported at the level of Areas, which are composed of ICES divisions. Landings and activity data is then reported for the ICES rectangles which lie in each Annex's areas. However, there is significant spatial overlap between areas. Effort and landings data for each ICES rectangle must therefore only come from one Annex and one Area to avoid double counting.

The resolution of data is also of varying quality. For some Annexes, beam and otter trawls are resolved into subclasses with different mesh sizes. However, in some Annexes gears are not resolved by mesh size. Furthermore, the activity and landings data is not reported at the level of the entire ICES rectangle. Instead it is reported for the part of the ICES rectangle that falls within the specified Area.

Discards data is reported at a much coarser resolution. In contrast to landings and activity data, actual discards statistics are of relatively low quality. Discards can only be estimated by placing observers on board fishing boats. This is a costly activity, and therefore only around 1% of fishing boats have observers on board. This inevitably introduces significant uncertainty into the data. Selection of boats may be non-random and it remains possible that fishermen discard fish differently in the presence of an observer.

Data processing

We first allocated species to the StrathE2E model guilds. These allocations are shown in Table 8.

Table 8 *Allocation of top 30 species by landings to guild. This covers 98% of total landings.*

Species	Common Name	Fishery guild	Species	Common Name	Fishery guild
MAC	Mackerel	1	ANF	Anglerfish	2
HER	Herring	1	COD	Cod	2
SAN	Sandeel	1	WHG	Whiting	2
WHB	Blue whiting	1	HKE	Hake	2
JAX	Horse mackerel	1	NOP	Norway pout	1
SPR	Sprat	1	SOL	Common sole	2
PLE	Plaice	2	LEZ	Megrims	2
OTH			DAB	Dab	2
NEP	Norway lobster	3	LIN	Ling	2
HAD	Haddock	2	LEM	Lemon sole	2
BOR	Boarfish	1	PIL	European pilchard(=Sardine)	1
CRE	Edible Crab	3	POL	Pollack	2
POK	Saithe	2	TUR	Turbot	2
SCE	Great Atlantic Scallop	4	RAJ	Rays	2
CSH	Common shrimp	3	ALB	Albacore	1

Before calculating landings at the level of individual geographic regions we first created a spatially explicit data set of activity and landings in each ICES rectangle over all of the relevant areas. This aggregated region is shown in Figure 9.

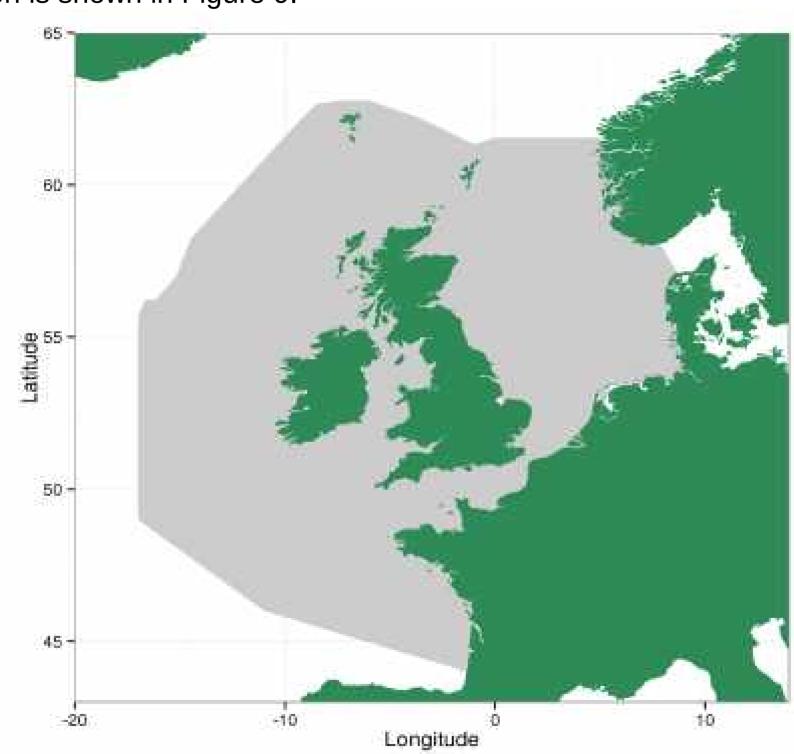

Figure 9. *Map of total area over which we created data sets of landings and activity by ICES rectangle*

Effort and landings in each ICES rectangle can appear under multiple Annexes and areas. However, the data quality varies significantly, with some Annexes not resolving gears by mesh size. This is most pronounced for the Deep Sea (DS) Annex, which covers the entire geographic region we are concerned with. DS does not resolve gear types by mesh size. As a result, exclusive use of data from the DS Annex would not allow the separation of the Nephrops and shrimp fisheries which have significantly different trawling characteristics compared with other boats in their DS gear categories. A strategy is therefore needed so that duplicates are removed while maximizing the how fine grained gear data is.

The only available Annexes which resolve gears by mesh size are IIA and CEL1. Importantly, these Annexes cover the vast majority of landings and activity (> 90%) in the overall geographic region we are considering. We therefore created a composite data set of activity and landings for the geographic regions of interest by adding data for each ICES rectangle from Annexes separately and in order of data quality. The processing order is shown in Table 9.

Table 9*. Order in which we added data to our spatial data set. Landings and activity data were calculated using their first appearance in the annexes and area shown.*

Number	Annex	Area	ICES Areas
1	IIA	3B2	IVa, IVb, IVc
2	IIA	3B3	VIIa
3	IIA	3C	VIIa
4	IIA	3D	VIa
5	CEL1	7BCEFGHJK	VIIb, VIIc1-2, VIIe-h, VIIj1-2, VIIk1-2
6	BOB	8A-BOB	VIIIa
7	BOB	8B-BOB	VIIIb
8	IIB	8C-9A	VIIIc, IXa
9	DS	6 EU	VIa,VIb1,VIb2
10	DS	8 EU	VIIId1,VIIId2, VIIIe1
11	DS	5 NON EU	Vb2,Vb1b

1.8% of landings come under the unclassified gear NONE. We therefore adjust the data to account for this. 70% of the landings for this gear class come under the OTH species listing. Landings can therefore not be used to make a reasonable estimate of the gear represented by NONE. We can only attribute the activity of the NONE category to the existing gears in each ICES rectangle. Effort in the NONE category is therefore attributed, by year and rectangle, to each gear in proportion to the total activity of each gear in that rectangle and year. A similar procedure is used for landings from the NONE gear, with landings spread in relation to relative landings, split by guild, by each gear in each ICES rectangle and year.

Data is processed according to the following procedure:
1. Data in ICES rectangles are processed in the order shown in in Table 9.
2. The proportion of the wet area of the ICES rectangle within the respective ICES division is calculated. If this is greater than 0.7, we use the STECF data for this Annex and area as the data for the ICES rectangle.
3. Total activity (A) and landings (L) in the rectangle is estimated using the following formula:
4.

$$A_G \mathrm{A} \quad _{G,Y} = \sum_{c c \in \mathrm{Countries}} \frac{\mathrm{A_{c,G,Y}}}{\mathrm{P}} P \qquad (35)$$

$$L_{G,Y} = \sum_{c c \in \mathrm{Countries}} \frac{\mathrm{L_{c,G,Y}}}{\mathrm{P}} P \qquad (36)$$

where Countries is the list of countries, is the respective gear, Y is the year, F is the fishing guild, P is the proportion of the ICES rectangle's wet area within the respective area.

Landings, activity and discards are estimated for the regions shown in figure 3. This was done by summing landings and activity that fall within each region. In cases where the region defined intersects an ICES rectangle we use proportion of the ICES rectangle's wet area falling within the region to estimate the landings and activity within the region.

As discussed below, activity is aggregated by bathymetry and sediment type. We also grouped a number of similar gears together, and split the TR2 and longlines gears to give a more accurate representation of the gears based on targeted species.

Classification by bathymetry and sediment type

Fishing activity was disaggregated according to sediment type and bathymetry. As described earlier, we divide the geographic region into two sea bed types: shallow and deep, with shallow being regions with bathymetry lower than 30 metres. We first estimated the proportion of the wet area in each ICES rectangle which falls under each depth category. This was carried out using data from the General Bathymetric Chart of the Oceans. This is a high resolution (1 by 1 minute) file. Each ICES rectangle is divided into 1800 cells (representing individual bathymetry points), with cells either classified as shallow or deep, and wet or dry. Finally, the proportion of wet area in each ICES rectangle that is shallow or deep is calculated by summing the areas of the relevant cells.

Sediment data was acquired from the British Geological Survey. Initial data is divided into five categories: coarse sediments, sand and muddy sand, mixed sediments, mud and sandy mud, rock or diamicton. In the model we have three classifications. Mud is mud and sandy mud; rock is rock or diamicton; and sediment is everything else. We therefore estimated the proportion of each ICES rectangle's wet area that falls under each of the three sediment types.

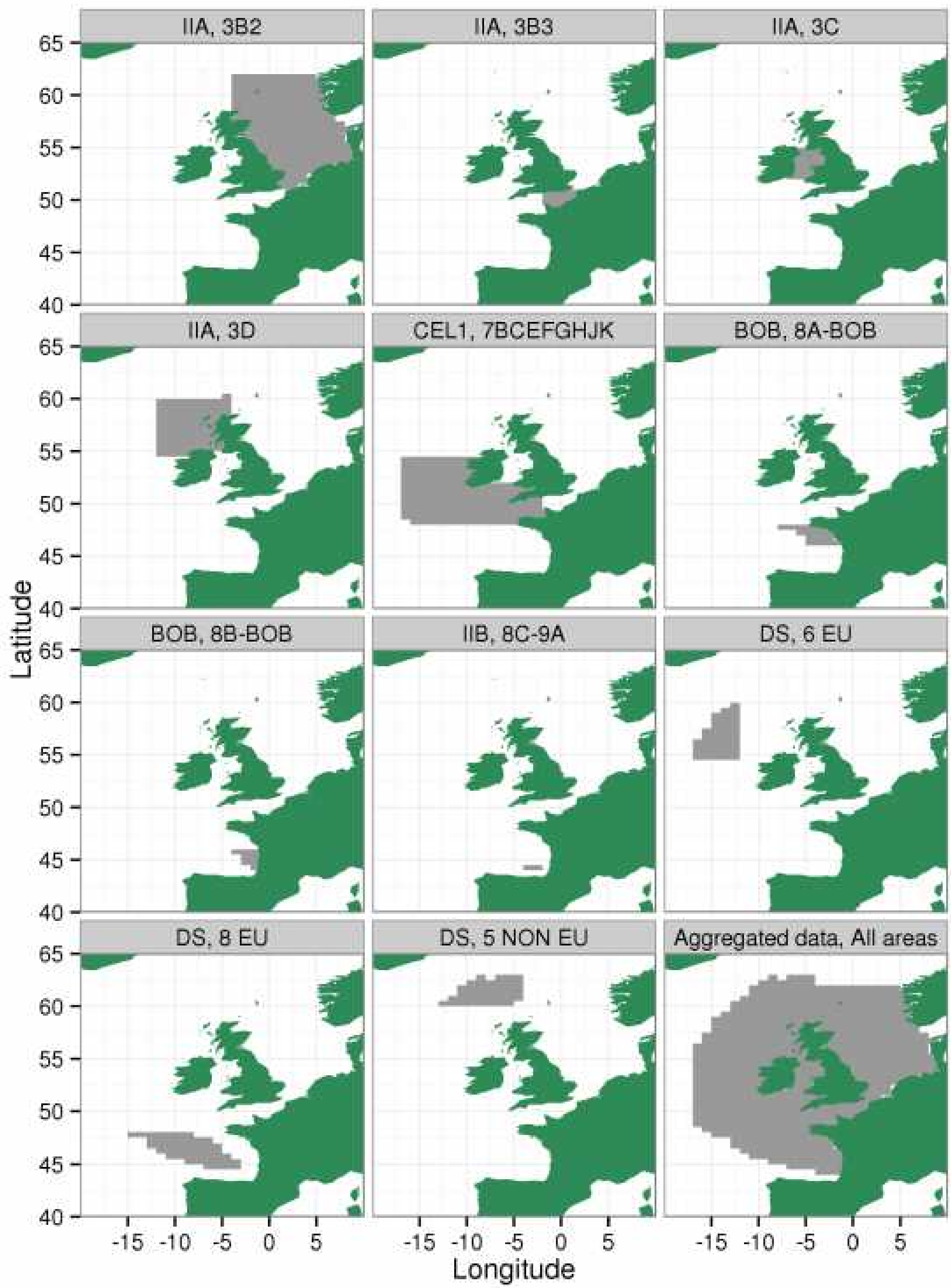

Figure 10. *Data sets of landings and activity by ICES rectangle were compiled from landings and activity data from Annex and area data. Annexes and areas were drawn from in the order shown here, giving the aggregated data sets.*

Table 10. *Proportion of activity and landings in the aggregated spatial data by annex.*

Annex	Activity	Landings	Area
IIA	70.06	77.26	46.36
CEL1	22.90	19.83	28.87
BOB	6.21	1.56	4.81
DS	0.74	1.31	19.82
IIB	0.10	0.03	0.15

Ad hoc gear classification

STECF gear classification is not fully sufficient to identify some key fisheries. For example, the BEAM classification overwhelmingly lands common shrimp in the North Sea, but generally lands demersal fish elsewhere. It is therefore necessary to create synthetic gears to account for this variation. Furthermore, some gears have almost identical powers, target the same guilds, and have similar impacts on the sea floor. It therefore makes sense to simplify the gear structure and merge gears that are very similar.

Beam trawls

There are three beam trawl classifications in STECF data: BEAM, BT1 and BT2. BT1 and BT2 more or less exclusively target demersal species throughout the regions considered. The species targeted by BT1 and BT2 (largely flat fish, such as plaice) are almost identical. It is therefore reasonable to combine BT1 and BT2 into a single model gear.

Care must be taken with the BEAM trawl classification. Where we draw on data from Annexes DS, BOB and IIB BEAM trawl represents all beam trawls, and it does not distinguish by mesh size. For Annexes IIA and CEL1, the BEAM classification covers beam trawls with mesh size between 100 and 120 mm. However, the guilds targeted are not consistent across regions. In the North Sea, landings from BEAM gears are more or less exclusively common shrimp (98.7% of the total). Elsewhere, landings from BEAM are more or less exclusively demersal fish. We therefore created a SHRIMP gear in the North Sea, and combined the activity and landings data from the other BEAM trawls with that from the BT1 and BT2 gears.

In effect, we have converted the BEAM, BT1 and BT2 gears into two new gears: BEAM and SHRIMP.

Long lines

The long line gear is used to target a number of species, both pelagic and demersal. However, the data combines all long lines fisheries. We therefore had to divide the long line activity data into two categories: LL1 and LL2, where LL1 is a pelagic long line and LL2 is a demersal long line.

Analysis of landings by ICES rectangle showed that there was little spatial overlap in pelagic and demersal long lines landings. We therefore split the long lines landings and activity into LL1 and LL2 using the following assumption: if the pelagic proportion of long lines landings in an ICES rectangle is greater than 50% all landings and activity from long lines in that ICES rectangle goes under LL1; if the proportion is less than 50% we place the landings and activity data under LL2.

Identifying Nephrops in TR2

Nephrops trawls have a relatively large impact on the sea floor. Area trawled per hour is higher than other gears and Nephrops trawls almost exclusively trawl in muddy areas. Nephrops trawls all come under the TR2 classification. However, not all vessels under the TR2 classification target Nephrops. Modifications must therefore be made to TR2 activity and landings to minimise misallocation of activity.

For example, there are three main fisheries which use the TR2 gear in the North Sea (Discard Atlas of North Sea fisheries 2014):

- A fishery for Nephrops, which has a significant bycatch of
- A mixed fishery in the southern North Sea, with whiting and other species as the main components.
- a 90-99 mm mesh mixed Danish and Swedish demersal fishery centred on the Skagerrak.

The non-Nephrops fisheries are country specific. Therefore country level landings data in each ICES rectangle enables us to provide a reasonably accurate division between the fisheries.
We therefore divide the TR2 gear into two synthetic gears when allocating activity to sediment: Nephrops and non-Nephrops. This was carried out using country level landings data in each ICES rectangle. If the Nephrops constituted more than 30% of landings by an individual country within an ICES rectangle we assigned that rectangle's TR2 landings and activity to the Nephrops gear. If it was less than 30% we assigned it to the non-Nephrops gear. We then assume that the Nephrops synthetic gear only fishes on mud, whereas activity for the non-Nephrops gear is evenly distributed throughout the ICES rectangle.

Otter trawls

Analysis of landings data shows that the OTTER, PEL_TRAWL and TR3 gears overwhelmingly land pelagic fish. The species landed are also sufficiently similar that we can assume the trawling impacts of the gears are indistinguishable. In the North Sea, 70% of landings from TR3 is sprat, 92% from OTTER is sandeel, and 71% from PEL_TRAWL landings are sprat and herring. Otter trawls targeting these species have very similar benthic impacts, so grouping them is sensible.

The TR1 gear largely targets demersal fish and has a different impact on the sea floor. This gear is therefore kept as an individual gear and is not combined with any others.

Trammel and gill nets

GN1 and GT1 both have minimal impact on the sea floor and more or less exclusively target demersal fish. We therefore combine the landings and activity from these two gears.

Estimating discards

STECF does not provide spatially explicit discards data at the level of ICES rectangles. Instead it provides estimates of aggregated discards, by species, at the level of countries, gears, Annexes and areas. We therefore estimated discards by guild for each gear and required geographic area using as much of the available information as possible.

Our original data is drawn from areas available in five Annexes (BOB, CEL1, DS, IIA and IIB). In some cases we use data from the entire area, and in others we have effectively used a subarea. However, it is reasonable to assume that the discards compositions in the subareas we use are relatively similar to that in the total area. Furthermore, country level discards composition for areas is more likely to be on average a better estimate for the country level discards composition in subareas.

Discards quality improved significantly over time. We therefore followed the approach taken by the North Sea Discards Atlas and only used discards data from 2010 onwards.

Our methodology for calculating region level discards by gear is as follows:

- We calculate total landings in the region from each gear and country, split by Annex and area.
- STECF Annex and area level landings and discards data is used to estimate the ratio between discards (for each of the four guilds) and total landings (summed across all species) by gear and country and split by Annex and area
- Discards to landings ratios are then used to estimate the discards in each guild for each gear, country, Annex and area.
- We derive the region's total discards, split by gear and guild, by summing up the discards across all countries, Annexes and areas

Caveats for discards estimates

We have created two longlines gear classes based on landings. It is impossible to distinguish between the discards from these two fisheries because of the poor spatial resolution of the discards data. However, the country level data will act as a proxy estimate for these two fish.
Quality of discard data has improved significantly in recent years. We therefore only use discards and landings data from the years 2010 onwards to estimate the discards to landings ratio.

Sediment ploughing rate for different fishing gears

The recent extensive review of Eigaard et al. (2015) quantitatively evaluated pressures on the seabed of a large number of fishing gears, including those under consideration here. Area impacted per hour of trawling was evaluated. This area was divided into surface (less than 2 cm) and subsurface (greater than 2 cm) impacts.

Here we use Eigaard et al.'s estimate of subsurface impact as our measure of area impacted. Using the landings composition by species (tables 5 and 6), we mapped our gear classes on to those of Eigaard et al. and produced estimates of ploughed area per unit time. This is shown in Figure 11.

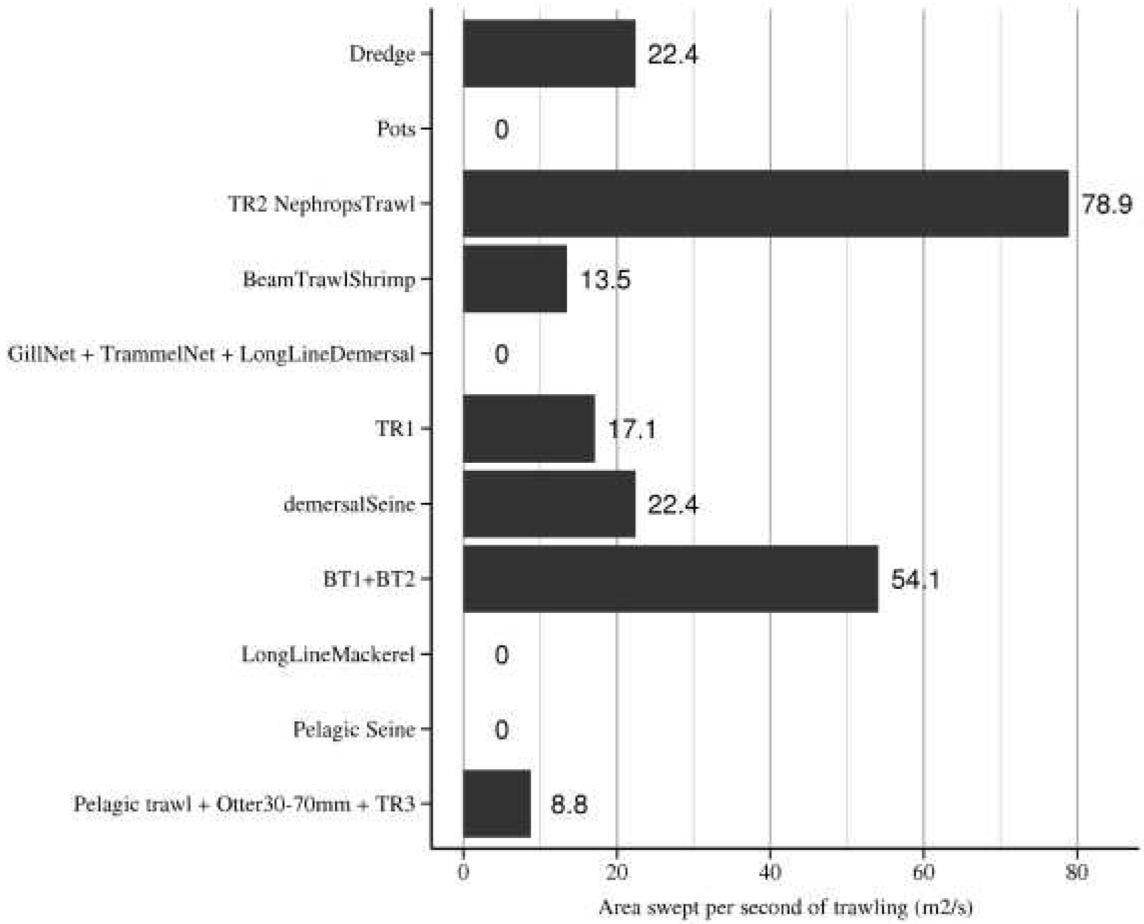

Figure 11*. Area ploughing rate of different gear categories, based on the >2cm depth impacted area per unit time estimates of Eigaard et al. (2015).*

Data analysis results

Landings by species

We first calculated the total landings of individual species for each region and for each gear. This was carried out to provide an accurate representation of the species composition of landings, which would enable us to more accurately map our gears to the gears shown by Eigaard et al. (2015). Furthermore, this enabled us to combine different gears with a similar landings composition into new synthetic gears for our modelling exercise.

Tables 11 and 12 show the landings of species between 2003 and 2013 in the North Sea and the West of Scotland. We have excluded species where less than 100 tonnes is landed per year.

Table 11. *Mean landings by gear in the North Sea in kt.y^{-1} (2003/2013)*

Species	BT1 + BT2	Demersal seine	Dredge	Gill net + Trammel net + Demersal LongLine	Long line mackerel	Pelagic Seine	Pelagic trawl + Otter30-70mm + TR3	Pots	Shrimp beam trawl	TR1	TR2 Nephrops Trawl
Sandeel	0.0	0	0.0	0.0	0.0	0.0	233.0	0.0	0.1	0.2	0.1
Herring	0.0	0	0.0	0.1	0.0	14.2	147.4	0.0	0.0	0.0	0.1
Sprat	0.0	0	0.0	0.0	0.0	0.1	84.1	0.0	0.0	0.1	0.0
Mackerel	0.0	0	0.0	0.0	0.6	15.1	56.8	0.0	0.0	0.1	0.5
Plaice	36.3	0	0.0	2.6	0.0	0.0	0.1	0.0	0.1	11.5	4.7
Common shrimp	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	29.1	0.0	0.0
Haddock	0.2	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.4	3.2
Saithe	0.0	0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	22.2	0.4
Norway lobster	0.2	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	17.3
Horse mackerel	0.0	0	0.0	0.0	0.0	0.2	15.5	0.0	0.0	0.1	0.2
Cod	2.0	0	0.0	2.4	0.0	0.0	0.0	0.0	0.0	11.3	1.2
Common sole	10.5	0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
Edible Crab	0.4	0	0.0	0.0	0.0	0.0	0.0	7.2	0.0	0.0	0.0
Whiting	0.4	0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	6.0	3.9
Dab	4.4	0	0.0	0.2	0.0	0.0	0.0	0.0	0.1	1.0	0.7
Great Atlantic Scallop	0.0	0	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Anglerfish	0.2	0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	3.4	1.3
Blue whiting	0.0	0	0.0	0.0	0.0	0.2	2.9	0.0	0.0	0.0	0.0
Norway pout	0.0	0	0.0	0.0	0.0	0.0	2.9	0.0	0.0	0.1	0.0
Hake	0.0	0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	2.6	0.1
Turbot	2.0	0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.3	0.3
Lemon sole	0.8	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.4
Ling	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.1
Megrims	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.1
Pollack	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0
Witch flounder	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.4
Northern prawn	0.0	0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Atlantic catfish	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0
Skates	0.3	0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Anchovy	0.0	0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
Atlantic halibut	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1
Boarfishes nei	0.0	0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
Flatfish, flounder	0.2	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rays	0.2	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Redfish	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Seabass	0.1	0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spurdog	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Tusk	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0

Table 12. *Mean landings by gear in the West of Scotland in kt.y^{-1} (2003/2013)*

Species	**BT1 + BT2**	**Demersal seine**	**Dredge**	**Gill net + Trammel net + Demersal LongLine**	**Long line mackerel**	**Pelagic Seine**	**Pelagic trawl + Otter30-70mm + TR3**	**Pots**	**Shrimp beam trawl**	**TR1**	**TR2 Nephrops Trawl**
Mackerel	0	0	0.0	0.0	0.1	3.3	88.3	0.0	0	0.0	0.0
Herring	0	0	0.0	0.0	0.0	0.8	50.9	0.0	0	0.0	0.0
Horse mackerel	0	0	0.0	0.0	0.0	0.0	12.2	0.0	0	0.0	0.0
Edible Crab	0	0	0.0	0.0	0.0	0.0	0.0	11.4	0	0.0	0.0
Norway lobster	0	0	0.0	0.0	0.0	0.0	0.0	1.7	0	0.5	7.5
Blue whiting	0	0	0.0	0.0	0.0	0.0	5.0	0.0	0	0.0	0.0
Haddock	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	4.9	0.3
Great Atlantic Scallop	0	0	4.2	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0
Saithe	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	3.2	0.0
Anglerfish	0	0	0.0	0.3	0.0	0.0	0.0	0.0	0	2.4	0.2
Cod	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	1.8	0.0
Whiting	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	1.0	0.2
Megrims	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.9	0.2
Hake	0	0	0.0	0.8	0.0	0.0	0.0	0.0	0	0.5	0.0
Sprat	0	0	0.0	0.0	0.0	0.0	0.8	0.0	0	0.0	0.0
Ling	0	0	0.0	0.2	0.0	0.0	0.0	0.0	0	0.6	0.0
Skates	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.3	0.1
Spurdog	0	0	0.0	0.1	0.0	0.0	0.0	0.0	0	0.3	0.2
Plaice	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.2	0.0
Black scabbardfish	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.1	0.0
Blue ling	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.1	0.0
Greater silver smelt	0	0	0.0	0.0	0.0	0.0	0.1	0.0	0	0.0	0.0
Lemon sole	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.1	0.0
Pollack	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.1	0.0

Species	BT1 + BT2	Demersal seine	Dredge	Gill net + Trammel net + Demersal LongLine	Long line mackerel	Pelagic Seine	Pelagic trawl + Otter30-70mm + TR3	Pots	Shrimp beam trawl	TR1	TR2 Nephrops Trawl
Rays	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.1
Redfish	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.1	0.0
Sandeel	0	0	0.0	0.0	0.0	0.0	0.1	0.0	0	0.0	0.0
Witch flounder	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.1	0.1

Landings and discards by guild

We estimated landings and discards for each guild and gear in the North Sea and the West of Scotland. Results are shown in figures 12 and 13.

In the North Sea the proportion discarded is largest for the two types of beam trawls. Over half of the demersal catch is discarded for the BT1 + BT2 and TR2 Nephrops gears. Over 10% of the shrimp beam trawl catch is demersal fish, but almost all of these fish are discarded. Discards for all other gears are below 10% of catch.

In the West of Scotland, there is relatively less discarding than in the North Sea. Only TR2 gears show noticeable levels of discards. Approximately 50% of TR2 catches are demersal fish, However the majority of these fish are discarded.

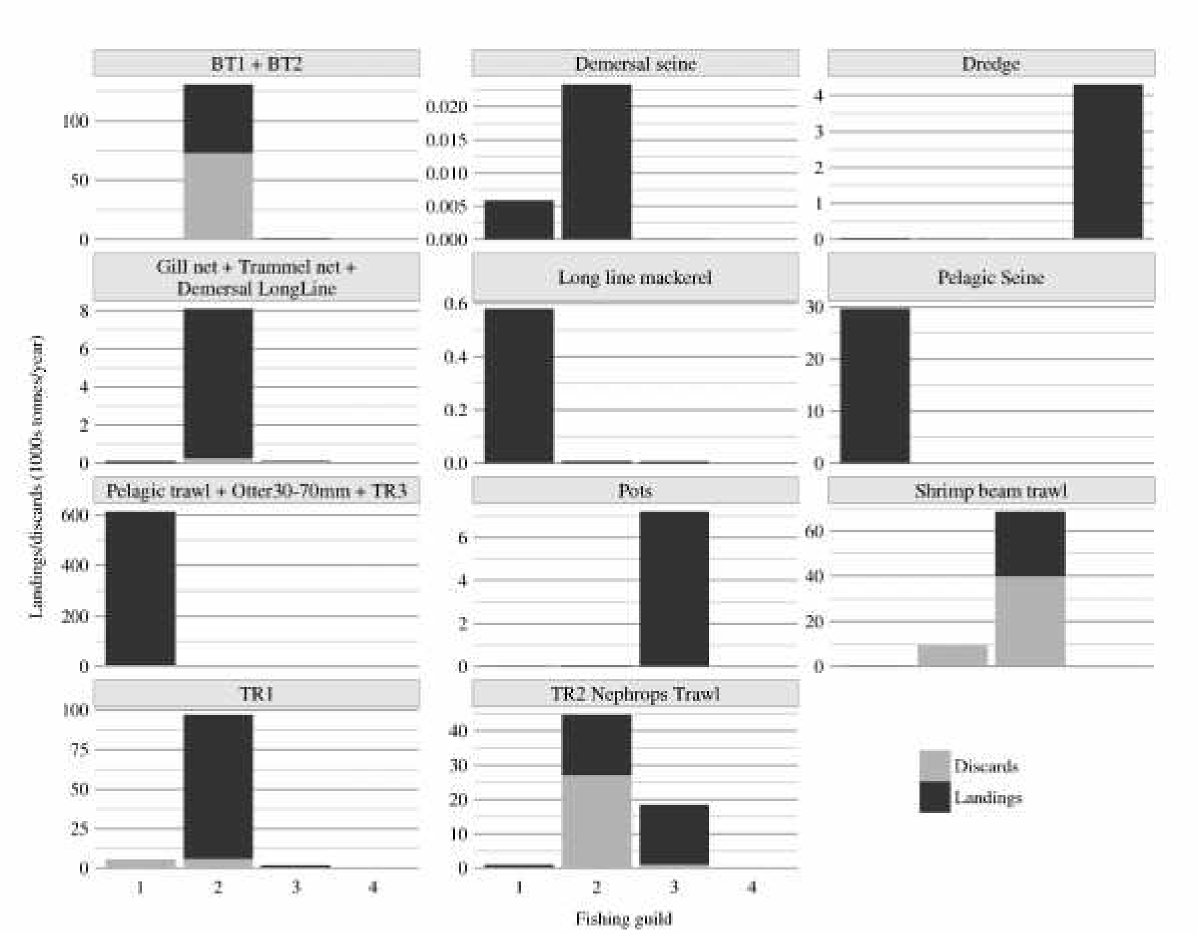

***Figure 12.**. Estimated annual landings and discards by each gear in the North Sea (2003-2013).*

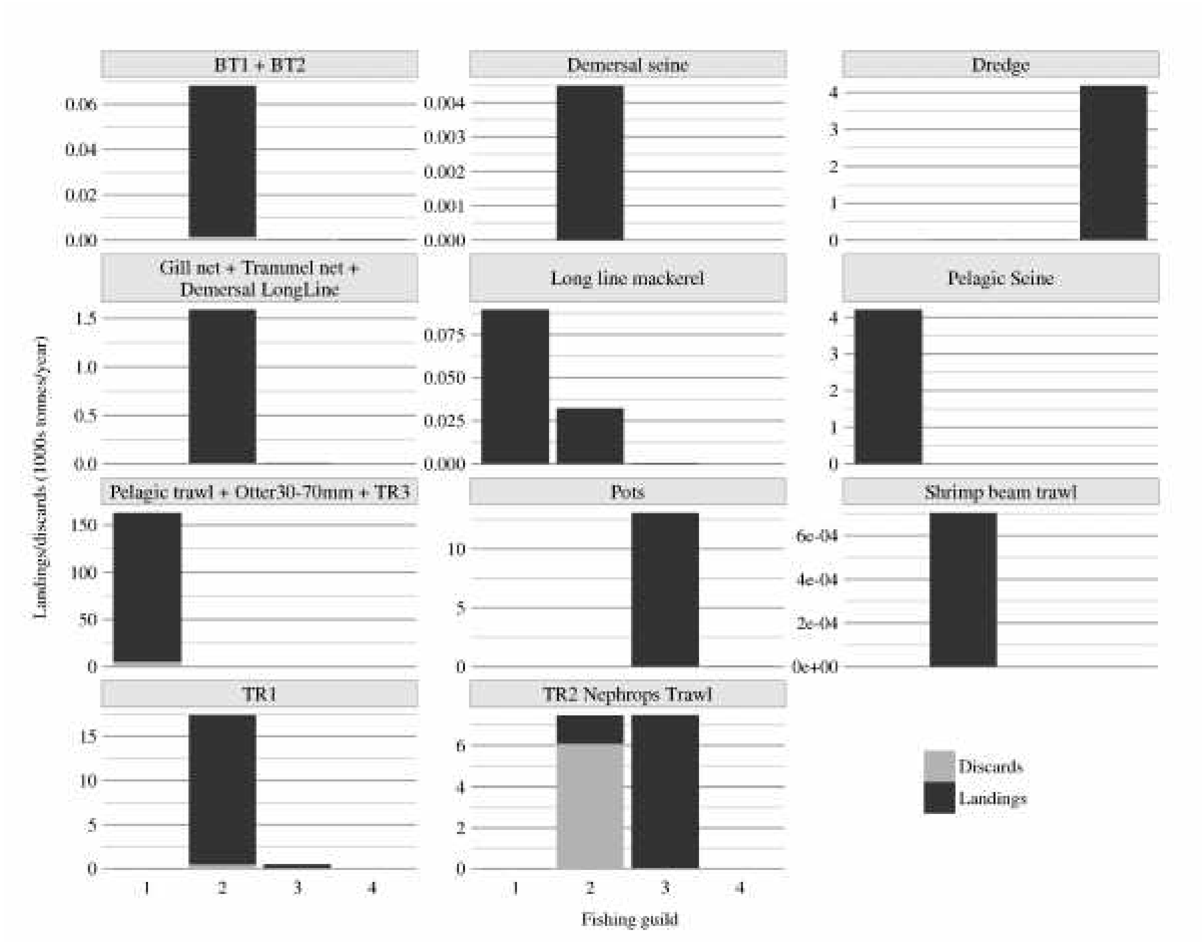

Figure 13. *Estimated annual landings and discards by each gear in the West of Scotland (2003-2013).*

Sediment classes

Figure 14 shows the geographic variations in sediment type aggregated from the original EUNIS level categories.

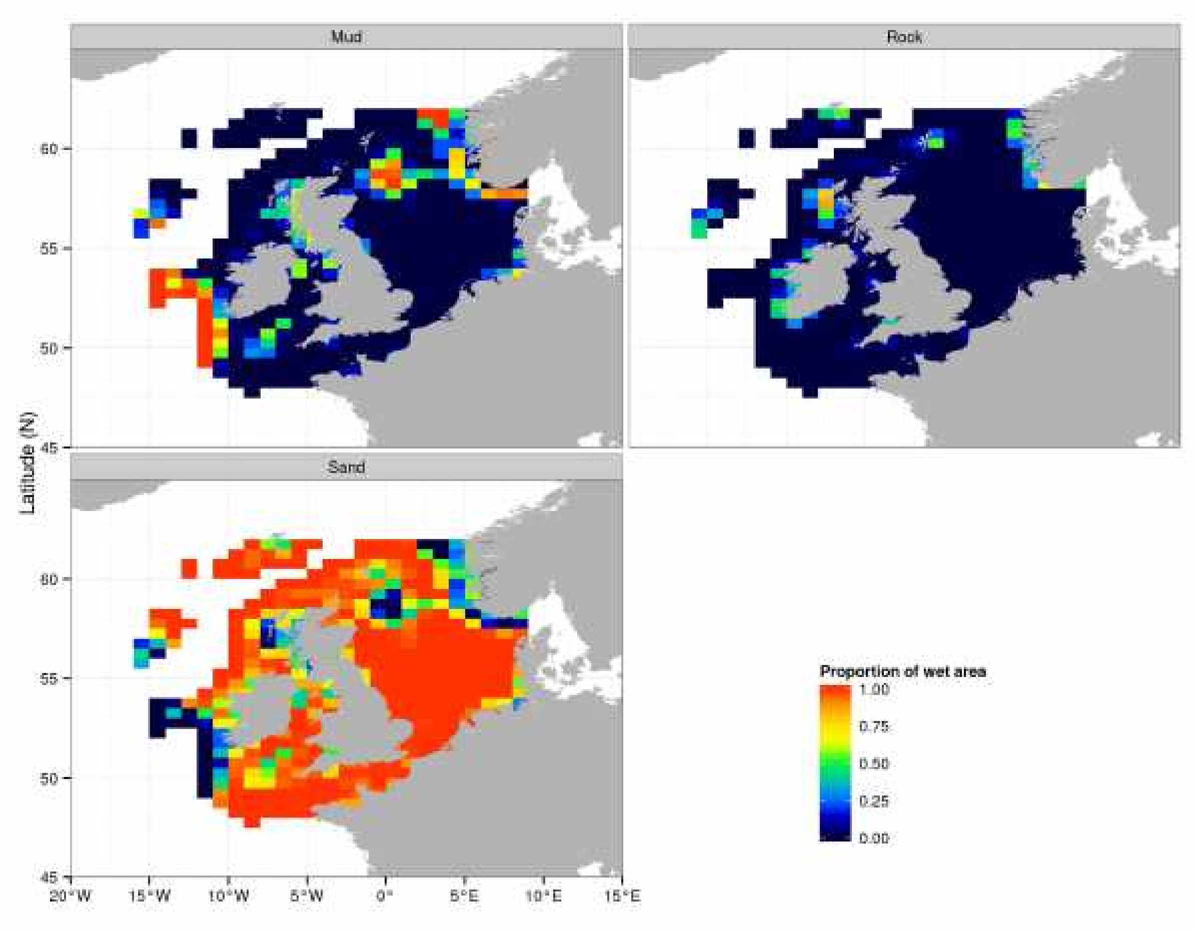

Figure 14. *Proportion of sediment in each sediment class. Proportions are for individual ICES rectangles*

Distribution of fishing activity

The geographical distribution of activity, averaged over the years 2003-2013, is shown in Figure 15.

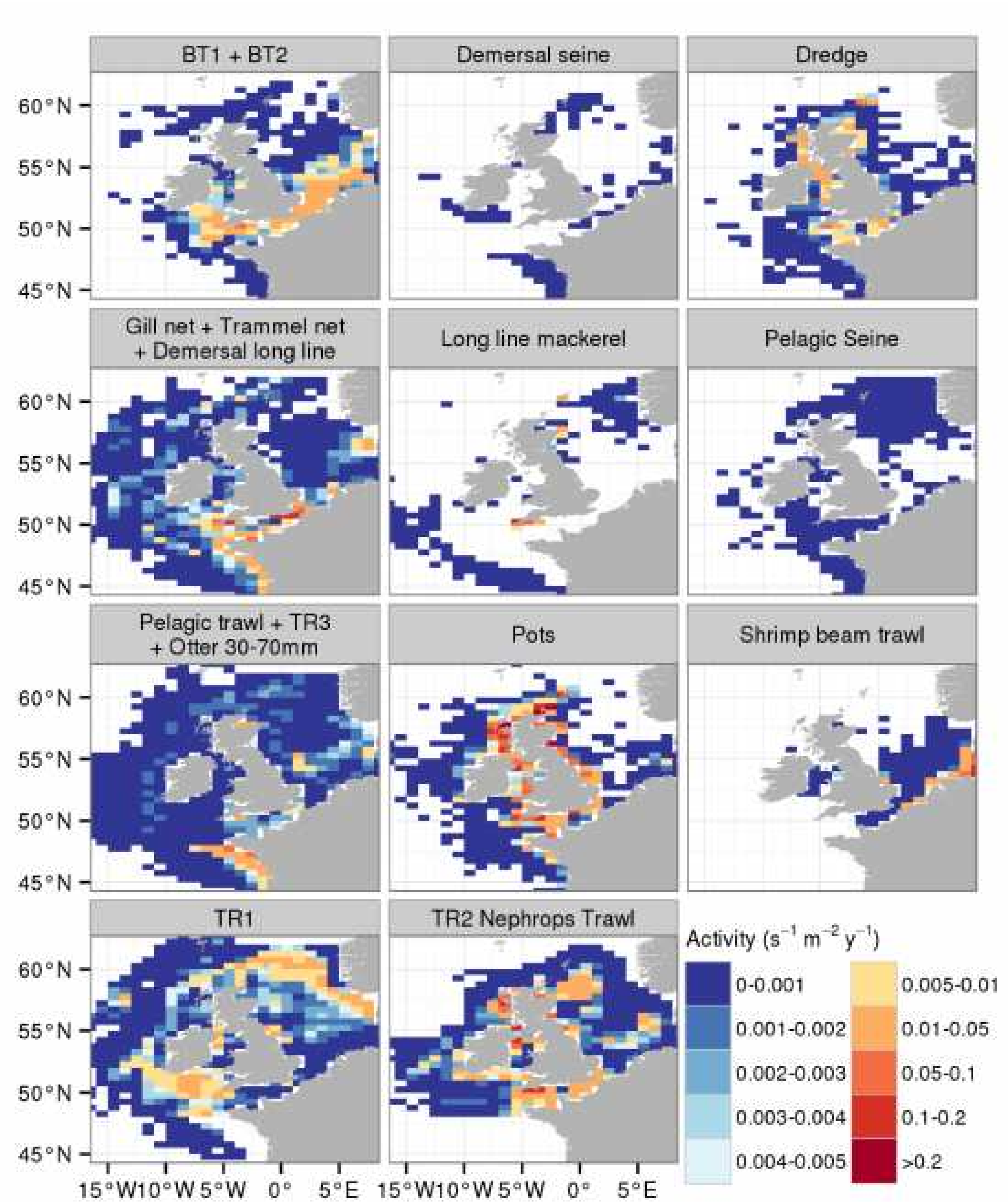

Figure 15. *The geographic distribution of activity from each gear. The area of ICES rectangles depends on latitude. We therefore normalise activity in each ICES rectangle by dividing annual activity by the area of the ICES rectangle.*

Figure 16 shows the total activity of each gear in the North Sea and the West of Scotland.

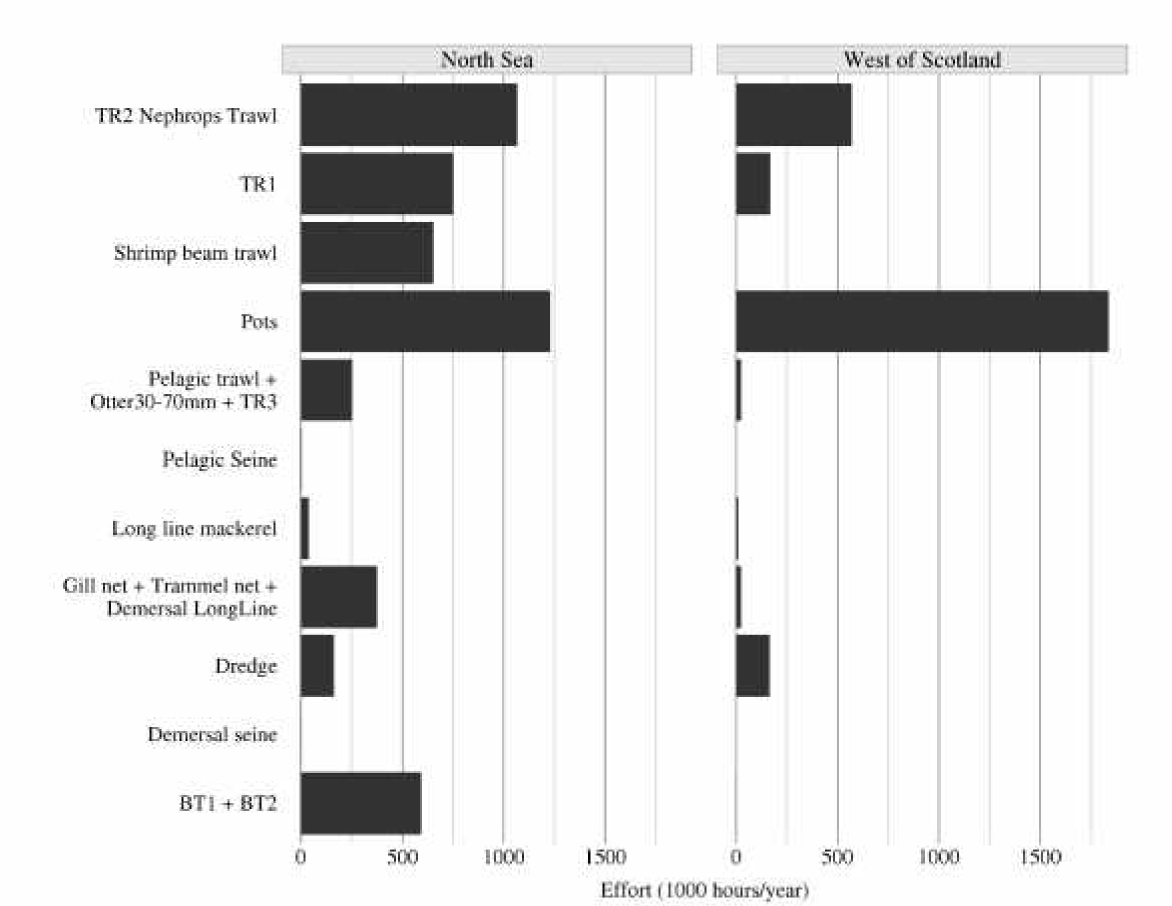

Figure 16. *Mean activity by each gear in the North Sea and West of Scotland (2003-2013)*

Figures 17 and 18 show the distribution of activity for each gear by sediment type. In both regions beam trawl trawl activity focuses exclusively on sandy sediments. The TR2 gear focuses almost entirely on deep mud, with a small level of activity in deep sand which results from our division of the TR2 activity into Nephrops and non-

Nephrops. The shrimp trawl focuses almost exclusively on coastal waters, and it is therefore mostly fishing on shallow sandy waters, and partly on shallow muddy waters.

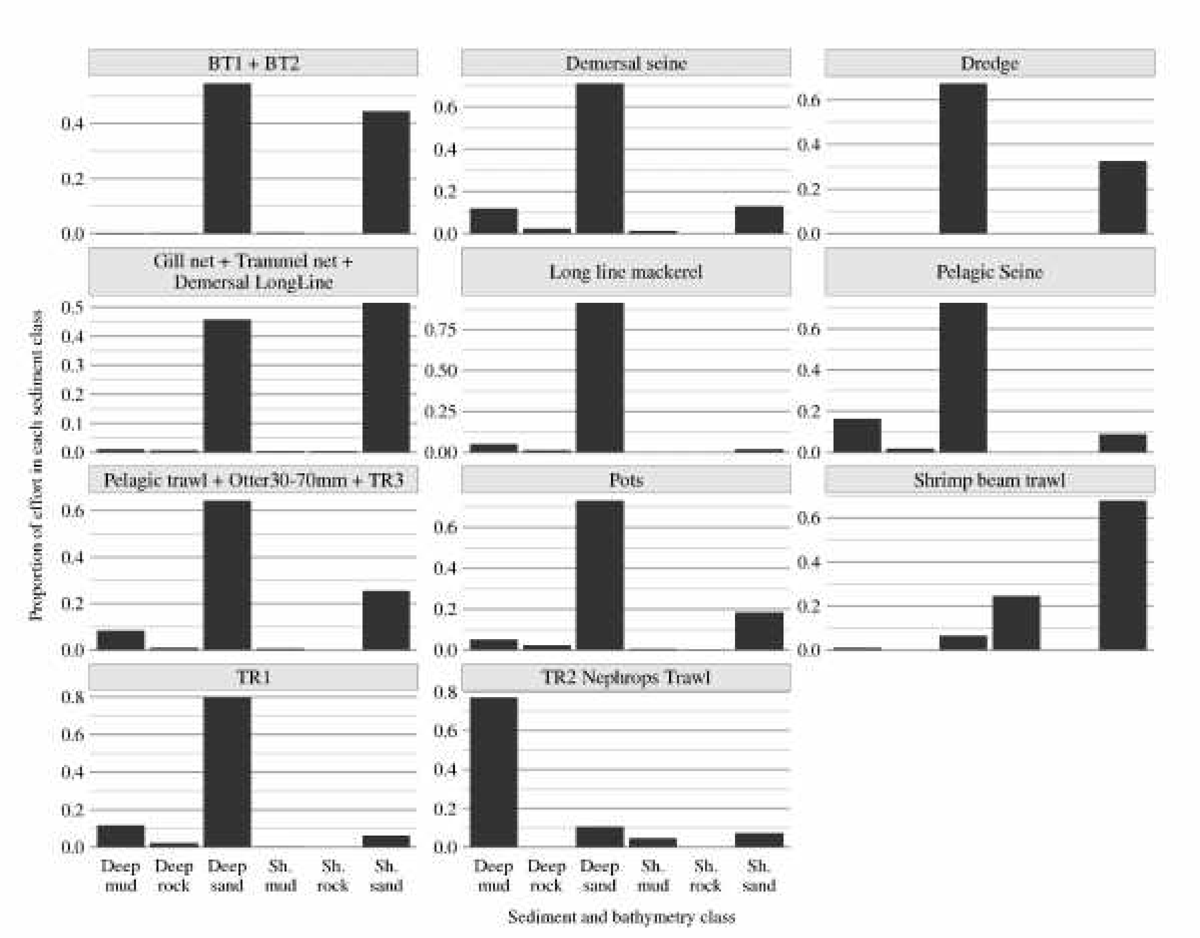

Figure 17. *Distribution of activity in the North Sea by sediment class (2003-2013).*

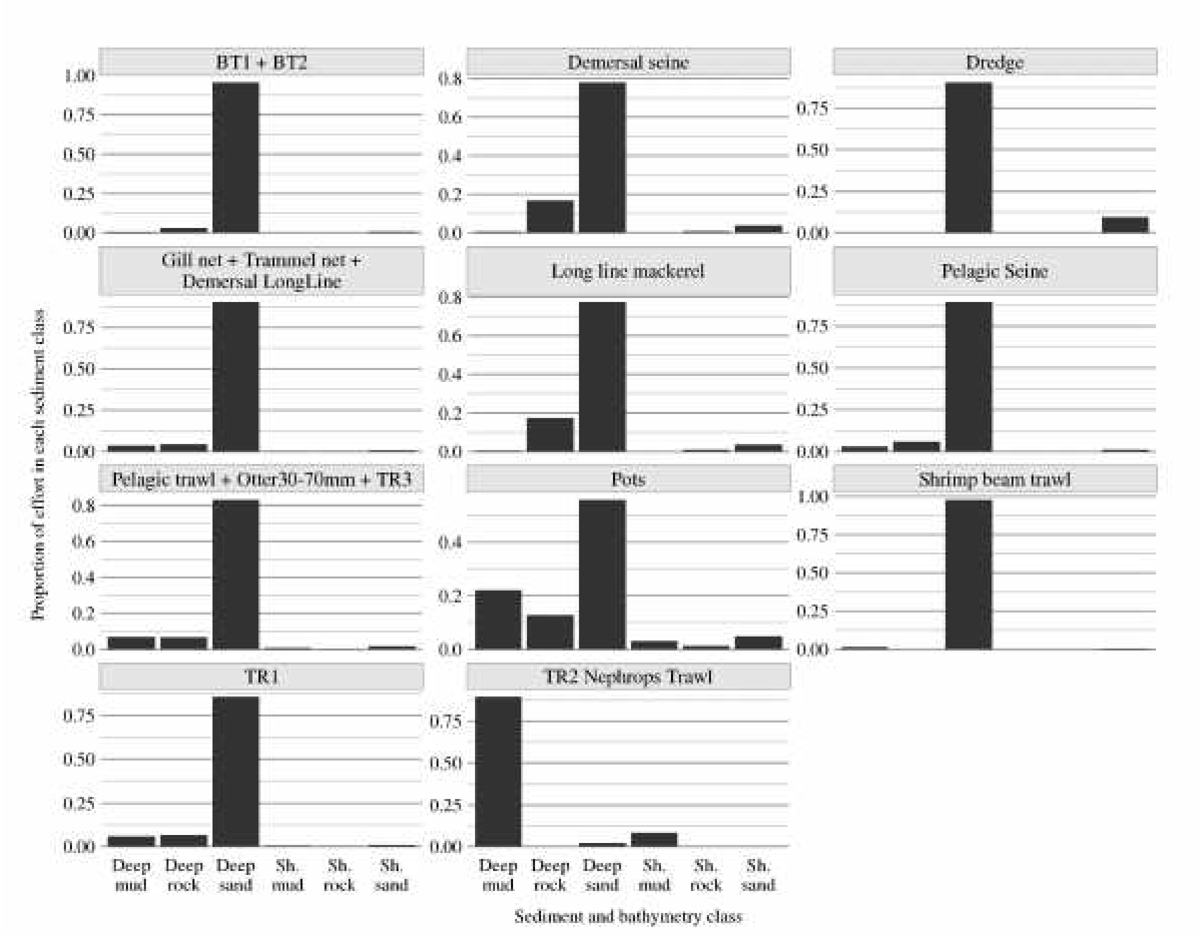

***Figure 18**. Distribution of activity in the west of Scotland by sediment class (2003-2013).*

Objective 2. Representation of direct effects of towed gear on benthos

Description: *"Mortality rates associated with physical damage to benthic fauna during the passage of a typical trawl have been summarised in the literature. In our case, we need to translate these into a mortality increment on the benthos categories in the StrathE2E model, based on the proportion of the regional seabed area which is swept by towed gear in a given time interval. We expect this increment to be gear specific, and depend also on the seabed sediment type."*

The methodology for including in the model a term for the mortality inflicted on benthos fauna which is fatally injured by the passage of a trawl gear but not caught, is described under Objective 1 (equation 25). Here, we needed to gather the evidence for assigning a value to the parameter ξ_j which represents the mortality per trawl pass per year.

Relevant empirical data have been summarised in the literature (Allen and Clarke 2007, Piet et al. 2000; Tables 13 and 14). The data are extremely variable and indicate a mortality rate of approximately 20% per trawl pass per year.

Table 13. *Estimated mortality rate (% of initial biomass in a trawl track) of benthic fauna on sandy and muddy sediments after an average of 1.5 trawl passes per year (from Piet et al.2000).*

Scientific name	Common name	Sand	Mud
Abra alba		39	39
Aphrodita aculeata	Sea mouse	38	38
Arctica islandica	Quahog	16	16
Astropecten irregularis	Burrowing starfish	45	22
Chamelea gallina	Striped venus >2 cm	7	40
Corystes cassivelaunus	Masked crab juvenile	63	63
Corystes cassivelaunus	Masked crab male	48	27
Corystes cassivelaunus	Masked crab female	22	26
Dosinia lupinus	Smooth artemis	44	44
Ensis spp.	Razor shells	13	3
Euspira catena	Large necklace shell	61	61
Gari fervensis	Sunset shell	81	81
Mactra corallina	Rayed-through shell	11	28
Ophiura texturata	Brittle star	6	6
Pelonaia corrugata		18	18
Phaxas pellucidus		15	38

Spisula solida	Thick-through shell	31	31
Spisula subtruncata	Cut-through shell	21	21
Thia scutellata	Thumb-nail crab	22	22
Turritella communis	Tower shell	14	14

***Table 14**. Mortality rates of benthos categories (% of initial abundance in a trawl track) for different trawl types and sediments (from Allen and Clarke 2007)*

Trawl type	Seabed type	Suspension feeders	Deposit feeders	Bacteria and meiofauna
Beam	Sand	73	23	67
Beam	Gravel	15	67	42
Otter	Mud	31	18	29
Otter	sand	4	23	15

Objective 3. Sensitivity analysis and scenario experiments.

Description: *"The aim of the sensitivity analysis will be to determine whether there are particular aspects of the towed gear impacts which have a disproportionately large effect on the ecosystem. This will enable us to advise on how gear may be designed or used to minimise its ecological footprint – for example if it turns out that the ploughing effect is the major factor causing impact, then we can recommend that gears be used in a semi-pelagic mode instead of being allowed to settle heavily on the seabed. Alternatively, it may turn out that the deposition of discards is actually the largest effect on the benthos, in which case we can conclude that the issue of trawling impacts is in fact tied up with that of implementing a landing obligation."*

In this section we describe five areas of work:

i) A stand-alone analysis of the equations used to represent sediment nutrient exchange and seabed ploughing in the StrathE2E model, to help understand what we expect to happen in the main model.

ii) Configuration of the new extended StrathE2E to represent the North Sea and its fisheries, and optimisation of the parameters to produce the best fit of the model to an extensive set of observed data.

iii) Identification of harvesting rates to be applied in a baseline model run, representing maximum sustainable yield (MSY) conditions for both pelagic and demersal fish in the North Sea.

iv) Sensitivity analysis of the North Sea model with respect to fishing gears, comparing scenario simulations with the baseline model results.

v) Repeating the sensitivity experiments for a west of Scotland version of the model.

Stand-alone analytical investigation of the effects of ploughing on sediments

We analysed, in isolation, the equations developed to represent sediment disturbance in the extended StrathE2E model (see Objective 1), in order to demonstrate how ploughing affects different types of sediments.

The basic equations developed for the rate of change of nutrient in pore-waters (n) and the overlying water column (N) of an isolated sediment-water system were (from equations 17 and 18):

$$dn/dt = q - u.n - (1 - \alpha).F - \alpha.n + \alpha.\varphi,\delta,N/\Delta \quad (37)$$

and in the water column by:

$$dN/dt = Q - U.N + (1 - \alpha).F + \alpha.n - \alpha.\varphi,\delta,N/\Delta \quad (38)$$

We can solve these equations analytically to get expressions for the steady-state mass of nutrient in the sediment (n*) and water column (N*):

$$n^* = (c2(q + Q) + qU) / (U(u - c3) + c2(u + c3)) \quad (39)$$

$$N^* = (Q - (c_3).n^*)/(U + c_2) \quad (40)$$

where $c_2 = (1/V).(H - \alpha(H - v))$; and $c_3 = (-H/v).(1 - \alpha) + \alpha$ (41)

The steady state pore water nutrient concentration n* depends on sediment properties (porosity and hydraulic conductivity), layer thicknesses, and the rate of trawling. We define n^*_R as the value of n* given α (proportion of seabed ploughed), *H* (hydraulic conductivity), *φ* (porosity), *δ* (thickness of the sediment layer), *and Δ* (thickness of the water column layer).

We calculated the steady-state values of nutrient concentrations n*/v and N*/V in the sediment pore water and water column respectively, for a range of values of hydraulic conductivity (H), porosity *φ,* and trawling rate (α). Results (Figure 19) show that for given values of production and consumption in the sediment and water column, the sediment nutrient concentration decreases with increasing hydraulic conductivity. This result is consistent with observations that concentrations are higher in fine grained muddy sediments than in coarse sands and gravels. Trawling disturbance decreased the concentration on the sediment pore waters. Increasing porosity decreased pore water concentrations, because v and *φ* are directly related.

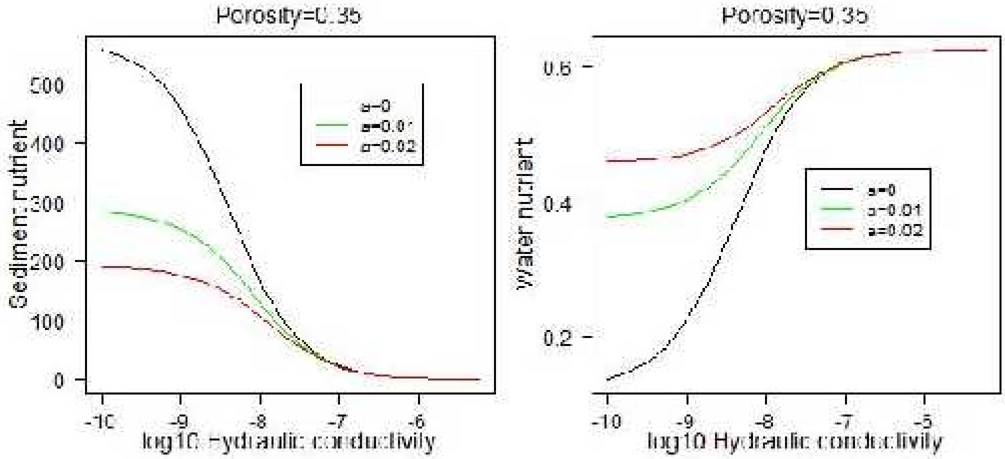

***Figure 19**. Analytical model results showing sediment porewater (left) and overlying water (right) steady state nutrient concentrations in relation to the hydraulic conductivity of sediments, for different levels of trawling disturbance. Black line shows the natural undisturbed sediment. Green and red lines show progressively increasing trawling activity (proportion of sediment area ploughed per day (a)). Low hydraulic conductivity (to the left of each diagram) corresponds to muddy sediments. High hydraulic conductivity corresponds to coarse-grained permeable sediments. Sediment porosity in each case set to 0.35.*

The conclusion of these analyses is that fine-grained muddy sediments (low hydraulic conductivity) are more sensitive to ploughing than coarse-grained permeable sediments. These simple analytical results will help to explain the results from our sensitivity analyses of the main StrathE2E model.

Configuration of the extended StrathE2E model for the North Sea and parameter optimisation

An extensive dataset of observed environmental conditions, fish stocks and landings in the North Sea during the period 1970-1999 was assembled by Heath (2012) as the basis for optimising the parameters of the StrathE2E model. A computational procedure (‘simulated annealing’) was developed to perform thousands of model runs and automatically search through the enormous range of possible combinations of parameters for the biological processes to find a combination that results in the model corresponding as best as possible to the observed data. During this procedure the model was driven by annual cycles of monthly data on ocean currents flowing into the North Sea and ocean nutrient concentrations, river nutrient discharges, water temperature and turbidity, sunlight intensities, and fishery harvest ratios corresponding to the same 1970-1999 period. As a result, we know that this ‘best fit’ parameter set provides the closest representation of the true dynamics of the whole North Sea ecosystem that the model is capable of achieving given its limitations and assumptions.

No new biological groups were included in the extended StrathE2E model, but the reconfiguration of sediment properties and depth layers, the inclusion of the ploughing process and natural disturbance of sediments, meant that we could expect the new model to require re-fitting to the observed dataset to ensure that it provides the best possible representation of reality.

In the configuration of the new extended StrathE2E model we defined 11 fishing gear fleets from the STECF data analysis. The spatial distribution of the international annual activity of each of these gears relative to the six seabed habitat types defined in the model was derived as an average for the years 2003-2013 (see Objective 1). For the fitting procedure, we assumed that these <u>relative</u> spatial distributions, and the <u>relative</u> importance of the different gears, applied also to the 1970-1999 fitting period, even if the total absolute level of effort was different. So, for example, we assumed that the TR2 trawl gear was always distributed in relation to seabed habitat in the same way, and made up the same proportion of the total fishing effort.

The fishing gear configurations which were used in the fitting model are shown in Figures 20-23. These relative distributions were scaled so that the overall harvesting rate on each of the model resource groups was as known for the 1970-1999 fitting period (Table 15)

Table 15. *Harvest ratios (proportion of biomass captured per day) for each of the model resource groups which apply in the North Sea during the model fitting period 1970-1999. These values were estimated from landings, discards, stock assessment and survey data by Heath (2012).*

StrathE2E group	**Daily harvest ratio d^{-1}**
Pelagic fish	0.00071
Demersal fish	0.00068
Carnivorous and scavenge feeding benthos	0.00000200
Filter and deposit feeding benthos	0.00000108

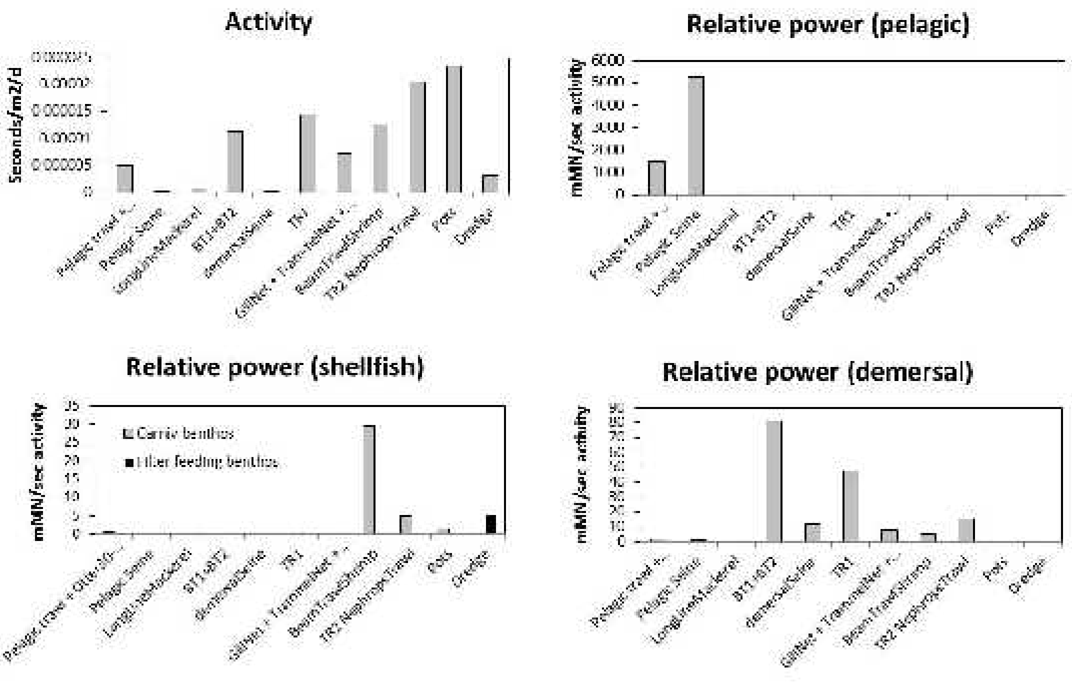

Figure 20. *Annual average international activity (seconds.m^{-2}.d^{-1}) of each of the 11 gear types in the North Sea (top left panel). Relative power of each gear type with respect to pelagic fish (top right), demersal fish (bottom right) and invertebrates (bottom left).*

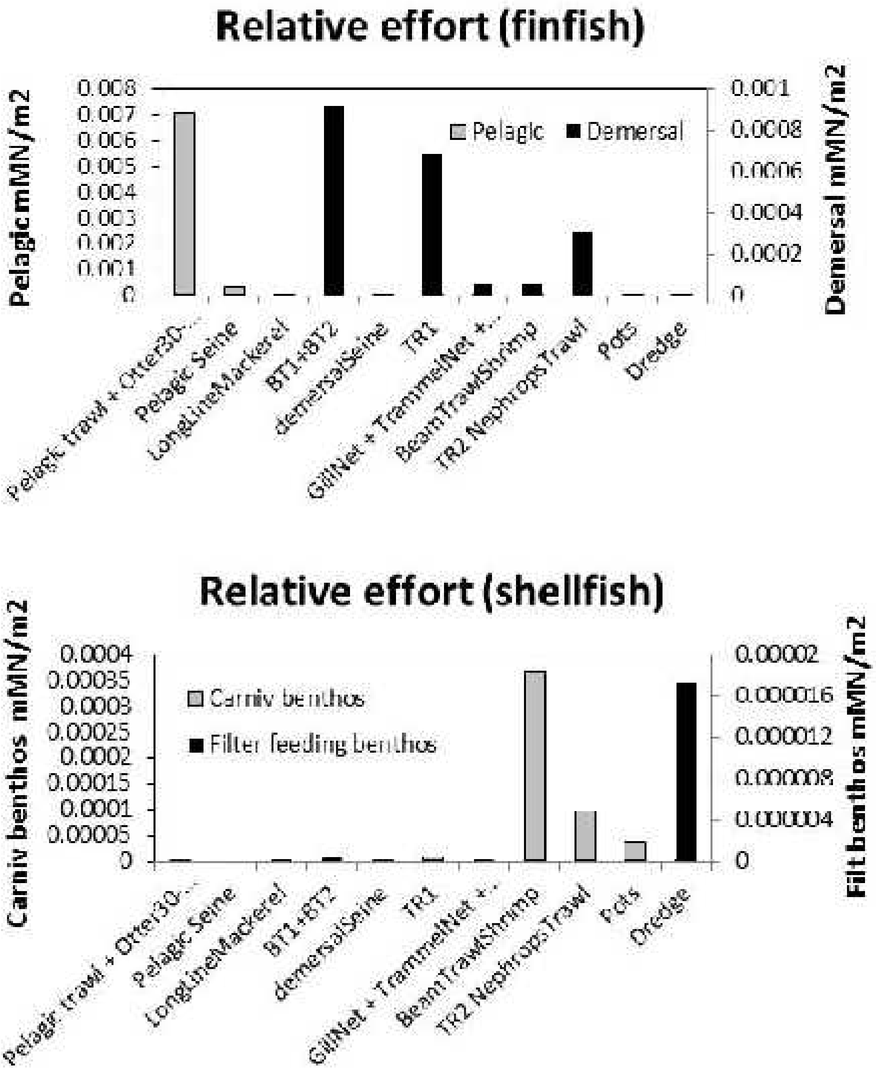

Figure 21. *International relative effort expended by each gear type in the North Sea, with respect to catching of pelagic and demersal fish, and invertebrates. Relative effort was the product of activity and relative power.*

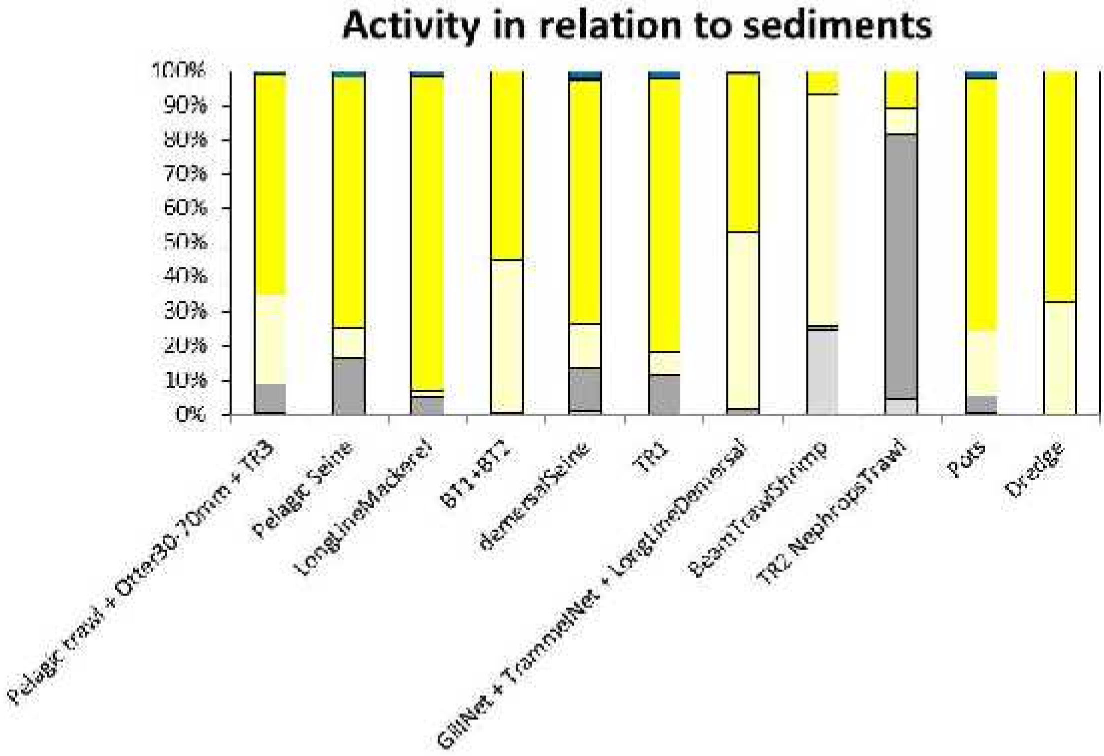

***Figure 22**. Distribution of international activity by each gear type with respect to seabed sediments in the North Sea (proportion of activity per sediment type). Pale grey – shallow muddy sediments; dark grey – deep muddy sediments; pale yellow – shallow permeable (sandy/coarse) sediments; dark yellow – deep permeable sediments. Shallow and deep rocky areas (blue) account for only a small proportion of activity by each gear.*

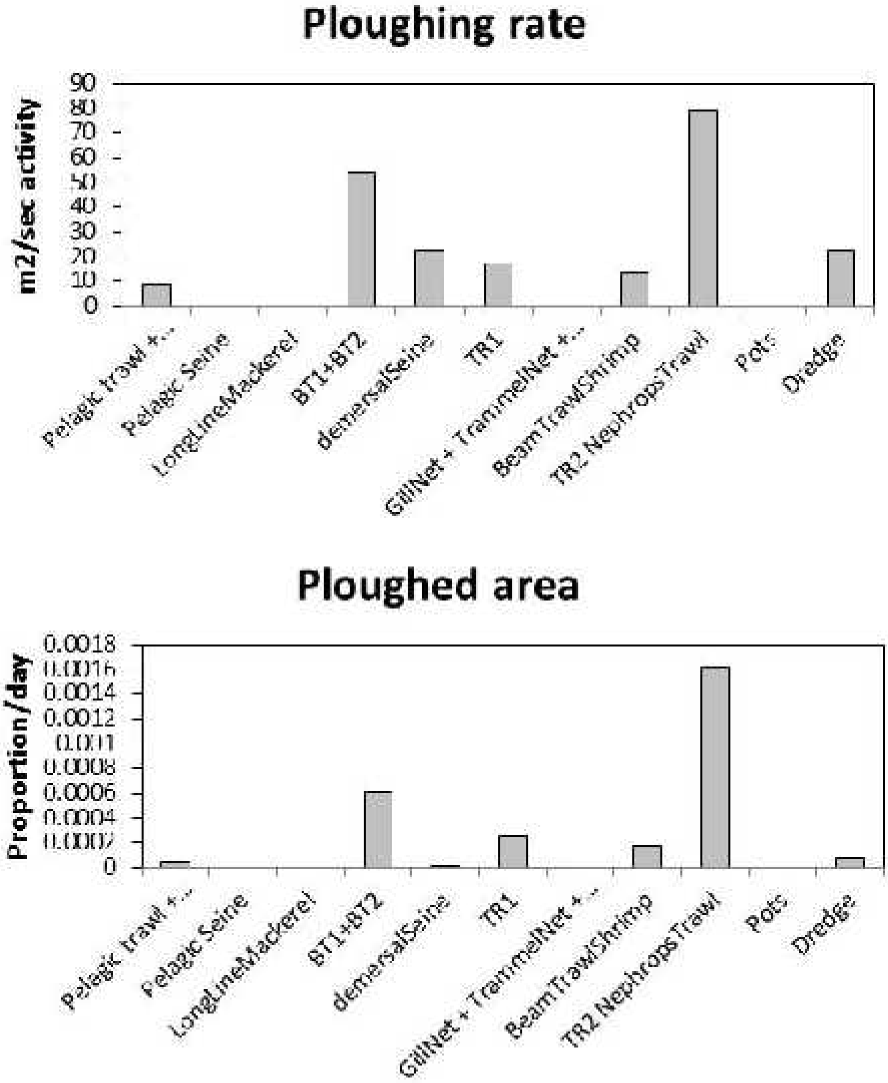

Figure 23. *Upper panel, ploughing rate (m2 of seabed ploughed per second of activity) by each gear type (from Eigaard et al. 2015). Lower panel, proportion of total North Sea seabed area ploughed per day by each gear (activity x ploughing rate).*

On completion of the computational fitting procedure, the best-fit model provided as good, or even slightly better account of the assembled observational data on the structure and fluxes in the North Sea ecosystem as the original simpler model, with a parameter probability given the observed data of 0.55. The best-fit model annual production and fluxes compared to the observed data are shown in Figure 24, and the monthly average concentrations of nutrients and plankton in Figure 25.

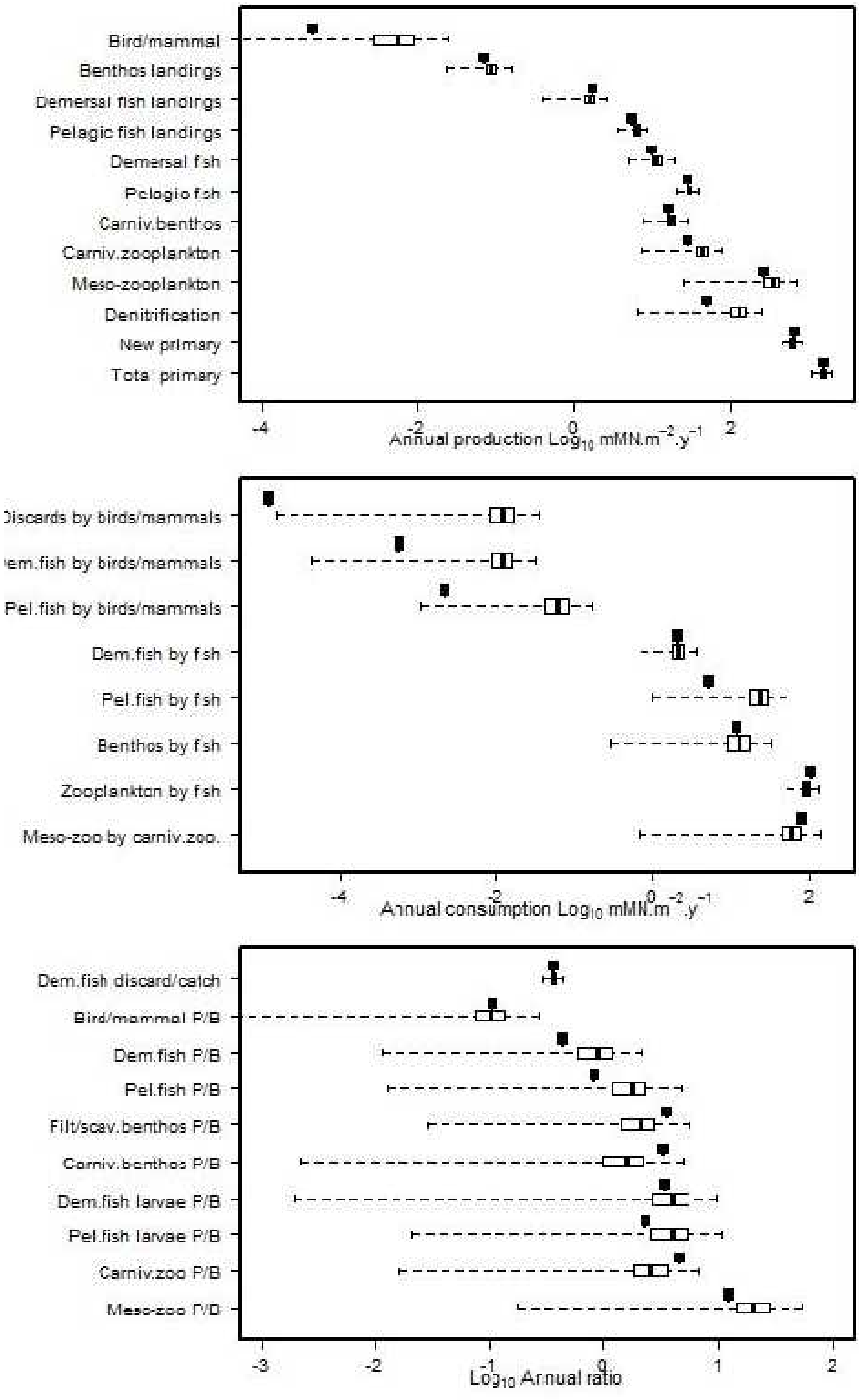

***Figure 24**. Comparison of the observed annual data set for the North Sea with the best-fit values generated by the StrathE2E model driven with environmental and fishing conditions for the corresponding period. Upper panel – annual production rates, middle panel – annual consumption rates of prey by predators, lower panel – annual production:biomass ratios and discard/catch ratio. The median and quartiles of the observed data are shown by the box-and-whisker plots. The corresponding best-fit model output is indicated by the square black symbol above each box-and-whisker.*

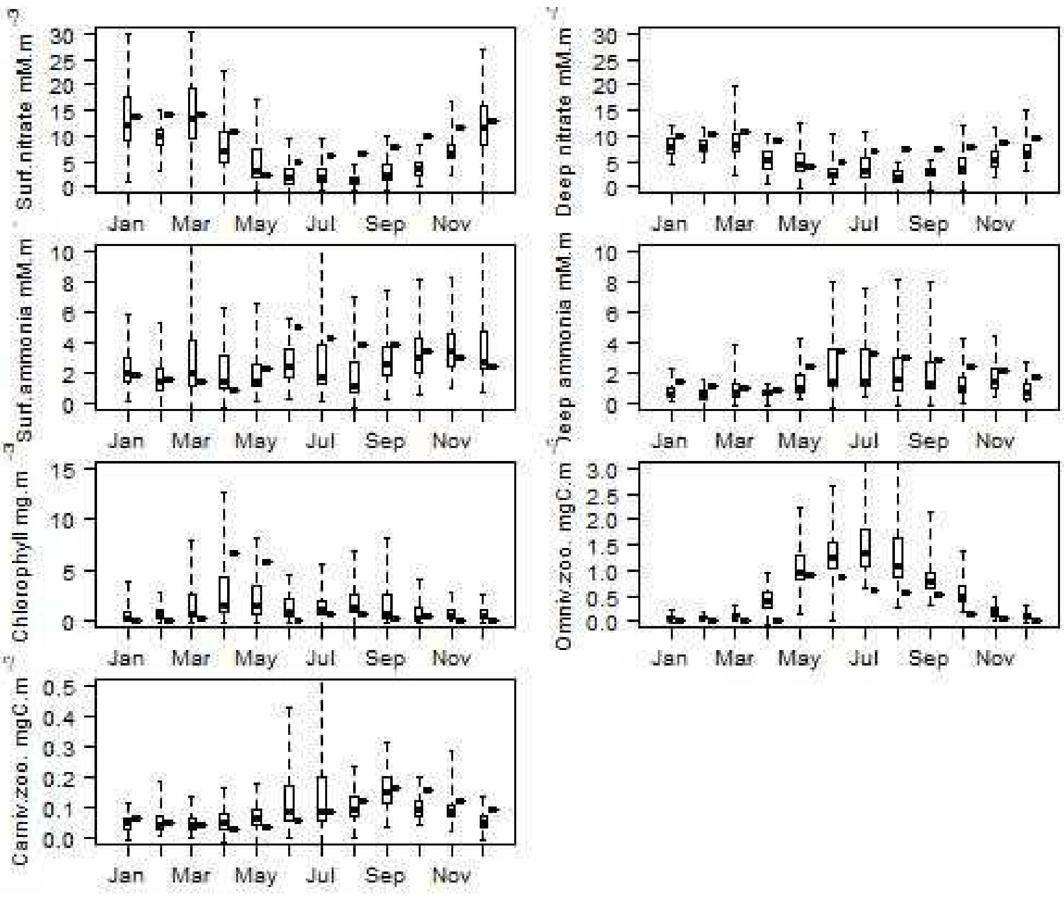

***Figure 25**. Comparison of the observed monthly data sets of nutrient and plankton concentrations for the North Sea with the best-fit values generated by the StrathE2E model driven with environmental and fishing conditions for the corresponding period. The median and quartiles of the observed data are shown by the box-and-whisker plots. The corresponding best-fit model output is indicated by the rectangular black symbol to the right of each box-and-whisker.*

Measuring the effects of trawling on the ecosystem – selection of a baseline model for comparison with scenario runs

The approach we adopt in this project is to simulate the states of the whole ecosystem under scenarios in which we adjust the activity or seabed-contact properties of different fishing gears, and compare these with some baseline state. Ideally, we would like to use the GES indicators which are specified in the EU Marine Strategy Directive to measure the impact of our fishing gear scenarios, since this is the key legislation under which human activities and their impacts will be judged.

Although the StrathE2E model explicitly spans the food web from microbes to birds and mammals, and includes a representation of nutrient cycling and biogeochemistry, it does so in a highly aggregated way in order to make the parameterization problem tractable. Hence, it can provide only condensed information on model components and certainly not at the level of individual species or small spatial sub-regions. Its utility for simulating GES indicators is therefore restricted to those which describe large scale, integrated measures of the health of the system. In addition, there remain a number of descriptors for which the model is completely inappropriate for providing advice. The descriptors on which the existing model could potentially advise are primarily Descriptor 3 (Commercial fish and shellfish), Descriptor 4 (Food webs), and Descriptor 5 (Eutrophication), though it is conceivable that the extended model developed as part of this project could provide advice on Descriptor 6 (seafloor integrity) (Table 16).

For some of the descriptors, specific indicators are well established (e.g. in relation to eutrophication). In other cases, the indicators are yet to be formally agreed and are under negotiation (especially in relation to food webs (Rogers et al. 2010)). Even where indicators are well defined, the ability of the model to precisely replicate the prescriptions for their derivation from field observations is limited. Hence we defined a series of model indicators, some of which map directly across to already defined GES indicators for the MSFD, and others which may be considered as prototypes for what may eventually become established indicators in the future (Table 17).

Table 16. *Applicability of the model to GES descriptors listed in the MSFD.*

Descriptor	**Highly informative**	**Moderately informative**	**Poorly informative**	**Uninformative**
D1. Biodiversity			X	
D2. Non indigenous species				X
D3. Commercial fish and shellfish	X			
D4. Food webs	X			
D5. Eutrophication		X		
D6. Sea floor integrity			X	
D7. Hydrographical conditions				X
D8. Contaminants				X
D9. Contaminants in seafood				X
D10. Marine litter				X
D11. Underwater noise				X

Table 17. *Indicators proposed for the GES descriptors D3 and D4, and corresponding indicators derived from model output.*

Descriptor	Objective	Criterion	Indicator	Reference	Comparable model indicator
D3. Commercial fish and shellfish	Maintain healthy stocks	Level of pressure of fishing activity	Average fishing mortality of stocks fished relative to the agreed reference level for fishing mortality (F/Fmsy)	Shephard et al.2014	Annual average harvest rates relative to the rates delivering MSY of both groups simultaneously in the 1970-1999 stationary model - separate indices for pelagic and demersal fish.
		Reproductive capacity of the stock	Proportion of stocks where spawning-stock biomass (SSB) is above critical (Blim) and precautionary (Bpa) reference points	Shephard et al.2014	Annual average adult biomasses relative to the biomass corresponding to 20% of MSY in the right-hand tail of the yield curve of the 1970-1999 stationary model – separate indices for pelagic and demersal fish.
D4. Food webs	Maintain energy pathways from plankton to higher trophic levels	Abundance of key trophic group	Ratios of biomass between feeding guilds (piscivorous and planktivorous)	Shephard et al.2014	Annual average biomasses of model trophic relative to their biomasses under MSY harvesting conditions in the 1970-1999 stationary model .
			Total pelagic fish biomass (t) across all age groups in a given stock	Shephard et al.2014	
		Foodweb function – Productivity of trophic guilds	Productivity (production/biomass) of key upper trophic level taxa	ICES Advice 2014, Book 11	Ratio of annual integrated gross production (food assimilated) to annual average biomass, for birds&mammals, demersal fish, pelagic fish, carnivorous zooplankton and carnivorous benthos.

Our chosen approach was to compare simulated annual average biomasses of each of the living components of the model and dissolved nutrients in scenario runs with values from a baseline model run representing harvesting at a rate providing maximum sustainable yields (MSY) for both pelagic and demersal fish.

To locate the harvesting rates corresponding to MSY we used the biological parameters estimated by the optimisation procedure, and systematically varied the activity rates of two groups of fishing gears by scaling their values between 0 and 3x the rates for the 1970-1999 fitting period, and re-ran the model. The two gear groups were defined as mainly pelagic gears (pelagic trawl, otter trawl 30-70mm mesh, and mackerel longlines), and the mainly demersal finfish gears (beam trawls BT1 & BT2, demersal seine, TR1 and the gill and trammel nets and demersal longlines). The mainly invertebrate gears (shrimp beam trawl, Nephrops trawl TR2, pots and dredges) were left un-scaled in these runs. In each case, the model was run for 100 years by which time it had reached a new stationary state.

The results from the 49 combinations of pelagic and demersal gear activity scaling showed a characteristic pattern of pelagic and demersal fish landings with respect to pelagic and demersal fish activity scaling (Figure 26). Considering pelagic fish landings, at any fixed value of demersal activity pelagic landings increased with pelagic activity to a peak value and then declined. The peak value represents the maximum sustainable yield (MSY) at the given level of demersal activity. MSY for pelagic fish increased with demersal fishing, because of the predator-prey interactions in the model – demersal fish are predators on pelagic fish, and vice versa (pelagic fish are predators on demersal fish larvae, and on the zooplankton that larvae feed on). Similarly, MSY for demersal fish increased with pelagic fish harvesting, i.e. as the abundance of pelagic fish in the ecosystem was depleted.

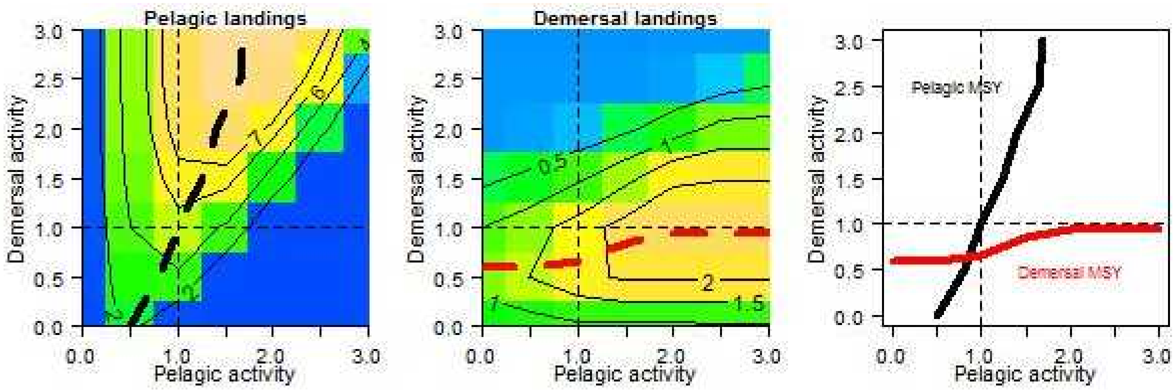

Figure 26. *Contour diagrams show modelled landings (mnN.m-2.y-1) of (left) pelagic fish and (centre) demersal fish in the North Sea model, in relation to scaling factors applied to activity levels of the groups of pelagic and demersal gears in the 1970-1999 fitting run model. So, values of 1 on the x and y axes indicate harvesting rates equal to the 1970-1999 values. The crest of the ridge in each contour map represents the MSY for each of the fish groups. The unique combination of harvesting rates satisfying the condition that both pelagic and demersal fish shall be exploited at MSY is met be the intersection of the dashed lines in the two left-hand panels, shown together in the right-hand panel.*

Clearly, the model indicates that there is no unique value of MSY for either pelagic or demersal fish. MSY for pelagic fish is conditional on demersal fishing and vice-versa. However, it is possible to specify a unique combination of pelagic and demersal activity which satisfies the condition that both groups shall be exploited at an MSY state. This combination is given by the intersection of the dashed lines shown in Figure 26. We refer to a model driven by pelagic and demersal fishing activity at these levels as the 'MSY model', and use it as the baseline against which to compare all of our scenario case runs for exploring the sensitivity of the ecosystem to gear properties and activity rates.

In passing, we note the results imply that the 1970-1999 harvesting rates used in the fitting model were in excess of MSY rates, for both pelagic and demersal fish, but especially for the latter. We estimated that the joint MSY state was achieved with pelagic and demersal activity rates at 90% and 64% respectively of their values in the 1970-1999 fitting model run.

<u>Scenario experiments with the North Sea model</u>

Our scenario experiments were designed to tease apart the individual effects of trawling on the ecosystem caused by:

- Capture of living biomass and removal from the ecosystem as landings.
- Capture of living biomass and its return to the ecosystem as discards.
- Ploughing of the seabed causing dispersion of sediment pore water nutrients and detritus into the water column.
- Ploughing of the seabed causing fatal injury to benthos fauna.

Definition of the experiments

In experiment 1, we re-run the baseline MSY model with the ploughing rate of all gears set to zero, and then with the ploughing rate for each gear individually set to zero. So this represents a hypothetical case where harvesting of fish, landing and discarding proceeds at the MSY rates, but the gears have no ploughing effect on the seabed and inflict no damage mortality on the benthos. We represented the results as a ratio for each group of biota and dissolved nutrient in the model, relative to its value in the MSY baseline run. The data were plotted as 'tornado sensitivity diagrams' with the groups ranked vertically in terms of their trophic level in the model (Figures 27 and 28).

In experiment 2, we repeated experiment 1 but with ploughing rates of each gear enabled and only the damage mortality parameter set to zero. So in this case we simulated a case in which harvesting and ploughing proceeded as under MSY conditions, but the gears inflicted no damage mortality. The results were almost indistinguishable from the baseline model so we do not show them here.

In experiment 3, activity and ploughing rates were as in the baseline MSY model, but the proportion of catches discarded by all gears was set to zero, so that all captured material was landed, including bycatches of benthos. The tornado diagram for this scenario is shown in Figures 27 and 28.

In experiment 4, ploughing rate, damage mortality and discarding rates were all as in the baseline model, but activity rates of each gear were reduced by an arbitrary 1% (Figures 27 and 28).

Results

Eliminating ploughing effects of all gears simultaneously increased sediment pore water ammonia concentrations as expected based on the stand-alone analytical model. This was also reflected in a slight increase in nitrate, phytoplankton, zooplankton and fish in the water column, and reductions in benthos and birds&mammals.

Eliminating discards had negative effects on all components of the model relative to the baseline state, but especially on the scavenging taxa (carnivorous benthos and birds&mammals). Note that in this scenario discard elimination is achieved by landing the entire catch, not by any changes in gear selectivity.

A 1% reduction across the board in the activity of all fishing gears has an effect which was similar in magnitude to the other experiments, but very different in emphasis in the food web. Fish and birds&mammals all showed increases in biomass relative to the baseline, whilst the scale of impact was rapidly attenuated with decreasing trophic level towards phytoplankton and nutrients in a classic 'top-down' trophic cascade.

Considering the response to removal of ploughing and reductions in activity of individual gears independently, we find very different responses between gears. Ploughing effects of the pelagic gears are extremely minimal, so there was no discernible effect of eliminating their ploughing rate. Reducing their activity by 1% caused a noticeable increase in the abundance of pelagic fish and a small increase in birds&mammals, a reduction in demersal fish and carnivorous zooplankton, and an attenuated trophic cascade down towards phytoplankton and nutrients. The reduction in demersal fish abundance here was caused by increased predation on their larvae by the pelagic fish. On the other hand, 1% reductions in each of the main demersal gears caused an opposite cascade effect, with reductions in pelagic fish and birds&mammals caused by predation from an increased abundance of demersal fish. For the TR2 Nephrops Trawl fleet, the impact of setting their ploughing rate footprint to zero was substantial and equivalent in magnitude to 1% reductions in activity, with reductions in the abundance of benthos and birds&mammals.

The reason for the high sensitivity of the model ecosystem to the ploughing rate footprint of the TR2 gear (demersal trawls and seines with mesh 70-99mm mainly targeting Nephrops) was clear. The activity of this gear was highly concentrated in the muddy sediment areas where our stand-alone analytical model shows that nutrient fluxes are more sensitive to ploughing than in the more permeable coarser and sandy sediments. The STECF data analysis showed that around 1% of the area of deep muddy sediments is ploughed per day, mainly by the TR2 gear, compared to ~0.2% of the more permeable coarse and sandy sediments (Figure 29).

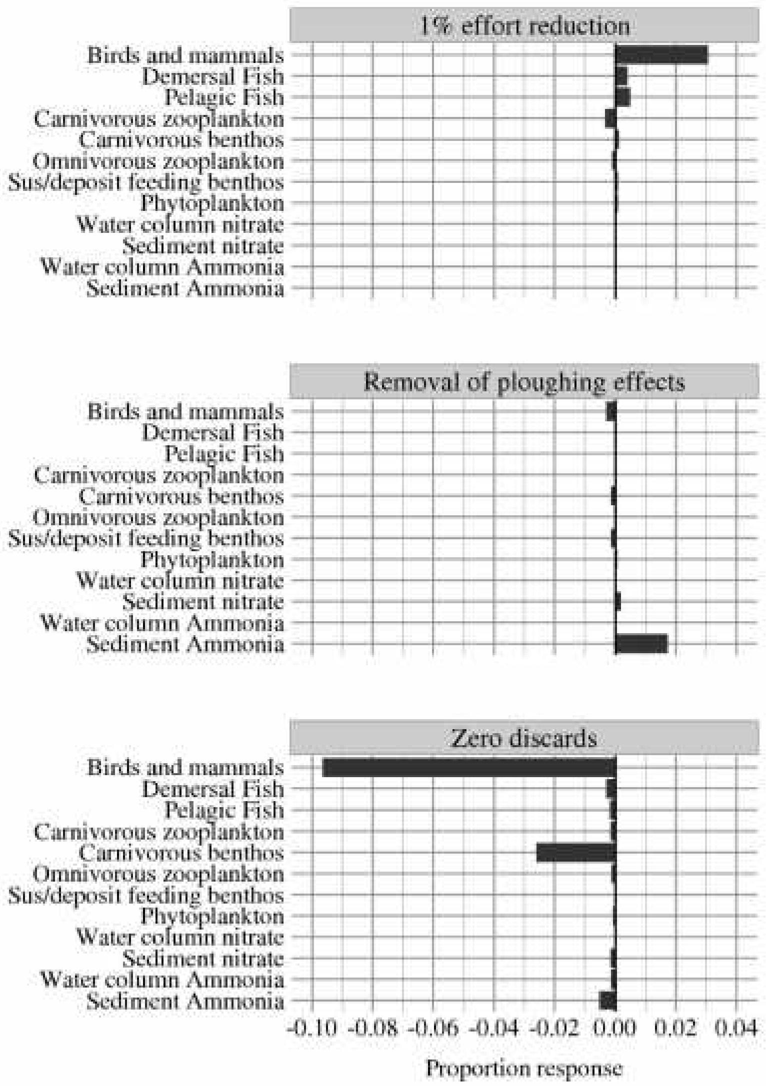

***Figure 27**. Tornado diagrams showing the effect on the modelled whole North Sea ecosystem of three different experiments in which the activity, ploughing, and discard rates were changed from the baseline MSY model. Length and direction of the bars shows the change in annual averaged abundance of a particular component of the ecosystem model from the baseline result of the MSY model. Upper panel, results of decreasing the activity rate of all gears in the model by 1% from the baseline rates. Middle panel, effect of reducing the ploughing rate of all fishing gears to zero but retaining their activity and hence harvest rates at MSY levels. Lower panel, effect of reducing the discarding rate of all fishing gears to zero, but retaining their activity and ploughing rates at baseline levels.*

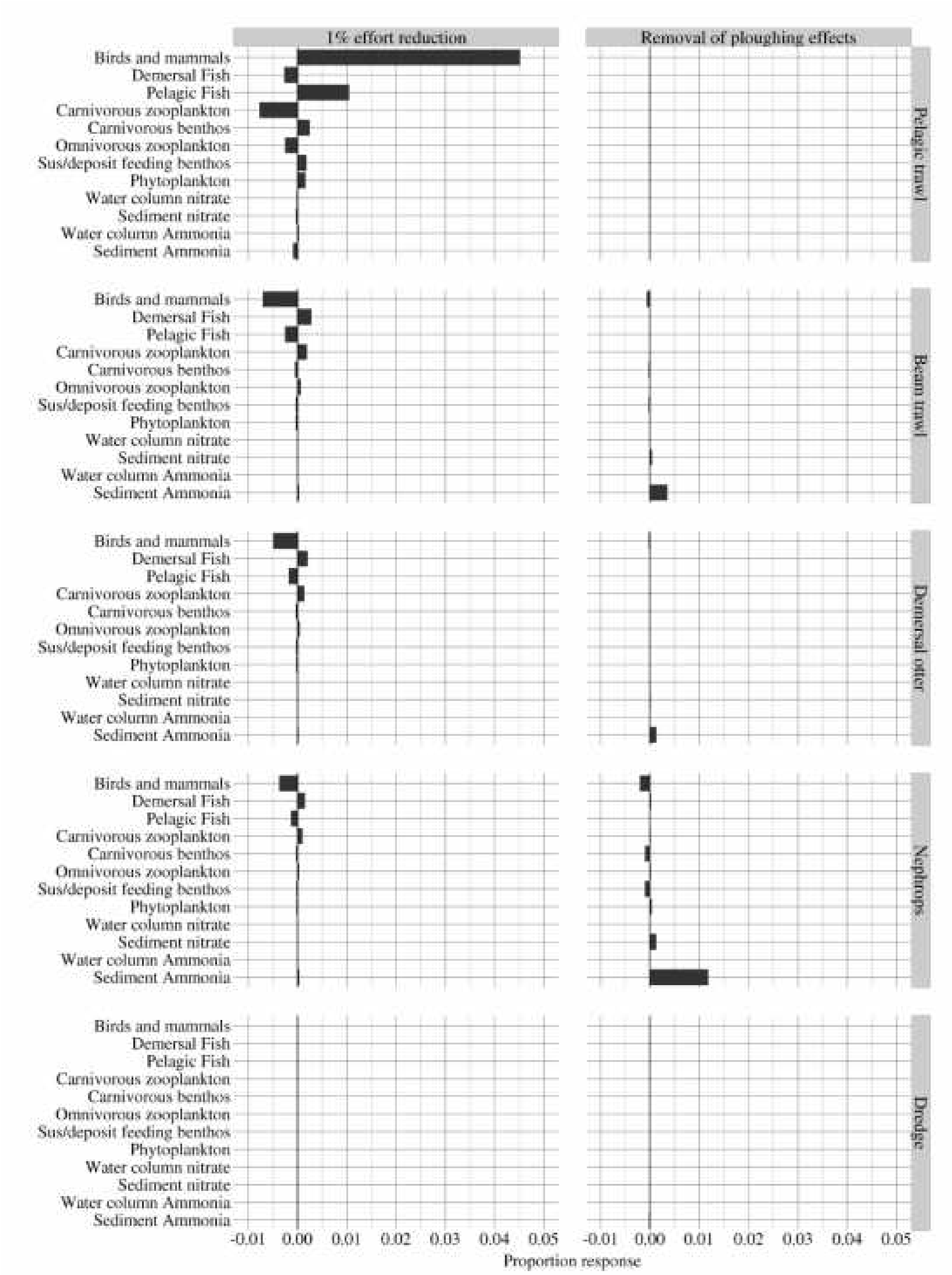

Figure 28. *Tornado diagrams showing the effect on the modelled whole North Sea ecosystem of either reducing the activity rate of a single gear (left column), or reducing the ploughing rate of a single gear to zero (right column) relative to the rates in the baseline model. Length and direction of the bars shows the change in annual averaged abundance of a particular component of the ecosystem model from the baseline result of the MSY model. Rows show results for different gears.*

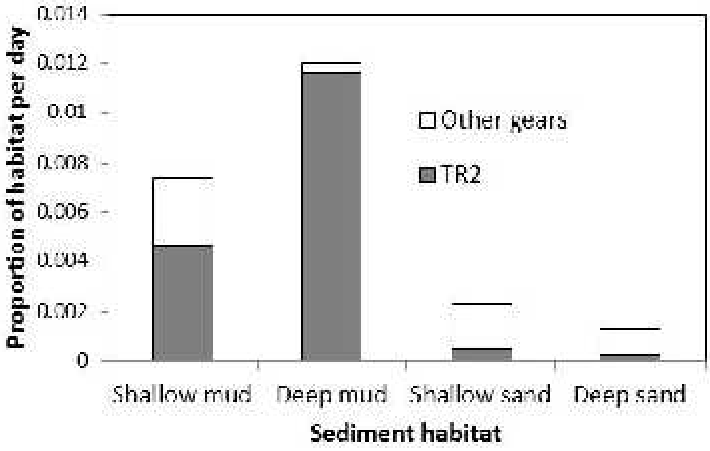

***Figure 29**. Area-proportion of sedimentary habitats ploughed by fishing gears in the North Sea. The TR2 gear represents the majority of ploughing in the muddy sediments.*

<u>Baseline model for the west of Scotland region</u>

Compilation of the STECF data analysis results for configuration of a west of Scotland version of the new StrathE2E model showed some very different patterns of fishing (Figures 30-34). The distribution of activity across the gear types was very different, and concentration of ploughing intensity in the muddy sediments was even more extreme than in the North Sea. Seabed ploughing was almost entirely dominated by the TR2 gear. Nevertheless, the overall level of ploughing was lower than in the North Sea.

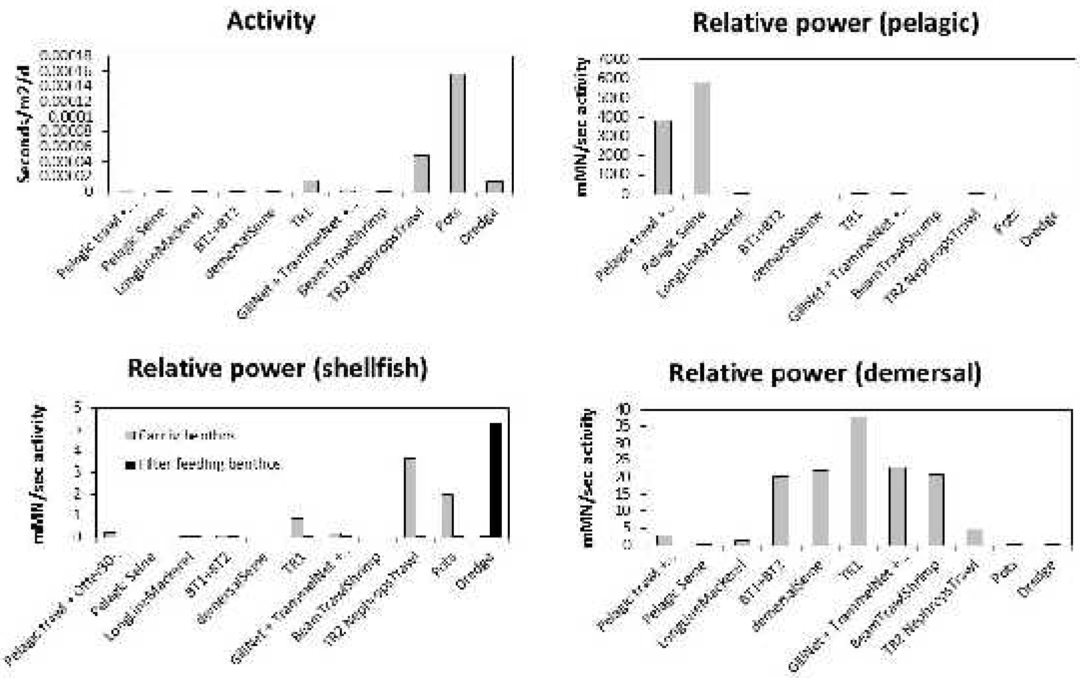

***Figure 30**. Annual average international activity (seconds.m^{-2}.d^{-1}) of each of the 11 gear types in the west of Scotland (top left panel). Relative power of each gear type with respect to pelagic fish (top right), demersal fish (bottom right) and invertebrates (bottom left).*

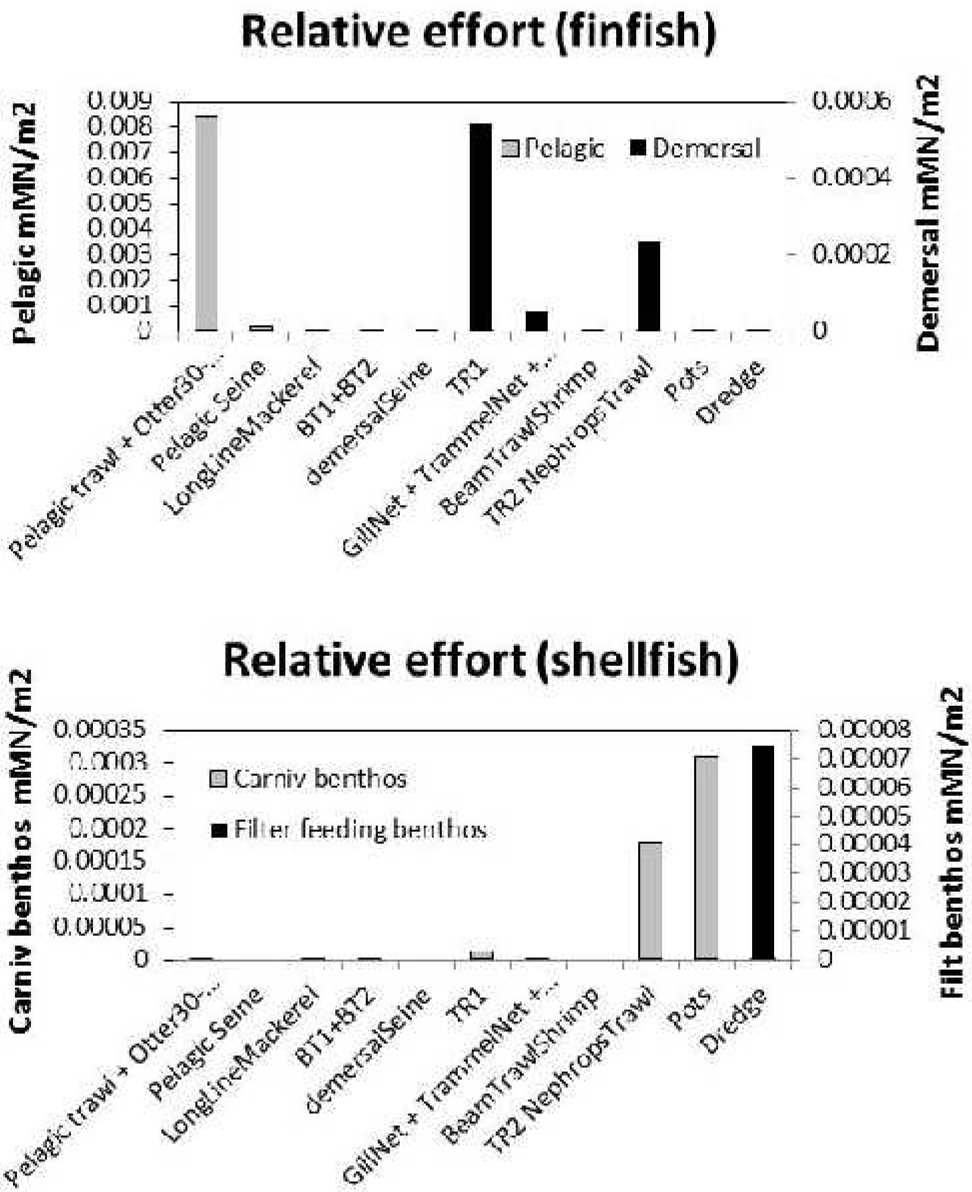

Figure 31. *International relative effort expended by each gear type in the west of Scotland, with respect to catching of pelagic and demersal fish, and invertebrates. Relative effort was the product of activity and relative power.*

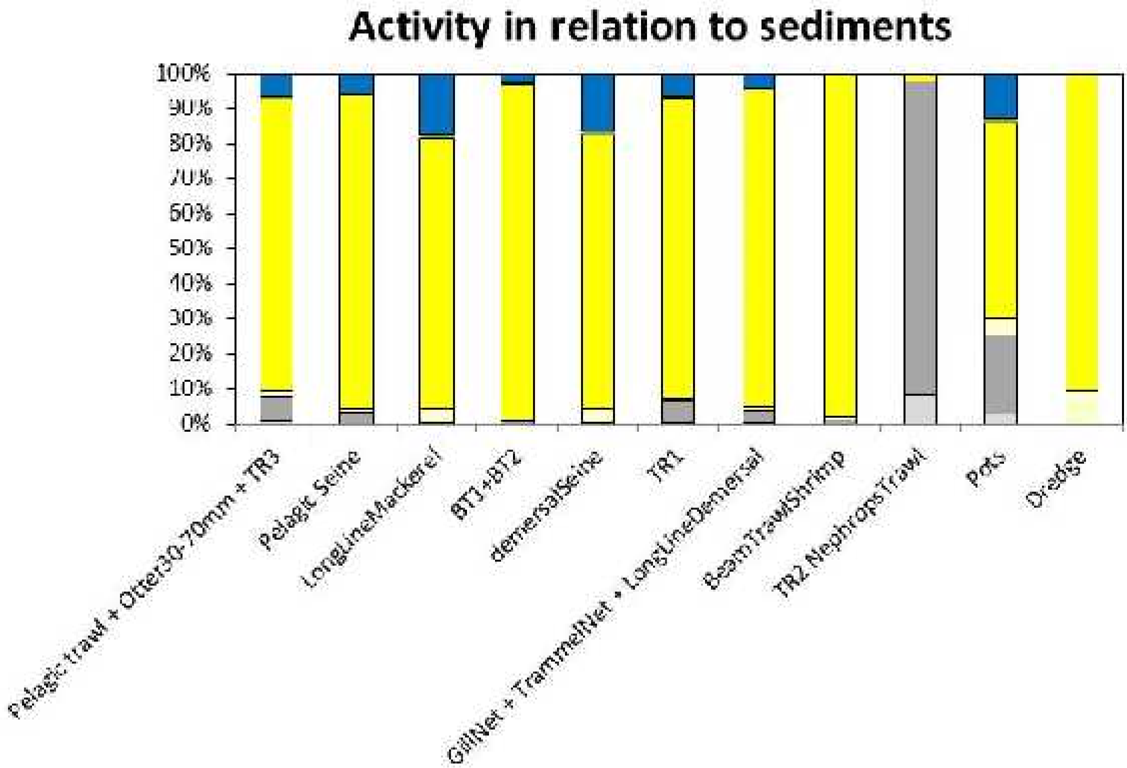

***Figure 32**. Distribution of international activity by each gear type with respect to seabed sediments in the west of Scotland (proportion of activity per sediment type). Pale grey – shallow muddy sediments; dark grey – deep muddy sediments; pale yellow – shallow permeable (sandy/coarse) sediments; dark yellow – deep permeable sediments. Shallow and deep rocky areas (blue) account for only a small proportion of activity by each gear.*

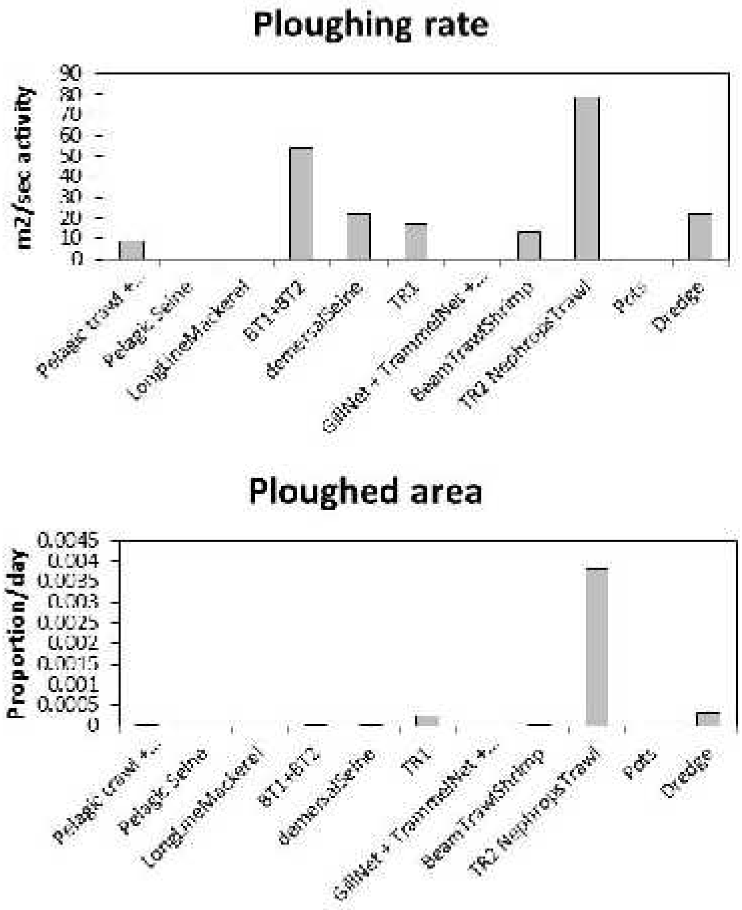

Figure 33. *Upper panel, ploughing rate (m2 of seabed ploughed per second of activity) by each gear type (from Eigaard et al. 2015). Lower panel, proportion of total west of Scotland seabed area ploughed per day by each gear (activity x ploughing rate).*

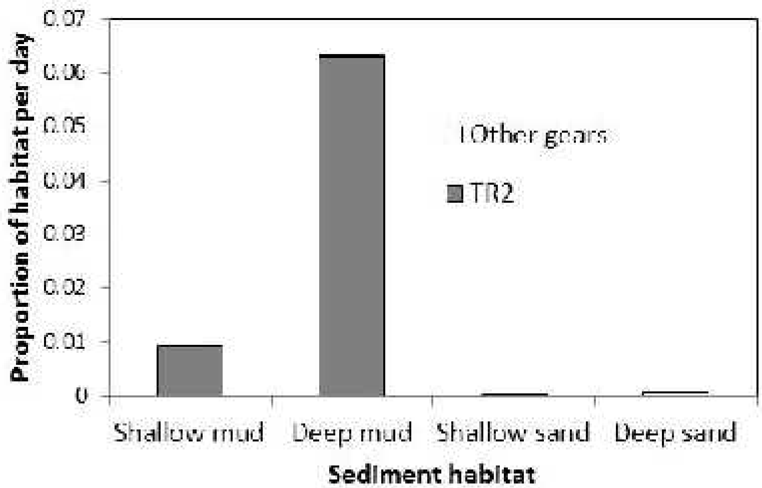

Figure 34*. Area-proportion of sedimentary habitats ploughed by fishing gears in the west of Scotland. The TR2 gear represents the majority of ploughing in the muddy sediments.*

Oceanographic, river and atmospheric nutrient input and volume exchange rate data, temperature and turbidity data for driving a west of Scotland version of the model were available from a recently complete EU FP7 project (European Basin-scale Analysis, Synthesis and Integration (EURO-BASIN, Project no. 246:933; Heath et al. 2015).

We do not yet have an assembled data set of observed conditions for the west of Scotland ecosystem to which we can fit the model. Hence, we used the biological parameters for the North Sea model without any adjustment, and the fishing gear activity patterns resulting from the analysis of the STECF database. We ran the west of Scotland model for the 7 x 7 combinations of pelagic and demersal activity scaling factors to identify the combination producing the joint MSY for both pelagic and demersal fish. Joint MSY for the west of Scotland region was found to be at 0.9-times the 1970-1999 activity rate for pelagic gears, and 1.86-times the activity rate for demersal gears (Figure 35). These scaling factors define our baseline model for scenario experiments using the west of Scotland model.

The scaling factors for the MSY state imply that the west of Scotland has a higher capacity to support demersal fisheries than the North Sea, and approximately similar for pelagics. The interaction between pelagic and demersal fish in the west of Scotland model was noticeable stronger than in the North Sea – relaxation of demersal harvesting so that demersal fish increased, significantly inhibited the yield and biomass of pelagic fish.

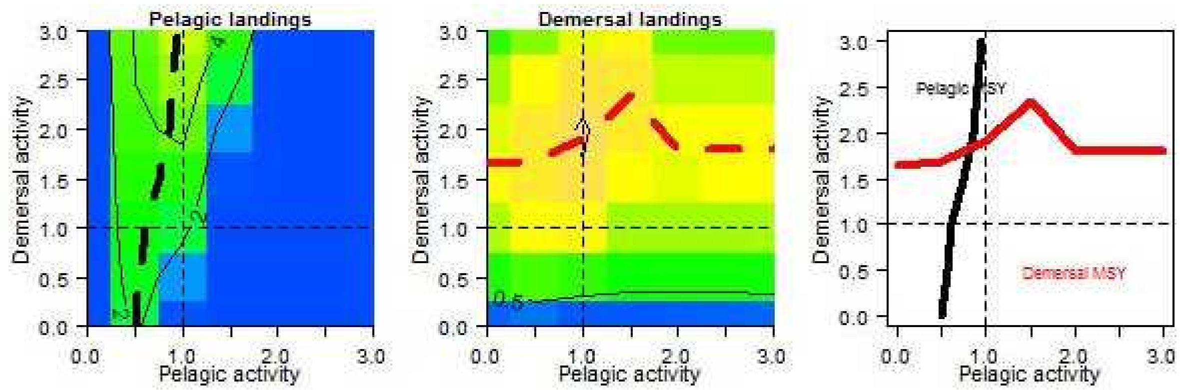

Figure 35. *Contour diagrams show modelled landings (mnN.m^{-2}.y^{-1}) of (left) pelagic fish and (centre) demersal fish in the west of Scotland model, in relation to scaling factors applied to activity levels of the groups of pelagic and demersal gears. So, values of 1 on the x and y axes indicate activity rates equal to 1970-1999 values. The crest of the ridge in each contour map represents the MSY for each of the fish groups. The unique combination of harvesting rates satisfying the condition that both pelagic and demersal fish shall be exploited at MSY is met be the intersection of the dashed lines in the two left-hand panels, shown together in the right-hand panel.*

<u>Scenario experiments with the west of Scotland version of the model</u>

As for the North Sea model, eliminating ploughing effects of all gears simultaneously increased sediment pore water ammonia concentrations in the west of Scotland case, and had a negative effect on carnivorous benthos and birds&mammals. Similarly, these two living groups in the west of Scotland model were affected by an elimination of discarding (Figure 36). The ploughing effects in the west of Scotland region were mainly due to the activities of the TR2 trawls (Figure 37).

As in the North Sea, a 1% reduction across the board in the activity of all fishing gears has an effect which was similar in magnitiude to the other experiments, but very different in emphasis with in the food web (Figure 36). Fish and birds&mammals all showed increases in biomass relative to the baseline, whilst the scale of impact was rapidly attenuated with decreasing trophic level towards phytoplankton and nutrients in a classic ‘top-down’ trophic cascade. The effects of activity reduction in the model were mainly due to the changes in pelagic trawls and demersal otter trawl activity (Figure 37).

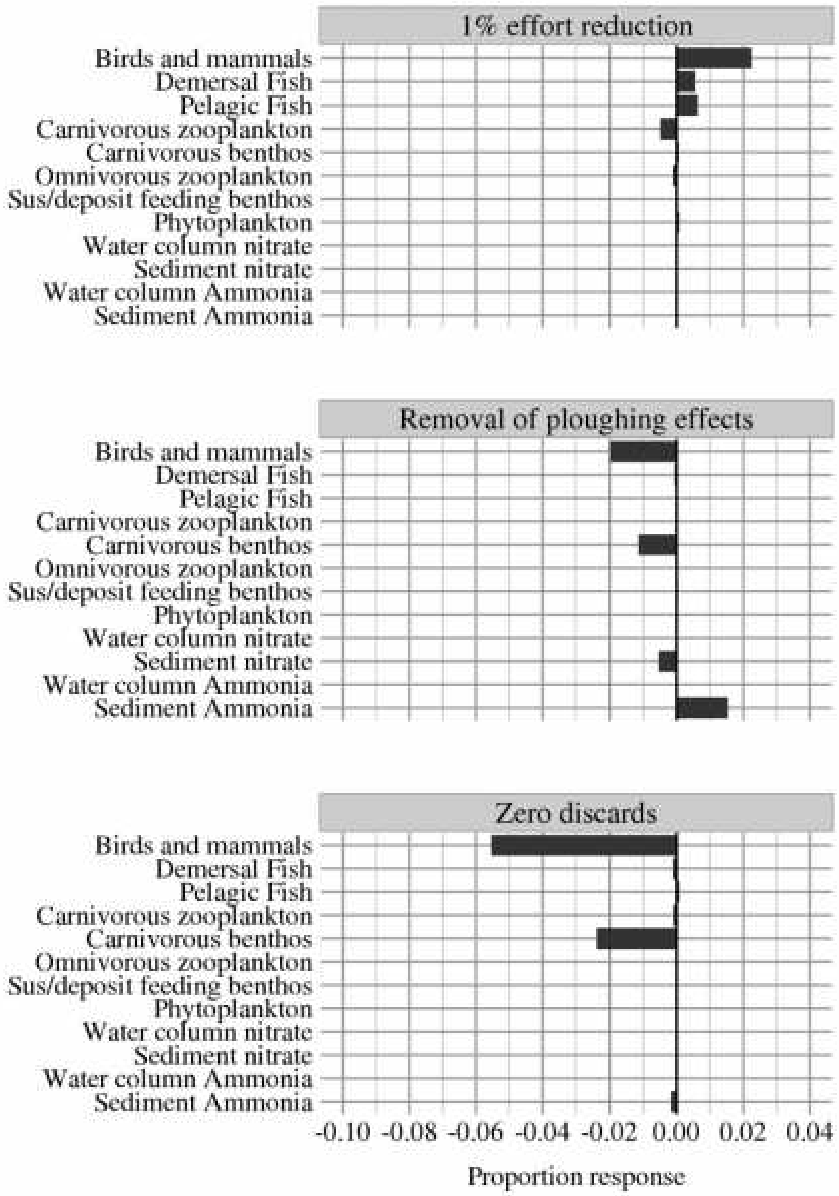

Figure 36*. Tornado diagrams showing the effect on the modelled whole West of Scotland ecosystem of three different experiments in which the activity, ploughing, and discard rates were changed from the baseline MSY model. Length and direction of the bars shows the change in annual averaged abundance of a particular component of the ecosystem model from the baseline result of the MSY model. Upper panel, results of decreasing the activity rate of all gears in the model by 1% from the baseline rates. Middle panel, effect of reducing the ploughing rate of all fishing gears to zero but retaining their activity and hence harvest rates at MSY levels. Lower panel, effect of reducing the discarding rate of all fishing gears to zero, but retaining their activity and ploughing rates at baseline levels.*

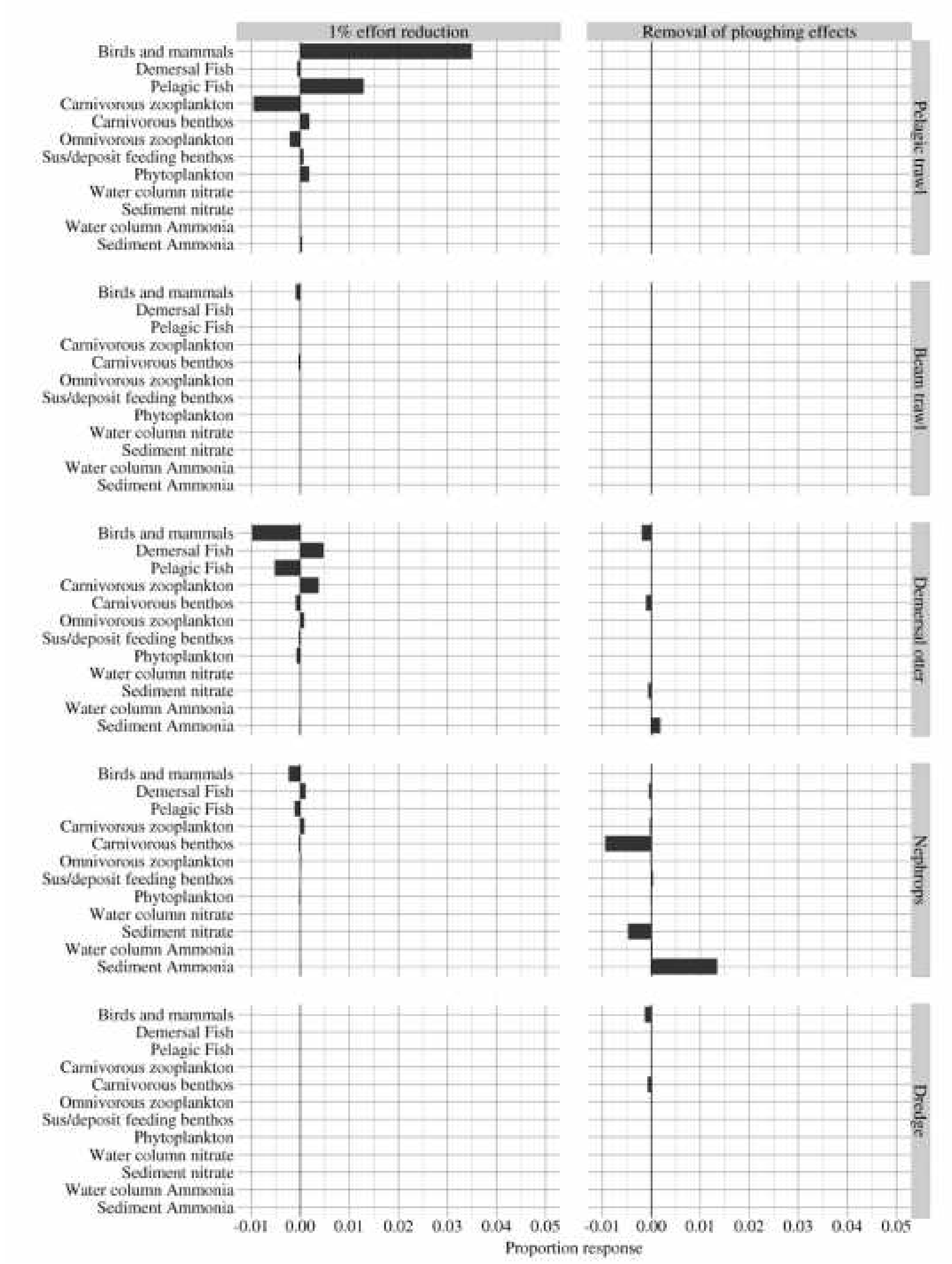

Figure 37. *Tornado diagrams showing the effect on the modelled whole West of Scotland ecosystem of either reducing the activity rate of a single gear (left column), or reducing the ploughing rate of a single gear to zero (right column) relative to the rates in the baseline model. Length and direction of the bars shows the change in annual averaged abundance of a particular component of the ecosystem model from the baseline result of the MSY model. Rows show results for different gears.*

Comparison of ecosystem responses in the North Sea and West of Scotland

Comparing the magnitudes of the ecosystem responses to the sets of experiments carried out on the North Sea and west of Scotland models (Figure 38), it is apparent that the two regions show very similar sensitivity to a 1% reduction in overall activity. However, the west of Scotland model was noticeably more sensitive to the removal of ploughing effects, and slightly less sensitive to the elimination of discarding. In the case of sensitivity to ploughing effects, this arises because the trawling disturbance rate of muddy sediments is around 5-times greater in the west of Scotland region than in the North Sea, almost entirely due to TR2 trawling activity (Figures 29 and 34).

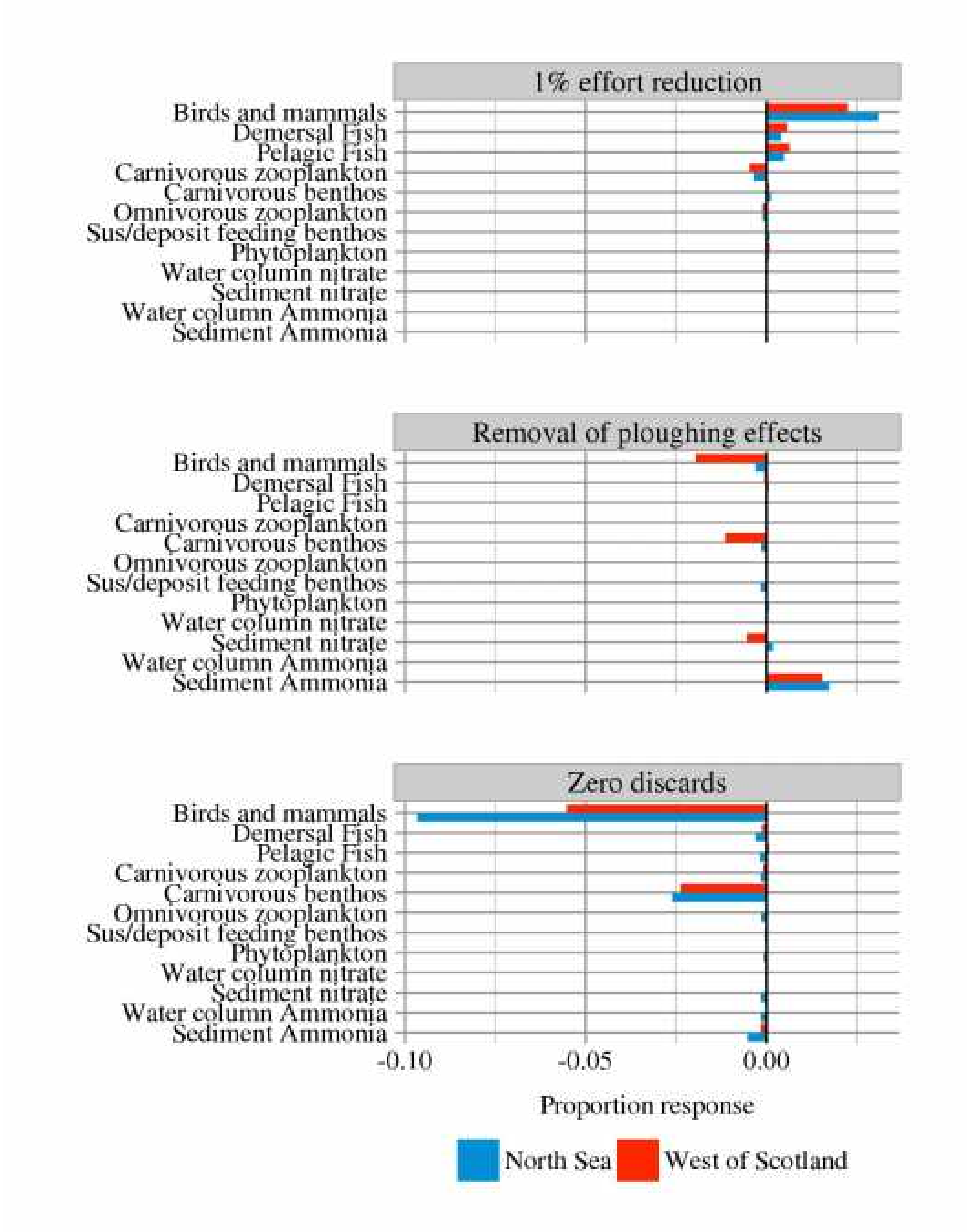

Figure 38. *Tornado diagrams comparing the effect on the modelled whole North Sea and West of Scotland ecosystems of three different experiments in which the activity, ploughing, and discard rates were changed from the baseline MSY models for each region, combining data from Figures 27 and 36. Length and direction of the bars shows the change in annual averaged abundance of a particular component of the ecosystem model from the baseline result of the MSY model. Upper panel, results of decreasing the activity rate of all gears in the model by 1% from the baseline rates. Middle panel, effect of reducing the ploughing rate of all fishing gears to zero but retaining their activity and hence harvest rates at MSY levels. Lower panel, effect of reducing the discarding rate of all fishing gears to zero, but retaining their activity and ploughing rates at baseline levels.*

Objective 4. Reporting and Knowledge Exchange

Description: "*The final month of the project will be devoted to finalising the report on the project and communicating the outputs to industry and policy stakeholders. We aim to achieve knowledge exchange goals in short workshops which we will arrange in the final month of the project."*

As planned the writing of this report has been undertaken in the final month of the project. However, we have not been able to undertake the output communication and knowledge exchange workshops, since the overall project duration was too short to have made sufficient progress ahead of organising a workshop.

As a substitute for not achieving this objective, which in hindsight was probably unattainable, we have committed to presenting the work as an oral presentation in a plenary session of the MASTS Annual Science Meeting on 1st October. We will also try to convene a workshop late in 2015 inviting Marine Scotland, FIS board and industry representatives, to present our results and encourage a discussion with the other funded FIS project on the physical impacts of fishing gears on the seabed.

Discussion

The main conclusion from the study is that whilst ploughing of the seabed by fishing gears certainly has an effect on the whole ecosystem, it remains small compared to the whole ecosystem effects of removing the targeted fish and shellfish biomass. Eliminating all seabed ploughing would be roughly equivalent to a 1% change in harvesting rates. However, this is absolutely not to deny that the effects of seabed ploughing are negligible at the local scale, where damage to fragile habitat and sensitive species can obviously be devastating.

Compared to ploughing, the effects of eradicating all discarding whilst continuing to fish at baseline rates would be smaller overall though concentrated on the scavenging taxa in the system (benthos and birds&mammals). Note however, that in this experiment discarding was eliminated by simply landing the entire catch and continuing to harvest at the same rate as the baseline model. The alternative of eliminating discards by proposing that gears become more selective so as to only capture targeted sizes and species, would be equivalent to a very substantial decrease in the power of individual gears. Elsewhere, using the original StrathE2E model, we have shown that eliminating demersal fish discards by a simulated improvement in selectivity would require the effective harvest ratio (or fishing power) to be reduced to around half of the baseline rate (Heath et al. 2014). This represents a huge change compared to the very small (1%) variation from baseline which we applied in the sensitivity analysis for this project. Hence, viewing the impacts of trawling in the context of the landing obligation, the changes in selectivity (effectively, fishing power) of gears that would be required to eradicate discarding by maintaining landings but never catching unwanted fish, would have very much greater (and beneficial) impacts on the regional ecosystem, than eliminating ploughing effects in their entirety. This is a really important conclusion from our study.

The key effect of ploughing is to mine the nutrients and organic matter stored in sediments and distribute it into the water column. Other investigators have concluded that this leads to an enhancement of phytoplankton production and stimulation of the food web – see especially Dounas et al. (2007). Our study shows that although ploughing certainly leads to large changes in the nutrient stored in sediments, the effect on primary production is not so clear. There are two main reasons for this difference of outcome. First is that previous modelling studies of the ploughing effect of trawling have been partial in that the models concerned did not span the entire ecosystem. So, they did not include the effects of harvesting on the targeted fish and shellfish in the system which act as predators directly or indirectly on the fauna which are directly impacted by ploughing. Secondly, the study by Dounas et al. (2007) was carried out in the eastern Mediterranean where nutrients are extremely limiting in the water column (oligotrophic) so that even small additional fluxes from the sediment might be expected to have a stimulating effect. In the North Sea, by comparison, nutrients are never in such limited supply so additional fluxes would not be expected to have such a strong effect.

Our study identifies the TR2 gear as being responsible for the majority of ploughing impacts on the ecosystem in both the North Sea and west of Scotland regions. This is because the gear has a high activity and ploughing rate, mainly targeted on catching Nephrops, and is therefore concentrated in muddy sediments. The effect of ploughing was stronger in the west of Scotland model than for the North Sea since the STECF data indicate that the disturbance rate of muddy areas is around 5-times higher in the west, almost entirely due to TR2 activity. Muddy sediments have low permeability and high porosity and hence represent a large nutrient store compared with sandy and coarser sediments. Ploughing of muddy sediments releases larger quantities of nutrient into the water column than the equivalent ploughing rate on sandy or coarse sediments. This explains why dredging activity targeting scallops, which was explicitly included in the model, does not appear as having a significant effect on the whole ecosystem. Again, this is not to deny any effects that dredging may have locally on the integrity of the seabed.

Modelling caveats

Mathematical modelling of marine ecosystem dynamics requires difficult assumptions and trade-offs between detail and utility. Highly detailed, computationally intensive models are usually impractical for statistical fitting to observed data, and therefore lack utility. On the other hand, models which are sufficiently computationally lightweight to enable statistical fitting and provide the confidence that accrues from this, often lack the detail expected by environmental and resource managers. The StrathE2E model is closest to the latter condition, and includes some ‘bold’ assumptions in the interests of utility. In general, these should not have a major impact on perceptions of the gross patterns of nutrient flux through the ecosystem, but may affect the detail of some of the responses to scenario experiments.

The principal simplification in the model involves the grouping of all living marine organisms into a few aggregated categories. This is clearly a necessary but inevitably contentious requirement for constructing a practical model. Experts in each area of marine ecology will argue that it is a step–too-far to aggregate across the known diversity of behaviour and form in their particular disciplinary area. However, it remains unclear whether the apparently extreme step of combining, for example, all birds, pinnipeds and cetaceans into a single bird&mammal category in the model is any less of an over-simplification than aggregating all phytoplankton into a single group. Nevertheless, the representation in the model of top-predators, such as birds and mammals, does present some particular mathematical and conceptual difficulties, We regard this part of the model in particular as requiring further development and possibly elaboration to discriminate between different sub-groups of top-predators and scavenging fauna. This work is planned to be carried out as part of the NERC Marine Ecosystems Programme.

There are some processes related to possible impacts of trawling that we have not yet been able to include in the model. First, whilst we do explicitly represent the dispersal of organic detritus from the sediment into the water column by ploughing, we do not make any representation of the effect that this may have on water turbidity and hence the penetration of sunlight to drive primary production. In shallow water this has been identified as a notable factor, especially over muddy sediments. However, we feel that it is unlikely to be a significant issue at the scale of the whole North Sea or west of Scotland since the majority of muddy sediments each region are in the deeper zone (>30m) where there is insufficient light to support photosynthesis anyway.

The second process-related aspect of trawling that we have not considered in the model is the scope for habitat damage by trawling to have an effect on the vulnerability of plankton and fish species to predation. Many investigators have argued that a more intricate habitat in terms of vegetation and boulders provides refuge for especially fish larvae and juveniles. Removal of these features by trawling potentially increases predation risk and compromises survival. Whilst this remains a theory which has not been widely or adequately substantiated, we felt that it was premature to include it in the model.

Future research priorities

In terms of improvements in the model, we can identify three main areas of work:

- Re-examination of the representation of birds and mammals in the model, with a view to resolving sub-groups with high and low dependency on scavenge-feeding
- Incorporation of larval stages of benthic fauna as an explicit group in the model, in the same way as is already done for fish larvae. This will be especially valuable for validating trends in the impact of trawling since empirical studies have correlated the abundance of benthic larvae collected by the Continuous Plankton Recorder Surveys with trawling activity, and cite this as evidence of an impact of trawling.
- Improvement in the representation of natural disturbance of sediments by physical processes. At present, we assume a constant rate of natural disturbance by tidal currents, and a seasonal pattern of disturbance by wave action. We can improve on this by separate modelling of combined tidal current and wave generated seabed shear stress on sediments (which was beyond the scope of this project) to generate input data for the model.

In relation to the data from STECF on activity by different fishing gears, we have so far only used the 2003-2013 annual averaged data to provide inputs to the ecosystem model. There is considerable scope for analysing the spatial and temporal trends in this data set to resolve shifts in the pattern of international fishing activity and changes in the overall rates, and how these related to the fishing mortality rates applied to the resource groups in the model. Such an analysis could become an atlas of fishing activity.

Measures of fishing activity and effort applied to static gears are problematic. Yet, these data are essential as we debate the relative merits of, for example, creels and the TR2 gear in the Nephrops fishery. Some thought as to how best to quantify the activity attributable to static gears would be helpful.

Our study explores one scenario for the implementation of the landing obligation (fishing as usual but land the entire catch), and contrasts this with a scenario in which all seabed ploughing effects of towed gears are eliminated. However, earlier work using the original simpler version of the StrathE2E model demonstrated very different consequences of achieving the landing obligation by improving selectivity (effectively a reduction in gear power and harvest ratio). Now that we have a model which resolves individual fishing gears, we should revisit the selectivity issue and use the new model to address the question of which gears should be the principal focus for selectivity improvements in order to achieve the maximum ecosystem benefit for the minimum technological change. This would be an achievable and practical use of the new model.

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