North SEE

A North Sea Perspective on Shipping, Energy and Environmental Aspects in Maritime Spatial Planning

Building, balancing, fitting and calibrating a simplified Ecopath with Ecosim North Sea model for the MSP Challenge Platform Edition game

August 2019

Interreg
North Sea Region
NorthSEE

Building, balancing, fitting and calibrating a simplified Ecopath with Ecosim North Sea model for the MSP Challenge Platform Edition game

August 2019

Author: Giovanni Romagnoni

Centre for Ecological and Evolutionary Synthesis (CEES), Department of Biosciences, University of Oslo, Norway. Giovanni.romagnoni@ibv.uio.no

Project information	
Funding programme:	INTERREG VB: North Sea Region Programme 2014 - 2020
Project Name:	NorthSEE: A North Sea Perspective on Shipping, Energy and Environment Aspects in MSP
Project Agreement nr:	38-2-2-15
Project implementation period:	May 2016 - January 2020
Lead Partner:	German Federal Maritime and Hydrographic Agency (BSH)
Work Package	WP6 – Multi-level and Cross-sectoral MSP coordination 6.3: MSP Challenge input
Links to Task(s):	Task: Building, balancing, fitting and calibrating a simplified Ecopath with Ecosim North Sea model for the Maritime Spatial Planning Challenge Platform Edition game.

Document information	
Document Title:	Building, balancing, fitting and calibrating a simplified Ecopath with Ecosim North Sea model for the MSP Challenge Platform Edition game.
Author(s):	Giovanni Romagnoni Centre for Ecological and Evolutionary Synthesis (CEES), Department of Biosciences, University of Oslo, Norway. Giovanni.romagnoni@ibv.uio.no
Publication Date:	August 2019
Reference:	Romagnoni, 2019. Building, balancing, fitting and calibrating a simplified Ecopath with Ecosim North Sea model for the MSP Challenge Platform Edition game. WP6.3. INTERREG VB: North Sea Region Programme 2014 - 2020: "NorthSEE: A North Sea Perspective on Shipping, Energy and Environment Aspects in MSP". Project n. 38-2-2-15.

Proprietary Rights statement

Disclaimer

Summary

Marine or Maritime Spatial Planning is a multi-dimensional discipline, entailing control over a complex system with unclear feedbacks. Understanding the key mechanisms of marine ecosystems, and the effects of human activities on them, can be a daunting task. Serious games allow users, generally stakeholders and planners, to test their skills on simulated systems, learning from their mistakes and successes. Simplification and realism must be tied together to grant player engagement and learning. The MSP Challenge game aims to provide all of this, and its latest version, the MSP Platform Edition, relies on the Ecopath with Ecosim (EwE) model and its spatial component Ecospace to add ecological realism to game action. This report describes the building and parameterisation of a spatial-temporally explicit EwE model of the North Sea, specifically developed for the purpose of coupling with the MSP Platform Edition – North Sea edition game and supported by the NorthSEE project. The goal of the project was to build an EwE model capable of providing realistic responses to environmental changes (pressures), caused by game play planning decisions (actions) in the context of development of a Marine Spatial Planning strategy. Examples of actions include the construction of off-shore wind farms. In response to such a construction, the ecosystem model must account for sensitive marine animals to respond to the building and operational phases of the windfarm, considering other game play pressures in addition to ecosystem dynamics. The ecosystem model need to be simple enough to be attractive and engaging for the players, while maintaining scientific robustness and respond in a realistic way. This report describes the steps taken to simplify an existing model in order to make it suitable for MSP game play use. The assumptions, decisions and parameterisations process behind the model are described. The final model results in a satisfactory compromise between realism and game enjoyableness. Reliability of model responses is ensured by establishing guidelines and testing the model adherence to the expected results. Limitations in this approach lay in subjectivity and assumptions in the parameterisation of some model components, related to the limited knowledge of impacts on specific components of the system. These, however, do not affect the scientific robustness of the model. It is important to note that patterns reported by the model should not be considered as accurate predictions of spatial dynamics in the real world, but rather as realistic responses to hypothetical scenarios. The purpose of this report is to serve as documentation for the model and game users, as well as to serve as guideline for future similar exercises.

Table of Contents

1. Introduction

This report describes the building and parameterisation of an Ecopath with Ecosim (EwE) model of the North Sea, specifically developed for the purpose of interacting with the Maritime Spatial Planning (MSP) Platform Edition serious game for the North Sea. This effort was supported by the NorthSEE project in order to provide a tool for stakeholder engagement and learning.

EwE is an ecosystem modelling software (see also 1.1), and its spatial-temporal module Ecospace was used to integrate the North Sea model with the MSP game. The MSP game relies directly on an underlying Ecospace model through real-time feedbacks between the two components. For the purpose of the MSP game, the underlying Ecospace model should be simple, retaining only the components and interactions essential for the overall ecosystem dynamics, and those directly relevant for the purpose of the game (e.g. fishing, impact on the substrate, and impact on species). The ecosystem components (e.g. species and fishing fleets) should be reduced in number to the minimal complexity required to retain a functioning food web whilst achieving low computational times, thus ensuring high model computational speed and game performance. The simplified model is expected to capture the most important aspects of the dynamics of the system, and the food-web interaction should not differ substantially from the original model. Through its simpler structure, however, the simplified model allows faster and smoother game play.

Rather than building an ad-hoc model, it is preferable to modify an existing model, appropriately simplifying where possible and necessary. This approach has two main advantages: relying on a published, possibly peer-reviewed model with robust building and parameterisation ensures that the model ecological responses are realistic. Secondly, using an already available model allows to reduce the time-consuming process of assembling data, building and calibrating an EwE model.

This report describes the steps taken to simplify an existing model in order to make it suitable for MSP Platform Edition game play use, following the guidelines of the “EwE model guidelines for MSP gameplay” (Steenbeek, 2018a). Thanks to the high number of published EwE models, this approach can be replicated in different systems worldwide.

1.1 Ecopath with Ecosim

Ecopath with Ecosim (EwE) and its spatial component Ecospace are a modelling framework used to build ecosystem models. The model and associated freely available software suite (www.ecopath.org) was originally designed to study marine ecosystems dynamics and the effects of fisheries (Christensen and Walters, 2004; Pauly *et al.*, 2000; Polovina, 1984). It is among the most widely used ecosystem modelling framework (Colléter *et al.*, 2015) and its flexibility and versatility allow to combine a simple yet efficient ecosystem model with external suites making it a perfect tool for complementing the MSP Platform game.

In short, the ecosystem model tracks the energy flow between components of an ecosystem (species or functional groups), under the assumption that the overall system is balanced, i.e. all the total biomass in the system is constant. The first component of the suite, Ecopath, describes a snapshot of the ecosystem, capturing the average trophic flows (Fig. 1). Its time-dynamic component, Ecosim, is based upon Ecopath as initial condition and uses a set of differential equations to describe the temporal behaviour of the ecosystem (Walters *et al.*, 2000). The capabilities and limitations of the approach have been described by

Christensen and Walters (2004) and Plagányi and Butterworth (2004). Ecospace is the spatially explicit component of EwE (Pauly *et al.*, 2000; Romagnoni *et al.*, 2015). Ecospace is represented by a set of water and land grid cells. Functional groups and fisheries interact with each other within the water cells according to modified versions of Ecosim equations, accounting for habitat preference, environmental variables, life history and movement rates, under the assumption that marine animals always try to move to more favourable conditions. The latest version of Ecospace includes a dynamic niche model. This tool, called "habitat foraging capacity model", considers the individual responses of functional groups to environmental conditions (Christensen *et al.*, 2014), by increasing or decreasing the local feeding conditions for a group for a given cell. The habitat capacity model has a very important role for the purpose of connecting the Ecospace and the MSP model: the pressures of activities implemented by players in the game translate directly into environmental drivers that influence habitat capacity of a given cell, driving the species distribution. For further information about Ecopath, Ecosim, Ecospace and their use, the reader is referred to the literature cited above.

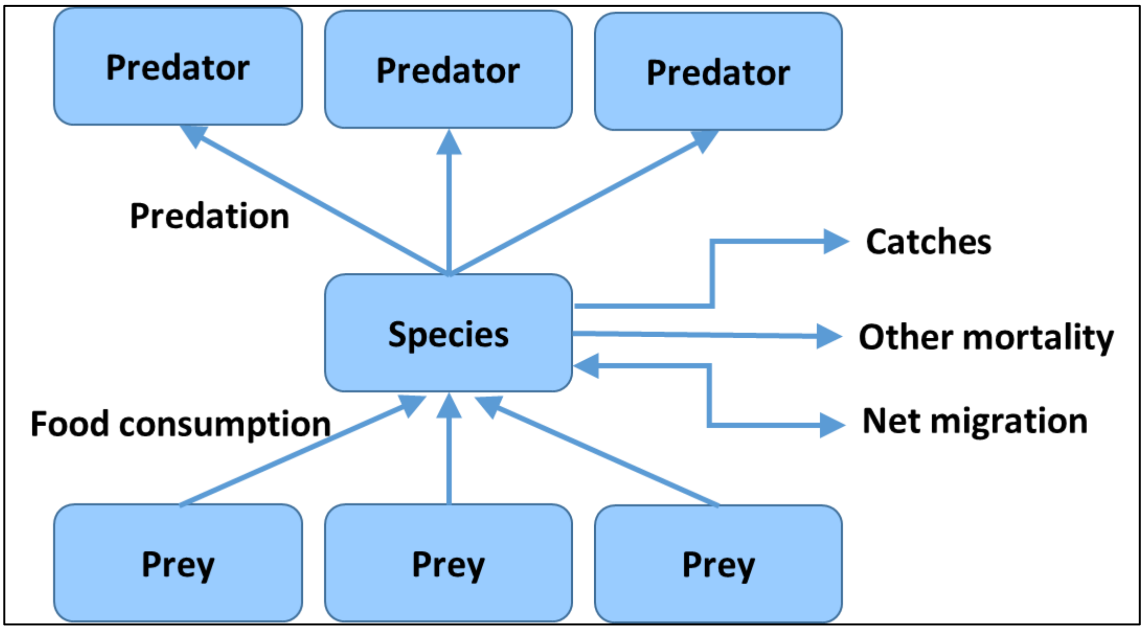


Figure 1. The simplified energy budget of each group in the ecosystem, showing a species' energy flow as a balance between food consumption, predation, and other flows. Groups are linked to each other via predation: predation (i.e. mortality) of a prey group corresponds to food consumption of its predators.

1.2. Original model and simplified model

The model described in this report (named "NorthSea 1991-2013 Key run - simplified MSP", hereafter shortened to "simplified") is a simplified version of an existing Ecopath with Ecosim model (ICES, 2015; Mackinson and Daskalov, 2007). The latest version of this model was published as the "EwE North Sea model 2015 Key run (1991-2013)", used and described in the WGSAM 2015 report (ICES, 2015). Unless otherwise specified, the simplified model is based on the 2015 model, hereafter referred to as the "original model". The Ecospace component of the simplified model is based on the Ecospace model used in Romagnoni *et al.* (2015), in turn based on Mackinson and Daskalov (2007).

All these models were built with 1991 as starting- and reference year, the year that a large effort for stomach content analysis was undertaken for assessing diet relationships in the North Sea (named “the year of the stomach”). For the purpose of MSP game, the base year was maintained because 1991 diet data are still the most important, up to date, and comprehensive. Moreover, constructing the model in the past allowed for using relatively long time series (1991-2013) to fit and calibrate the model to changes observed in the system in this time period.

Please note that the notation “simplified model” should not suggest in any way that the model is simple. An ecosystem model is always highly complex even if “simplified”. The building and parameterisation ex novo or the process of simplification of an existing model require in-depth knowledge of the modelling framework and the system under study, methodical assessment and sound scientific approach including EwE “best practices” (Heymans *et al.*, 2016).

2. Species and fleets

2.1. Simplification criteria

The original model (ICES, 2015) included 69 trophic groups (68 in Mackinson and Daskalov, 2007) and 12 fleets, judged too many to be managed by the MSP interface and not useful for game purpose. The number of species/trophic groups was thus reduced through aggregation wherever possible. The species groups were reduced from 69 to 23. Species in the original and simplified models are described in table 1. Similarly, fishing fleets were aggregated to reduce the number from 12 to 7 (table 2). The simplification of the model, with reduction of the number of groups, was based on three main criteria:

1- Those species/trophic groups considered important for the purpose of the game were maintained: charismatic species (e.g. seals, cetaceans), commercially important species (e.g. cod, herring, sandeel), species subject to anthropogenic impacts and thus subject to legal protection at international level and/or indicative of anthropogenic impacts, and thus in need of monitoring (e.g. seabirds, benthic invertebrates). These important groups were predefined by the commissioner of the MSP game, Rijkswaterstaat, and further refined through the advice of a panel of external experts (see Appendix).

2- Groups not falling under the previous classification but ecologically or commercially important, were examined in order to assess where group aggregation would be appropriate. Aggregation was based on ecological, taxonomic and practical reasoning. The main criteria was the predator-prey niche overlap of groups in the Mackinson and Daskalov (2007) model, i.e. the extent to which prey and predators between two groups were similar, which is an output of the Ecopath model. Taxonomically similar groups were aggregated where appropriate: baleen whales and toothed wales were grouped into "cetacean". Ecologically similar groups were aggregated (e.g. 10 groups of flatfish species were lumped together in one "flatfish" group). However, due to the spatial aspect of the Ecospace model, spatial distribution was also considered. For example, Norway pout and blue whiting have similar niche overlap with the groups "Other gadoids small" and "Small demersal fish". However, Norway pout and blue whiting are distributed exclusively in the northern portion of the North Sea basin, while the latter are rather ubiquitous, and for this reason the groups were separated into small pelagic gadoids (in the north) and small demersal fish (distributed throughout the study area), respectively.

3- For game play simplicity we collapsed life stages of multi-stanza[1] (Christensen and Walters, 2004) configurations into single groups. A number of groups were expressed as multi-stanza groups in the original model, to account for differences between juveniles and adults (e.g. cod, whiting, haddock, saithe, herring). However, detailed representation of ontogenetic changes was not considered a fundamental requirement for the MPS game purposes, adding to computational cost without providing significant added value for game play.

[1] Multi-stanza groups allow splitting a species into life stages (e.g. juveniles and adults) which differ in growth rate, consumption, predation, fishing mortality and diet.

2.2. Description of trophic groups

Groups included in the simplified model are described below. Ecopath input parameters for these groups were directly taken from the most recent version of the original model (ICES, 2015). For aggregated groups, biomasses were summed, while other basic input parameters required by EwE (e.g. production to biomass ratio, P/B; consumption to biomass ratio, Q/B) were calculated as weighted averages, using biomass as weight factor (see section 2.4 and tables 3 and 4).

The resulting group composition was as follows:

- **Cetacean**
  This group is composed of the baleen whales and toothed whales groups of the original model. Cetaceans were included as they are a highly charismatic group. The two groups were aggregated since they are closely related, with relatively similar ecology (e.g. slow growth and reproduction, at least compared to other organisms in the area) and the impacts they suffer tend to be largely similar. For example, all cetacean species are affected by noise. Additionally, they might suffer bycatch from the Drift and fixed net fishing fleet. In particular, harbour porpoises are highly vulnerable to this fishing gear (ICES, 2016).
- **Seals**
  This group was left unchanged from the 2015 model, as it was identified as one of the key groups for MSP game play due to their status as charismatic organism.
- **Seabirds**
  In the Mackinson and Daskalov (2007) model there was only one seabird group, which was split into surface-feeding seabirds and diving seabirds in the 2015 model (ICES, 2015). The subdivision was maintained in the simplified model because the splitting reflects largely the division between bird species which are negatively impacted (diving seabirds in the 2015 model, renamed "windfarm avoiding seabirds" in the simplified model) and those which show no major negative effect ") from windfarms (surface-feeding seabirds in the 2015 model, renamed "windfarm indifferent seabirds, one of the key activities of interest for the MSP Platform Edition game. Birds that migrate or that spend most of their life in open waters (e.g. terns, gannets) seem to actively avoid windfarms (Garthe *et al.*, 2007; Stienen *et al.*, 2007). In contrast, birds with a local, coastal habit (e.g. smaller gulls, cormorants) can learn to live in windfarms, showing habituation to the rotors, and can benefit of increasing habitat for resting and increased feeding opportunities offered by windfarms (which, being closed to fishing, can provide shelter to prey fish). These species show generally indifference or even mild attraction to windfarms (Lindeboom *et al.*, 2011; Stienen *et al.*, 2007).
- **Windfarm avoiding seabirds**
  This group includes northern gannet (*Morus bassanus*), common guillemot (*Uria aalge*) and razorbill (*Alca torda*). Due to their behaviour of windfarm avoidance, terns (*Sterna spp.*) were considered to fit better in this group, in contrast to the original model where terns were included among the surface feeding seabirds. However, the parameterisation of the two groups was not modified from the ICES (2015) model.
- **Surface feeding seabirds**
  This group includes e.g., gulls (*Larus* spp), kittiwakes (*Rissa* spp), shag (*Phalacrocorax aristotelis*).
- **Cod**
  This group was maintained as single species group as in the original model, due to its commercial importance and its cultural value. In the original model, the species was divided in two life stages,

juvenile and adult. While their differences are ecologically important, for the purpose of the game a simplification was necessary, and only the adult group was included in the model.

- **Other commercial gadoids**
  This group was built by aggregating whiting, haddock and saithe, three commercially important species. These species were maintained due to their ecological and commercial relevance. They were however aggregated into one group, based on their taxonomic proximity and their diet similarity (as confirmed by niche overlap). Saithe and haddock are more abundant in the northern part of the basin, while whiting is more widespread. Since whiting constitutes more than half of the biomass of the adult stanza of this group, we assumed that a ubiquitous distribution for the aggregated group is realistic. Also for this group, for the simplified model only the adult stanzas of the original model's groups were used.
- **Demersal predators**
  This group includes many groups/species characterised by notable ecological and/or commercial importance, but not important enough for being represented as individual groups or species (e.g. hake, monkfish, wolffish, pollock, sharks). These groups have in common the mainly bottom-dwelling habits, relatively large size, and being largely piscivorous predators. The group ecological robustness was shown by the high predator-prey niche overlap between the most abundant groups (e.g. monkfish with "Other large gadoids").
- **Pelagic small gadoids**
  This group includes Norway pout and blue whiting, both pelagic fishes with northern distribution, targeted by industrial trawl fisheries for fishmeal. They also form an important component of the food-web, being preyed upon by a number of predators and linking pelagic and benthic components. Their predator-prey niche overlap and similar spatial distribution justified grouping them.
- **Herring**
  This species has high economic importance and was therefore considered a key group to be included in the model explicitly. In the original model, herring was a multi-stanza group. For the purpose of this model, multi-stanza for herring was considered not necessary and the stanzas were aggregated, due to their similarity. Basic input was calculated as weighted average of the parameters in the two stanzas.
- **Sandeel and sprat**
  Sandeel was considered an important species to be included in the model due to its key role as forage food for e.g. seabirds, and for its commercial importance. Sprat, although less abundant, has similar ecological role. These two species were grouped based on their high predator-prey overlap index, their high commercial importance for industrial trawl fisheries for fishmeal and their mainly southern-central distribution.
- **Small pelagic fish**
  This group was created by grouping horse mackerel and "filter feeding pelagic fish". These groups are also forage fish with a mainly southern distribution, but have lower economic and ecological importance than sandeel and sprat, and where thus not merged with the previous group.
- **Flatfish**
  The ten species included in the original model were lumped into a unique flatfish group. Despite the differences in geographical distribution, ecology and economical importance between these species, the overall similarities (e.g. high predator prey niche overlap between plaice and sole, sole and which, dab and plaice, dab and long-rough dab, long-rough dab and lemon sole) and the method of capture, chiefly bottom trawl, lead to placing them into a unique group.

- **Large demersal fish**
  This group includes species such as e.g. John Dory, redfish, bluemouth, rays and skates. These are all bottom-dwelling fish which can attain relatively large size but are not notable piscivorous predators and where thus not grouped with “demersal predators”.
- **Small demersal fish**
  This group includes species such as e.g. grey gurnard, red gurnard, red mullet, weever, eelpout, sculpin and other small demersal fish. These species belong to groups which in the original model show relatively high predator-prey niche overlap. Most of them have limited or no commercial value, and are preyed upon by larger demersal fishes.
- **Zooplankton**
  This group includes three groups of zooplankton from the original model: carnivorous zooplankton, herbivorous zooplankton, and gelatinous zooplankton. Although these groups are ecologically very different, for the purpose of the game this simplification was considered adequate.
- **Large crabs**
  This group was left unchanged from the original model.
- **Large benthic invertebrates**
  This group was built by merging four originally separated groups of benthic invertebrates, including organisms that actively move around the substrate. Some of these species represent commercially important groups (e.g. shellfish, shrimps, Norway lobster).
- **Small benthic invertebrates**
  This group was also composed of four previously separated groups of invertebrates, mainly of small or microscopic size, with no commercial importance.
- **Microflora**
  This group was created by lumping the original “benthic microflora” and “pelagic microflora”.
- **Phytoplankton**
  This group was left unchanged from the original model.
- **Detritus and discards**
  This group was created by merging the two detritus groups and discard group. Discard include the fish caught by fishing gears that are not landed: these are thrown at sea dead or dying, and constitute a locally important food source for many other organisms. For the purpose of the game, discards feeding was not explicitly considered, and discards were merged with the two other detritus groups.

Table 1. Trophic groups included in the simplified model, corresponding groups in the previous models and species and taxonomic units included in each group.

	Group name in Simplified model	Corresponding groups in ICES WGSAM 2015	Included species and families
1	**Cetaceans**	Baleen whales, Toothed whales	Minke whale (*Balenoptera acutorostrata*), harbour porpoise (*Phocoena phocoena),* white-beaked dolphin (*Lagenorhynchus albirostris*) and Atlantic white-sided dolphin (*Lagenorhynchus acutus*)
2	**Seals**	Seals	Gray seal (*Halichoerus grypus*) and harbour seal (*Phoca vitulina*)

3	**Windfarm avoiding seabirds**	Diving seabirds	fulmar *(Fulmarus glacialis)*, gannet *(Morus bassanus)*, terns *(Sternidae)*, guillemot *(Uria aalge)*, razorbill *(Alca torda)*, puffin *(Fratercula arctica)*, great skua *(Catharacta skua)*.
4	**Windfarm indifferent seabirds**	Surface-feeding seabirds	shag *(Phalacrocorax aristotelis)*, herring gull *(Larus argentatus)*, great black backed gull *(Larus marinus)*, lesser black backed gull *(Larus fuscus)*, kittiwake *(Larus tridactyla)*
5	**Cod**	Cod	Cod (*Gadus morhua*)
6	**Commercial gadoids**	Whiting, Haddock, Saithe	whiting (*Merlangius merlangus*), haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens)*
7	**Demersal predators**	Hake, Monkfish, Other gadoids (large), Catfish (wolffish), all Sharks groups	Hake (*Merluccius merluccius*), monkfish (*Lophius piscatorius*), wolffish (*Anarrhichas lupus*), pollock (*Pollachius pollachius*), tusk (*Brosme brosme*), Ling (*Molva molva*), greater forkbeard (*Phycis blennoides*), tope (*Galeorhinus galeus*), spiny dogfish (*Squalus acanthias*), lesser-spotted dogfish (*Scyliorhinus canicula*), smoothhound (*Mustelus spp.*), velvet-belly lantern shark (*Etmopterus spinax*)
8	**Pelagic small gadoids**	Blue whiting, Norway pout	blue whiting (*Micromesistius poutassou*), Norway pout (*Trisopterus esmarkii*)
9	**Herring**	Juvenile herring, Adult herring	Herring (*Clupea harengus*)
10	**Sandeels and sprat**	Sandeels, Sprat	Sandeels (*Ammoditidae*), sprat (*Sprattus sprattus*)
11	**Mackerel**	Mackerel	Mackerel (*Scomber scombrus*)
12	**Small pelagic fish**	Horse mackerel, miscellaneous filterfeeding pelagics	horse mackerel (*Trachurus trachurus*), shad (*Alosa spp.*), anchovy (*Engraulis encrasicolus*), sardine *(Sardina pilchardus*), *Maurolicus muelleri*
13	**All flatfish**	Sole, Plaice, Witch, Dab, Long-Rough Dab, Flounder, Lemon Sole, Turbot and Brill, Megrim, Halibut	Sole (*Solea solea*), plaice (*Pleuronectes platessa*), witch (*Glyptocephalus cynoglossus*), dab (*Limanda limanda*), long-rough dab (*Hippoglossoides platessoides*), flounder (*Platichtys flesus*), lemon sole (*Microstomus kitt*), turbot (*Psetta maxima*), brill (*Scopthalmus rhombus*), megrim (*Lepidorhombus whiffiagonis*), halibut (*Hippoglossus hippoglossus*)
14	**Large demersal fish**	Large demersal fish, all Skates and rays groups	Rabbit fish (*Chimaera monstrosa*), John Dory (*Zeus faber*), sea trout (*Salmo trutta*), Norway red fish (*Sebastes viviparous*), Bluemouth (*Helicolenus dactylopterus*), roundnose grenadier (*Coryphaenoides rupestris*), starry ray (*Amblyraja radiata*), thornback ray (*Raja clavata*), spotted ray (*Raja montagui*), Common skate (*Dipturus batis*), cuckoo ray (*Leucoraja naevus)*

15	**Small demersal fish**	Small demersal fish, Other gadoids small, Dragonets, Gurnards	Eelpout (*Zoarces viviparous*), shorthorn sculpin (*Myoxocephalus Scorpius*), Vahls's eelpout (*Lycodes vahlii*), longspined bullhead (*Taurulus bubalis*), hooknose (*Agonus cataphractus*), common seasnail (*Liparis liparis*), greater weever (*Trachinus draco*), lesser weaver (*Echiichthys vipera*), snake blenny (*Lumpenus lampretaeformis*), striped red mullet (*Mullus surmuletus*), solenette (*Buglossidium luteum*), thickback sole (*Microchirus variegatus*), mediterranean scaldfish (*Arnoglossus laterna*), argentine (*Argentina spp.*), dragonet (*Callionymus spp.*), piper gurnard (*Trigla sp.*), grey gurnard (*Eutrigla sp.*) and red gurnard (*Aspitrigla sp.*)
16	**Squid & cuttlefish**	Squid and cuttlefish	veined squid (*Loligo forbesi*), European squid (*Loligo vulgaris*), common cuttlefish (*Sepia officinalis*), little cuttlefish (*Sepiola atlantica*)
17	**Zooplankton**	Carnivorous zooplankton; Herbivorous & Omnivorous zooplankton (copepods); Gelatinous zooplankton	*Calanus finmarchicus, Psedocalanus elongates, Paracalnus parvus, Microcalanus pusillus, Acatia spp, Temora longicornis,* Euphasiids, chaetognaths, amphipods, mysiids, ichthyoplankton, *Aurelia aurita, Cyanea lamarckii and Cyanea capillata*
18	**Large crabs**	Large crabs	*Liocarcinus holsatus, Cancer pagurus* and *Hyas coarctatus*
19	**Large bottom invertebrates**	Nephrops; Epifaunal macrobenthos (mobile grazers); Infaunal macrobenthos; Shrimps	*Nephrops norvegicus;* Free-living surface living macrobenthos: mostly echinodermes (brittle stars, sea urchins), small crabs, gasteropods, scallops. Bivalves and gasteropods mostly larger than 2 mm, eg, cockles*, cardium and buccinium.* Filter feeders and grazers. *Crangon sp., pandalus sp. etc.*
20	**Small invertebrates**	Small mobile epifauna (swarming crustaceans); Small infauna (polychaetes); Sessile epifauna; Meiofauna	Small mobile epifauna: *Crustaceans, molluscs,* and polychaetes that live on the benthic interface and mysids, gammarids and amphipods that swarm off the bottom. Sessile epifauna: Suspension and filter feeders including anemones, sponges (dead-man's fingers), corals, tunicates, gorgonians, hydroids, anthozoans, pelecypods, barnacles (e.g. *Balanus*), bryozoans, attached bivalves (mussels), and crinoids, ascidians, oysters). Small infauna: Mostly polychaetes (*Sabella, Nereis, sipunculus, turbellaria, arenicola, sagitta* and others) and small crustaceans that live in the sediment. Filter feeders and predators. Meiofauna: nematodes, harpacticoid copepods, turbellarians, polychaetes, oligochaetes, ostracods, tardigrades, isopods, gastrotrichs, kinorhynchs.
21	**Microflora (bacteria, protozoa)**	Benthic microflora including bacteria and protozoa, Planktonic microflora including bacteria and protozoa	Benthic microflora including bacteria and protozoa, planktonic microflora including bacteria and protozoa
22	**Phytoplankton**	Phytoplankton	Various groups of phytoplankton

23	**Detritus and discards**	Detritus - DOM -water column; Detritus - POM - sediment; Discards	Detritus - DOM -water column; Detritus - POM - sediment; Discards

2.3 Description of fleets

The fishing fleet structure of the simplified North Sea model is as follows:

- **Bottom trawl**
  This fleet included the four fleets “demersal trawl and seine”, “beam trawl”, “shrimp trawl”, “nephrops trawl”. These fleets were lumped together as they all employ towed gears, targeting demersal fish and invertebrate species; they also have similar economic characteristics with high variable costs mainly due the fuel-intensive fishing practice, and all have regionally or locally important economic role, compared to other fleets.
- **Industrial and pelagic trawl**
  This fleet included “industrial trawl” (in the 2007 model known as “sandeel trawl”) and “pelagic trawl”. Both these fleets target small pelagic fish (typically forage fish for seabirds, mammals and larger fish species) such as herring, sprat, and sandeel, with few other species ending up in the catches. Except for herring, most of the catches are used for fishmeal.
- **Drift and fixed nets**
  This fleet has small importance at the regional level as landings are much smaller than bottom trawl and industrial trawl. However, it has high importance in terms of occupation for small-scale fisheries and relative economies of small coastal communities. Moreover, it is a locally important cause of mortality for cetaceans, and it has non-negligible catches of few demersal fish species. For all these reasons, this fleet was thus included in the game explicitly.

All other fleets (Gears using hooks, Dredges, Pots, Others) were left unchanged from the original model. They will be needed for internal operation of the EwE model to keep the catches and fishing mortality in check, but they cannot be controlled by MSP game players. Their operation will not be exposed to MSP game players. Inclusion of a pulse fishing fleet was considered but eventually excluded. Although this fleet has been used at experimental level, the effects of pulse fishing are largely unknown and the gear is at present only used at experimental level.

Table 2. Fleets included in the simplified model, corresponding fleets in the original models, and gear categories used for calibration. Note: only the first three fleets (Bottom trawl, Industrial and Pelagic trawl, Drift and fixed nets) can be controlled by MSP game players, and their operation will be summarized in EwE outcome layers for MEL.

Fleet name in simplified model	Corresponding fleets in ICES WGSAM 2015	Gear categories from STECF Effort database:
Bottom trawl (otter, beam, seine)	Demersal trawl and seine	Demersal seines (fly shooting, anchored and pair); Regulated bottom otter trawls (multi rig and pair) >= 100 mm;
	Beam trawl	Regulated beam trawls >= 120 mm; Regulated beam trawls >= 80 <120 mm
	Nephrops trawl	Regulated bottom otter trawls (multi rig and pair) >= 70 <100 mm
	Shrimp trawl	Beam trawl (targeting shrimps);
Industrial and pelagic trawl	Industrial trawl (= sandeel trawl)	Bottom otter trawls (multi rig and pair); Regulated bottom otter trawls (multi rig and pair) >= 16 <32 mm
	Pelagic trawl	Pelagic seines (purse, fly shooting and anchored); Pelagic trawls (otter and pair)
Drift and fixed nets	Drift and fixed nets	Regulated gill nets; Regulated trammel nets
Gears using hooks	Gears using hooks	Regulated longline
Dredges	Dredges	Dredges
Pots	Pots	Pots and traps
Other	Other	Unknown

2.4 Weighting of input parameters for aggregated groups

All basic input, diet and other group-level information for the simplified model were calculated by aggregating the data from the original model, weighted by relative biomass contribution. Basic inputs of the original model are reported in table 3. For groups in the simplified model resulting from aggregation of several groups of the original model, biomasses were added. Other basic inputs were calculated as weighted averages, where the contribution of each species/group to the aggregated group in the simplified model was proportional to its contribution in biomass. Unassimilated consumption was estimated at 0.2 for all groups with the exception of zooplankton. For example, the Cetaceans group is composed of the former "baleen whales" and "toothed whales". Their biomass in the original model was 0.067 and 0.017 (0.798 and 0.202 are the respective proportions). Biomass of Cetacean in the simplified group is therefore the sum, 0.084, and production rates (P/B) and consumption rates (Q/B), weighted by relative biomass, are 0.02 and 11.4644. For some groups, input values such as B and P/B were missing in the original. For these groups, values for the missing parameters were estimated in order to obtain the weight factor used for the process of aggregation. The values estimated through balancing of the original model were therefore used for this purpose. Basic input which formed the basis of model aggregation are reported in table 3, while the basic input and other input data of the simplified model after aggregation are reported in tables 4. Similar to the basic inputs, inputs for diet composition, fleet description, landings, discards and off-vessel price were weighted by species and by fleets. Input for fleets are reported in table 6-8. Table 9 reports the basic inputs of simplified model after balancing the simplified model. Input for diet matrix is reported in table 10. Table 11 shows a comparison of model-estimated parameters between the original and simplified model for comparable groups.

Table 3. Basic input used as basis for group aggregation. Includes most of the inputs from original model (ICES 2015), and some of the model-estimated basic input necessary for weighting the groups (in blue). Total mortality is only relevant for multi-stanza groups.

	Group name	***B (t/km²)***	***Total mortality (year)***	***P/B (/year)***	***Q/B (/year)***	***EE***	***P/Q***	***Unassim. consumption***
1	Baleen whales	0.067		0.020	9.900			0.200
2	Toothed whales	0.017		0.020	17.630			0.200
3	Seals	0.008		0.090	26.842			0.200
4	Diving seabirds	0.004		0.450	86.970			0.200
5	Surface-feeding seabirds	0.002		0.237	77.280			0.200
6	Juvenile sharks	0.001		0.500	2.500			0.200
7	Spurdog	0.130		0.480	2.000			0.200
8	Large piscivorous sharks	0.001		0.440	1.600			0.200
9	Small sharks	0.002		0.510	2.960			0.200
10	Juvenile rays	0.268		0.660	1.700			0.200
11	Starry ray + others	0.390		0.660	1.700			0.200
12	Thornback & Spotted ray	0.066		0.780	2.300			0.200
13	Skate + cuckoo ray	0.050		0.350	1.800			0.200
14	Cod (juvenile 0-2)	0.100	1.790		4.967			0.200
15	Cod (adult)	0.130	1.190		2.170			0.200
16	Whiting (juvenile 0-1)	0.027	2.360		17.402			0.200
17	Whiting (adult)	0.430	0.890		5.460			0.200
18	Haddock (juvenile 0-1)	0.008	2.000		7.685			0.200
19	Haddock (adult)	0.120	1.140		2.350			0.200
20	Saithe (juvenile 0-3)	0.116	1.000		8.511			0.200

21	Saithe (adult)	0.210	0.880		3.600		0.200
22	Hake	0.014		0.820	2.200		0.200
23	Blue whiting	0.230		2.500	9.060		0.200
24	Norway pout	1.310		2.200	5.050		0.200
25	Other gadoids (large)	0.065		1.000	2.500	0.950	0.200
26	Other gadoids (small)	0.280		1.800	4.000	0.990	0.200
27	Monkfish	0.042		0.700	1.700		0.200
28	Gurnards	0.180		0.820	3.200		0.200
29	Herring (juvenile 0-1)	0.143	1.310		11.537		0.200
30	Herring (adult)	2.680	0.800		4.340		0.200
31	Sprat	0.579		2.280	5.280		0.200
32	Mackerel	0.750		0.600	1.730		0.200
33	Horse mackerel	0.750		0.900	3.500		0.200
34	Sandeels	1.850		2.280	5.240		0.200
35	Plaice	0.580		0.850	3.420		0.200
36	Dab	2.800		0.672	4.000		0.200
37	Long-rough dab	0.350		0.700	4.000		0.200
38	Flounder	0.250		1.100	3.200		0.200
39	Sole	0.135		0.800	3.100		0.200
40	Lemon sole	0.140		0.864	4.320		0.200
41	Witch	0.082		0.900	3.000		0.200
42	Turbot	0.027		0.860	2.100		0.200
43	Megrim	0.034		0.720	3.100		0.200
44	Halibut	0.033		0.160	3.140		0.200
45	Dragonets	0.045		1.440	6.900		0.200
46	Catfish (Wolf-fish)	0.014		0.480	1.700		0.200
47	Large demersal fish	0.025		0.550	2.540	0.900	0.200
48	Small demersal fish	0.345		1.420	3.700	0.990	0.200
49	Miscellaneous filterfeeding pelagic fish	0.029		4.000	10.190	0.990	0.200
50	Squid & cuttlefish	0.060		4.500	15.000		0.200

51	Fish larvae	0.349	4.000	20.000	0.990		0.200
52	Carnivorous zooplankton	3.147	4.000	12.500	0.990	0.320	0.200
53	Herbivorous & Omnivorous zooplankton (copepods)	16.000	9.200	30.000			0.380
54	Gelatinous zooplankton	0.066	2.900	6.444		0.450	0.200
55	Large crabs	1.200	0.550	2.750		0.200	0.200
56	Nephrops	0.980	0.370	1.850		0.200	0.200
57	Epifaunal macrobenthos (mobile grazers)	78.000	0.388	1.942		0.200	0.200
58	Infaunal macrobenthos	136.000	1.000	3.333		0.300	0.200
59	Shrimp	0.074	11.000	22.000			0.200
60	Small mobile epifauna (swarming crustaceans)	30.000	1.360	3.886		0.350	0.200
61	Small infauna (polychaetes)	150.000	0.900	3.000		0.300	0.200
62	Sessile epifauna	105.000	0.260	1.300		0.200	0.200
63	Meiofauna	3.821	35.000	125.000	0.990		0.200
64	Benthic microflora (incl Bacteria protozoa))	0.105	9470.000	18940.000		0.500	0.300
65	Planktonic microflora (incl Bacteria protozoa)	1.440	571.000	1142.000		0.500	0.300
66	Phytoplankton	7.500	286.667	86.970			0.000
67	Detritus - DOM -water column	25.000					0.200
68	Detritus - POM - sediment	25.000					0.200
69	Discards	0.000			0.000		0.000

Table 4. Groups and basic input parameters used in the simplified model. Data from ICES 2015, aggregated and weighted.

	Group name	***B (t/km²)***	***P/B (/year)***	***Q/B (/year)***	***EE***	***P/Q***	***Unassim. consumption***
1	Cetacean	0.084	0.020	11.464			0.200
2	Seal	0.008	0.090	26.842			0.200
3	Windfarm avoiding seabirds	0.004	0.450	86.970			0.200
4	Windfarm indifferent seabirds	0.002	0.237	77.280			0.200
5	Cod	0.130	1.190	2.170			0.200
6	Commercial gadoids	0.760	0.927	4.455			0.200
7	Demersal predators	0.269	0.658	2.076			0.200
8	Pelagic small gadoids	1.540	2.245	5.649			0.200
9	Herring	2.823		4.705	0.990		0.200
10	Sandeel and Sprat	2.429	2.280	5.250			0.200
11	Mackerel	0.750	0.600	1.730			0.200
12	Small pelagic fish	0.779	1.015	3.747			0.200
13	Flatfish	4.431	0.734	3.818			0.200
14	Large demersal fish	0.799	0.647	1.782			0.200
15	Small demersal fish	0.850	1.419	3.862			0.200
16	Squid & cuttlefish	0.060	4.500	15.000			0.200
17	Zooplankton	19.213	8.327	27.053			0.350
18	Large crabs	1.200	0.550	2.750			0.200
19	Large benthic invertebrates	215.054	0.779	2.828			0.200
20	Small benthic invertebrates	288.821	1.166	4.088			0.200
21	Microflora (incl Bacteria protozoa)	1.545	1175.786	2351.573			0.300
22	Phytoplankton	7.500	286.667	0.000			
23	Detritus and discards	25.000					

Table 5. Fleet description and economic data used in the simplified model. Data from ICES 2015, aggregated and weighted.

	Fleet name	Fixed cost (%)	Effort related cost (%)	Sailing related cost (%)	Profit (%)	Total value (%)
1	Demersal trawl	29.75	68.75	0	1.5	100
2	Industrial and Pelagic trawl	39.65	67.85	0	-7.5	100
3	Drift and fixed nets	19	77	0	4	100
4	Gears using hooks	16	72	0	12	100
5	Dredges	22	71	0	7	100
6	Pots	21	64	0	15	100
7	Other	22	60	0	18	100

Table 6. Landings by fleets, by species used in the simplified model. Data from ICES 2015, values aggregated by fleet and species.

	Group name	Bottom trawl	Industrial and pelagic trawl	Drift and fixed nets	Gears using hooks	Dredges	Pots	Other	Total
1	Cetacean	0	0	0.001	0	0	0	0	0.001
2	Seal	0	0	0	0	0	0	0	0
3	Windfarm avoiding seabirds	0	0	0	0	0	0	0	0
4	Windfarm indifferent seabirds	0	0	0	0	0	0	0	0
5	Cod	0.114	0.001	0.003	0.000	0.000	0.000	0.001	0.118
6	Commercial gadoids	0.383	0.004	0.000	0.000	0.000	0.000	0.070	0.457
7	Demersal predators	0.072	0.001	0.003	0.000	0.000	0.000	0.003	0.079
8	Pelagic small gadoids	0.000	0.334	0.000	0.000	0.000	0.000	0.060	0.394
9	Herring	0.001	0.853	0.000	0.000	0.000	0.000	0.001	0.856
10	Sandeel and Sprat	0.000	1.000	0.000	0.000	0.000	0.000	0.000	1.001
11	Mackerel	0.008	0.209	0.000	0.001	0.000	0.000	0.000	0.218
12	Small pelagic fish	0.004	0.085	0.000	0.000	0.000	0.000	0.000	0.089
13	Flatfish	0.436	0.001	0.008	0.000	0.000	0.000	0.007	0.452
14	Large demersal fish	0.018	0.001	0.001	0.000	0.000	0.000	0.000	0.020
15	Small demersal fish	0.173	0.012	0.008	0.000	0.000	0.000	0.013	0.206
16	Squid & cuttlefish	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.002
17	Zooplankton	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	Large crabs	0.005	0.000	0.000	0.000	0.000	0.006	0.000	0.011
19	Large benthic invertebrates	0.088	0.010	0.000	0.000	0.006	0.000	0.000	0.104
20	Small benthic invertebrates	0	0	0	0	0.580	0	0	0.580
21	Microflora (incl Bacteria protozoa)	0	0	0	0	0	0	0	0
22	Phytoplankton	0	0	0	0	0	0	0	0
23	Detritus and discards	0	0	0	0	0	0	0	0
24	Sum	1.303	2.511	0.024	0.002	0.586	0.007	0.156	4.588

Table 7. Discards by fleets, by species used in the simplified model. Data from ICES 2015, values aggregated by fleet and species.

	Group name	Bottom trawl	Industrial and pelagic trawl	Drift and fixed nets	Gears using hooks	Dredges	Pots	Other	Total
1	Cetacean	0	0	0.000	0	0	0	0	0.000
2	Seal	0	0	0	0	0	0	0	0
3	Windfarm avoiding seabirds	0	0	0	0	0	0	0	0
4	Windfarm indifferent seabirds	0	0	0	0	0	0	0	0
5	Cod	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.006
6	Commercial gadoids	0.054	0.003	0.000	0.000	0.000	0.000	0.000	0.058
7	Demersal predators	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	Pelagic small gadoids	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.002
9	Herring	0.001	0.024	0.000	0.000	0.000	0.000	0.000	0.025
10	Sandeel and Sprat	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	Mackerel	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
12	Small pelagic fish	0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.010
13	Flatfish	0.240	0.000	0.000	0.000	0.000	0.000	0.020	0.260
14	Large demersal fish	0.019	0.001	0.000	0.000	0.000	0.000	0.000	0.020
15	Small demersal fish	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.002
16	Squid & cuttlefish	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	Zooplankton	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	Large crabs	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.003
19	Large benthic invertebrates	0.034	0.000	0.000	0.000	0.000	0.000	0.000	0.034
20	Small benthic invertebrates	0	0	0	0	0.000	0	0	0.000
21	Microflora (incl Bacteria protozoa)	0	0	0	0	0	0	0	0
22	Phytoplankton	0	0	0	0	0	0	0	0
23	Detritus and discards	0	0	0	0	0	0	0	0
24	Sum	0.367	0.031	0.001	0.000	0.000	0.000	0.020	0.419

Table 8. Off-vessel price (i.e. price at landing) by fleets and by species used in the simplified model. Data from ICES 2015, values aggregated by fleet and species.

	Group name	***Bottom trawl***	***Industrial and pelagic trawl***	***Drift and fixed nets***	***Gears using hooks***	***Dredges***	***Pots***	***Other***
1	Cetacean			0				
2	Seal							
3	Windfarm avoiding seabirds							
4	Windfarm indifferent seabirds							
5	Cod	2.093	0.745	2.064	1.490	1.690	1.490	2.067
6	Commercial gadoids	1.287	0.460	1.000	2.632	0.920	0.920	0.920
7	Demersal predators	3.145	1.275	2.832	2.971	2.640	2.550	2.546
8	Pelagic small gadoids	0.453	0.425	0.851	1.000	1.000	1.000	0.874
9	Herring	0.220	0.096	0.299	0.000	1.000	0.191	0.191
10	Sandeel and Sprat	0.038	0.095	0.034	0.000	0.034	0.000	0.034
11	Mackerel	0.848	0.355	0.710	0.710	0.710	0.710	0.710
12	Small pelagic fish	0.437	0.195	0.354	0.000	1.000	0.354	0.354
13	Flatfish	1.767	0.760	1.453	1.388	1.420	1.247	1.497
14	Large demersal fish	1.225	0.534	1.302	0.269	0.361	0.185	0.219
15	Small demersal fish	0.906	0.323	1.692	0.053	9.746	0.647	1.883
16	Squid & cuttlefish	5.576	1.000	4.925	1.000	4.925	1.000	7.000
17	Zooplankton	1.000	1.000	1.000	1.000	1.000	1.000	1.000
18	Large crabs	8.089	5.000	7.605	6.669	6.586	10.054	20.820
19	Large benthic invertebrates	1.726	0.783	0.285	1.206	2.921	0.542	3.338
20	Small benthic invertebrates					0		
21	Microflora (incl Bacteria protozoa)							
22	Phytoplankton							
23	Detritus and discards							

3. Model balancing

Balancing an Ecopath model requires applying reasoned changes to the input parameters and data of the model so to achieve the requirement of mass-balancing of the model, according to thermodynamic and ecological rules. The main criteria for balancing is that the request of biomass matches the available biomass across the whole system, i.e. mass-balancing. This is obtained by ensuring that the Ecotrophic Efficiency parameter (EE) estimated by Ecopath, is maintained below 1 for all groups. There are guidelines for balancing Ecopath models, summarised in (Heymans *et al.*, 2016). The approach used here for simplifying the original model was based on maintaining the simplified model as close as possible to the original model, reducing changes to the model initial inputs to a minimum. This approach was based on the high trust in the original model's construction and parameterisation, which was essential as the North Sea model has been widely applied for studying the ecosystem and for management strategy evaluation (Mackinson *et al.*, 2018). For other models with lower confidence on data and model performance this approach might be inappropriate, and critical evaluation of the original model inputs should be undertaken.

Model balancing of a new EwE model usually requires a number of steps and reasoned changes. Balancing the simplified model was instead easier and only required one change to the original input. It is plausible that this is due to the high fidelity of the simplified model to the original, showing a sensible group aggregation that allowed maintaining the flows and dynamics of the original model. Specifically, the unbalanced simplified model showed only one group with Ecotrophic Efficiency (EE) exceeding 1: squid and cuttlefish, with EE=1.15809. In order to balance the model, the diet matrix was modified. Predation of zooplankton on squids was identified as a relationship of concern, since squids and cuttlefish hatch as relatively large, fully-formed individuals; the vulnerability of juveniles to carnivorous zooplankton is thus considered irrelevant. For this reason, this value was changed from 0.0001719 to 0. This was sufficient for the model to balance. Table 9 shows the estimated basic inputs of the simplified model after balancing, and table 10 shows the diet matrix. Trophic level (TL), EE and Production to Consumption ratio (P/Q) estimated by the simplified model are very close to those estimated by the original model in groups were direct comparison is possible (table 11).

Table 9. Basic inputs of simplified model after balancing. Values in blue are estimated from the model.

	Group name	***TL***	***B (t/km²)***	***P/B (/year)***	***Q/B (/year)***	***EE***	***P/Q***	***Unassimilated consumption***
1	Cetacean	4.278	0.084	0.020	11.464	0.396	0.002	0.200
2	Seal	4.886	0.008	0.090	26.842	0.000	0.003	0.200
3	Windfarm avoiding seabirds	4.084	0.004	0.450	86.970	0.000	0.005	0.200
4	Windfarm indifferent seabirds	3.139	0.002	0.237	77.280	0.000	0.003	0.200
5	Cod	4.668	0.130	1.190	2.170	0.916	0.548	0.200
6	Commercial gadoids	4.225	0.760	0.927	4.455	0.963	0.208	0.200
7	Demersal predators	4.534	0.269	0.658	2.076	0.647	0.317	0.200

8	Pelagic small gadoids	3.440	1.540	2.245	5.649	0.794	0.397	0.200
9	Herring	3.274	2.823	0.504	4.705	0.990	0.107	0.200
10	Sandeel and Sprat	3.319	2.429	2.280	5.250	0.896	0.434	0.200
11	Mackerel	3.745	0.750	0.600	1.730	0.772	0.347	0.200
12	Small pelagic fish	3.763	0.779	1.015	3.747	0.311	0.271	0.200
13	Flatfish	3.951	4.431	0.734	3.818	0.384	0.192	0.200
14	Large demersal fish	4.254	0.799	0.647	1.782	0.086	0.363	0.200
15	Small demersal fish	4.045	0.850	1.419	3.862	0.860	0.367	0.200
16	Squid & cuttlefish	3.608	0.060	4.500	15.000	0.825	0.300	0.200
17	Zooplankton	2.261	19.213	8.327	27.053	0.620	0.308	0.350
18	Large crabs	3.680	1.200	0.550	2.750	0.961	0.200	0.200
19	Large benthic invertebrates	2.991	215.054	0.779	2.828	0.412	0.275	0.200
20	Small benthic invertebrates	2.851	288.821	1.166	4.088	0.933	0.285	0.200
21	Microflora (incl Bacteria protozoa)	2.143	1.545	1175.786	2351.573	0.729	0.500	0.300
22	Phytoplankton	1.000	7.500	286.667	0.000	0.208		
23	Detritus and discards	1.000	25.000			0.931		

	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	Cetaceans																					
2	Seals																					
3	Windfarm avoiding seabirds																					
4	Windfarm indifferent seabirds																					
5	Cod (adult)		0.066			0.008		0.002														
6	Commercial gadoids (adult)	0.017	0.117			0.123	0.007	0.097							0.002							
7	Demersal predators	0.004	0.083	0.001	0.002	0.000	0.001	0.019							0.000							
8	Pelagic small gadoids	0.051		0.000	0.013	0.096	0.249	0.141	0.014			0.010	0.264	0.007	0.062	0.062	0.022					
9	Herring	0.148	0.006	0.060	0.049	0.065	0.067	0.159				0.001	0.004	0.000	0.005	0.000	0.001					
10	Sandeel and Sprat	0.495	0.317	0.395	0.256	0.069	0.343	0.166	0.002			0.326	0.053	0.012	0.360	0.192	0.055					
11	Mackerel	0.082		0.021	0.006	0.014	0.001	0.061								0.000						
12	Small pelagic fish	0.024	0.013		0.003	0.003	0.011	0.021	0.002			0.007	0.002	0.000	0.000	0.000	0.033					
13	Flatfish	0.000	0.250	0.000	0.003	0.289	0.007	0.050						0.012	0.029	0.023	0.039					
1	Large demersal fish			0.00	0.01	0.00	0.00	0.00							0.00	0.00						

4				0	5	0	0	1							0	0						
15	Small demersal fish	0.010	0.148	0.001	0.003	0.061	0.032	0.100				0.012	0.050	0.010	0.058	0.057	0.006					
16	Squid & cuttlefish	0.044		0.000	0.004	0.002	0.006	0.039				0.017	0.000	0.001	0.002	0.014	0.055	0 (0.0002)				
17	Zooplankton	0.126		0.001	0.020	0.001	0.106	0.030	0.758	0.978	0.704	0.286	0.518	0.015	0.027	0.172	0.525	0.129		0.000		
18	Large crabs			0.011	0.031	0.104	0.012	0.013						0.015	0.100	0.038			0.001			
19	Large benthic invertebrates			0.367	0.029	0.162	0.131	0.092	0.184		0.005	0.005	0.054	0.435	0.163	0.228	0.021	0.000	0.605	0.092		
20	Small benthic invertebrates			0.109	0.029	0.002	0.027	0.008	0.041	0.022	0.191	0.155	0.001	0.492	0.191	0.212	0.188	0.017	0.195	0.231	0.128	
21	Microflora (incl Bacteria protozoa)										0.060	0.182	0.052					0.059	0.099	0.333	0.537	0.125
22	Phytoplankton										0.040						0.055	0.754		0.019	0.036	
23	Detritus and discards			0.033	0.471													0.042	0.101	0.326	0.299	0.875
	Import				0.067																	
	Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 10. Diet matrix of balanced model. In bracket and red, the values before balancing, changed to corresponding values in black.

Table 11. Comparison between original and simplified model-estimated inputs (in blue) for trophic groups directly comparable.

	Group name	***TL***	***B (t/km²)***	***P/B (/year)***	***Q/B (/year)***	***EE***	***P/Q***
original	Seals	4.98	0.008	0.090	26.842	0.000	0.003
simplified	Seal	4.89	0.008	0.090	26.842	0.000	0.003
original	Diving seabirds	4.06	0.004	0.450	86.970	0.000	0.005
simplified	Windfarm avoiding seabirds	4.08	0.004	0.450	86.970	0.000	0.005
original	Surface-feeding seabirds	3.21	0.002	0.237	77.280	0.000	0.003
simplified	Windfarm indifferent seabirds	3.14	0.002	0.237	77.280	0.000	0.003
original	Cod (adult)	4.81	0.130		2.170	0.911	0.548
simplified	Cod	4.67	0.130	1.190	2.170	0.916	0.548
original	Mackerel	3.89	0.750	0.600	1.730	0.745	0.347
simplified	Mackerel	3.75	0.750	0.600	1.730	0.772	0.347
original	Squid & cuttlefish	3.82	0.060	4.500	15.000	0.992	0.300
simplified	Squid & cuttlefish	3.61	0.060	4.500	15.000	0.825	0.300
original	Large crabs	3.76	1.200	0.550	2.750	0.994	0.200
simplified	Large crabs	3.68	1.200	0.550	2.750	0.961	0.200
original	Phytoplankton	1.00	7.500	286.667		0.212	
simplified	Phytoplankton	1.00	7.500	286.667	0.000	0.208	

4. Ecosim

In Ecosim, the process of calibrating the model to data takes place in two different steps, both based on time series of data: 1) fitting the model to time series for estimating predator-prey parameters which influence the changes to biomass in time; 2) assessing whether the parameterisation leads to credible behaviour (Heymans et al., 2016).

The original model used 116 time series (1991-2013) mainly including data of biomass, catches, fishing effort, Z (total mortality) and F (fishing mortality), out of 300 time series available in the complete dataset (ICES, 2015). For the simplified model, we aggregated the 116 time series by group, reducing them to 50 time series. The time series were weighted across groups, to obtain time series at the group level of our model (i.e. for 23 groups). For biomass and catches time series were summed; for F time series were calculated as weighted average using weights of biomass. If biomass for a group was missing, its contribution was estimated based on its weight in biomass. The weight factor of the time series was also weighted by the respective biomasses in the same way as for basic input (see paragraph 2.4).

4.1 Fitting to time series

Fit to time series was performed using the stepwise fitting procedure (Scott *et al.*, 2015). This procedure seeks the best fit across a range of time series, modifying the vulnerability parameter V (which regulates the trophic interaction) alternatively by predator only, or for predator/preys interactions. The selection criteria “baseline”, “fishing” and “fishing and vulnerabilities” were selected, using up to 33 time series of catches and biomass to be tested for best fit. Time series were tested with and without fishing, for predator only and predator/prey. This allowed to identify the combination of vulnerabilities setting providing the overall best fit. Primary production anomalies were not included in the estimation of vulnerabilities. For the simplified model, no environmental drivers were included either in the estimation of the Vs nor the fitting. That’s because during game play, Ecospace does not use environmental drivers from Ecosim. Fishing was included in the estimation of the Vs and in fitting, and then removed when Ecospace is used for MSP game play. In addition to optimising for the whole set of species, an optimisation was ran including only a subset of key species in order to provide a focus on the species and groups of most interest in the simplified model. The key species used were: Cod, Commercial gadoids, Demersal predators, Mackerel, Herring, Sandeel and sprat, Flatfish and Large benthic invertebrates. Sum of Squared residuals (SS) of the key species was used as a measure to identify the three best runs for predator only and three best run for predator prey. Among these, the best absolute run was finally selected based on Akaike Information Criteria (AIC), a commonly used metric of model comparison (Burnham and Anderson, 2002) available in Ecosim. The combination of vulnerabilities with best fit is highlighted in table 12, and the corresponding vulnerability matrix is shown in table 13.

Table 12. Three best runs (model iterations) by SS of the key species for predator-prey and for predator only relationships. Number of vulnerabilities changed (Vs), SS for all species, SS of key species alone, AIC are shown for each model iteration. ΔAIC shows the difference between the best AIC and the others. The overall best model iteration (Fishing and 31v) is highlighted with bold font.

Predator-prey

model iteration	Vs	K	SS total	SS key species	AIC	ΔAIC
Fishing and 31v	**31**	**31**	**391.535**	**89.753**	**-446.018**	**0.000**
Fishing and 26v	26	26	400.246	89.124	-440.012	6.006
Fishing and 27v	27	27	399.593	89.182	-439.110	6.908

Predator only

model iteration	Vs	K	SS total	SS key species	AIC	ΔAIC
Fishing and 8v	8	8	449.671	97.399	-388.769	57.250
Fishing and 9v	9	9	440.967	94.941	-401.654	44.365
Fishing and 10v	10	10	436.004	97.278	-408.248	37.771

Table 13. Vulnerability matrix providing the best fit to data and used in the model

	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	Cetaceans	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2	Seals	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
3	Windfarm avoiding seabirds	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
4	Windfarm indifferent seabirds	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
5	Cod (adult)	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
6	Commercial gadoids (adult)	2	2	2	2	1	2	1.546915	2	2	2	2	2	2	2	2	2	2	2	2	2	2
7	Demersal predators	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
8	Pelagic small gadoids	2	2	2	2	2	1.00E+10	1.00E+10	2	2	2	2	2	2	2	2	2	2	2	2	2	2
9	Herring	2	2	2	2	1	2	1.00E+10	2	2	2	2	2	2	2	2	2	2	2	2	2	2
10	Sandeel and Sprat	2	2	2	2	2	2	1.00E+10	2	2	2	1	2	2	2	2	2	2	2	2	2	2
11	Mackerel	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
12	Small pelagic fish	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
13	Flatfish	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

14	Large demersal fish	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
15	Small demersal fish	2	1.00E+10	2	2	2	1.00E+10	1.00E+10	2	2	2	2	2	1	2	2	2	2	2	2	2	2
16	Squid & cuttlefish	2	2	2	2	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
17	Zooplankton	2	2	2	2	2	2	2	1	1.00E+10	2	1	2	2	2	2	1	2	2	2	2	2
18	Large crabs	2	2	2	2	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2
19	Large benthic invertebrates	2	2	2	2	1	2	1.00E+10	2	2	2	2	2	1.00E+10	2	2	2	2	1	2	2	2
20	Small benthic invertebrates	2	2	2	2	2	2	2	2	2	2	1	2	3.413447	2	2	2	2	2	2	2	2
21	Microflora (incl Bacteria protozoa)	2	2	2	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2
22	Phytoplankton	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
23	Detritus and discards	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

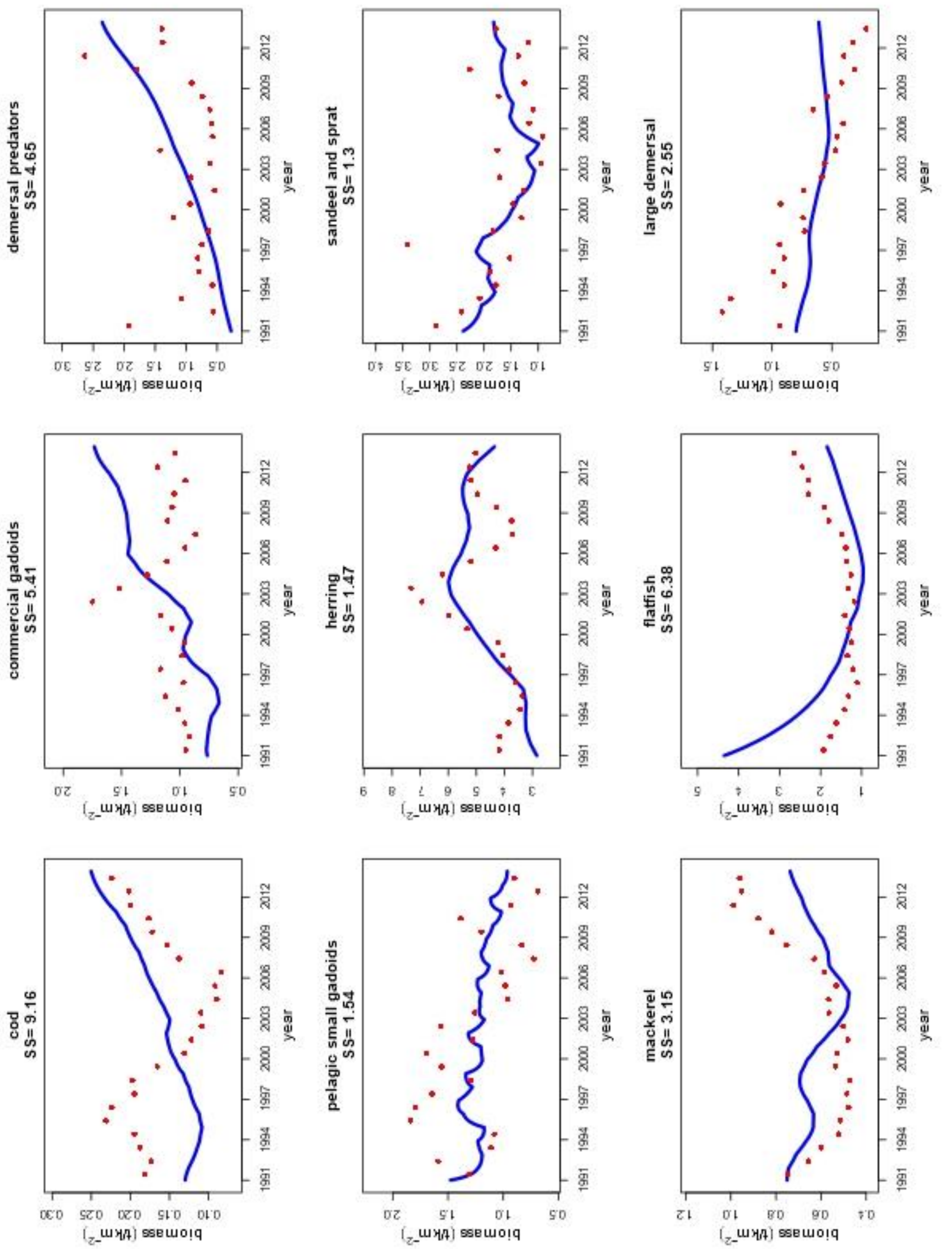


Fig. 2. Fits of biomass of selected groups. Biomass (t/km^2) modelled trajectories (blue line) are compare with time series of data (red dots). Sum of Squared residuals (SS) are shown as measure of goodness of fit.

The fit to time series was judged reasonable for most groups (Fig. 2), and the dynamics of the species in time (also in the long term) were realistic (Figs. 3 and 4). The increase observed in demersal predators is confirmed by the data. The figures below, plotted with time series, show the dynamics of all groups in 23 years of simulation for which data are available, and for a longer period (75 years) with fishing pressure maintained at the level of the last year of data. These dynamics show stable dynamics for most groups, with the increase in demersal predators being supported by data.

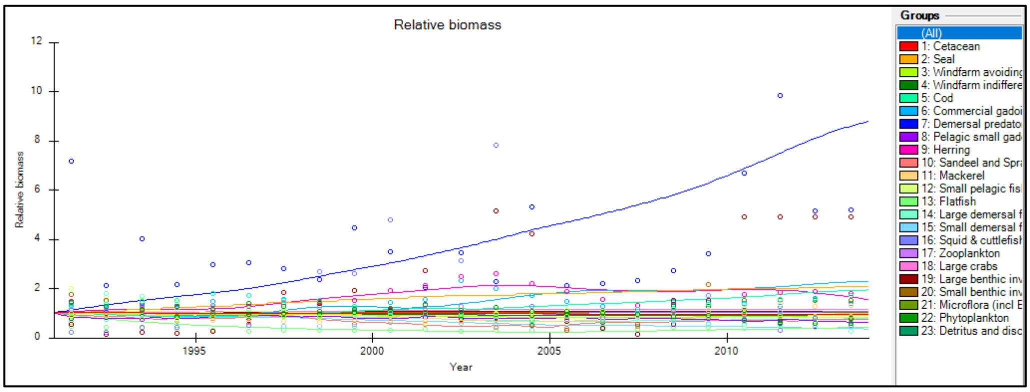


Figure 3. Simulation with time series, 23 years. The group showing largest increase in biomass is demersal predators (blue line).

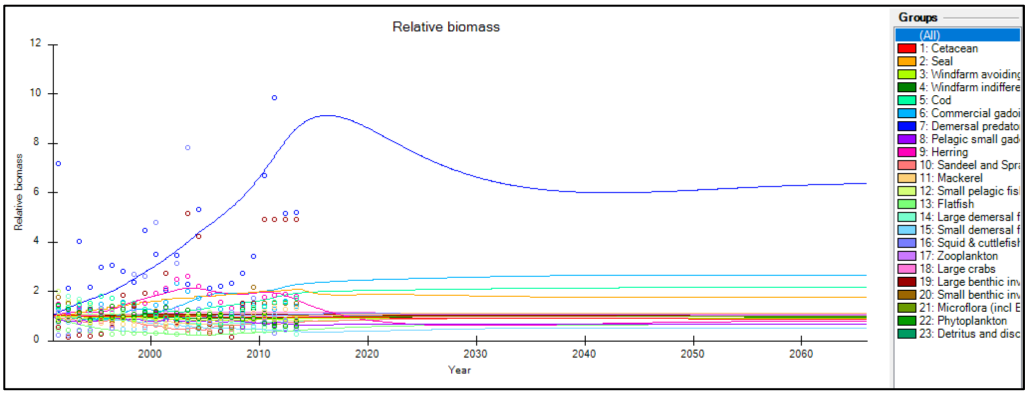


Figure 4. Simulation with time series, 75 years. Fishing effort kept at constant level after the end of time series. The group showing largest increase in biomass, followed by stabilisation, is Demersal predators (blue line).

5. Ecospace

Ecospace is based on the Ecopath and Ecosim models, from which it inherits all inputs. Ecospace distributes the groups' biomasses across a map, divided in equally sized cells. Species are distributed based on habitat, defined as groups of cells with similar characteristics, and the flow of biomass depends on dispersal rates. Settings of habitat, dispersal rate and other parameters are required. Values for these parameters are usually based on data obtained from literature, field experiments and surveys.

Fishing effort intensity in the Ecospace model was kept at default levels, as fishing effort can be varied by MSP players during game play. The model is assumed to be stable in time, so any temporal forcing must be excluded. For this reason, all time series and efforts used in Ecosim were removed for Ecospace parameterisation, and only included for validating model realism.

The approach followed for building a suitable Ecospace model for coupling with MSP was incremental approximation, guided by literature searches through published data. The model was calibrated with initial settings based on literature and ecological reasoning. Thereafter, the model's reactions to these settings was tested to achieve the expected responses:

a) flat-line biomass dynamics, when no environmental pressure was in place, to allow the MSP game to run smoothly without change, i.e. replicating an "ecosystem in balance". The principle is that, during gameplay, the only changes to the ecosystem dynamics should be caused by game play actions. Thus, the ecosystem in itself should be at a stable state.

b) the ecosystem should respond realistically to the various pressures, individual or combined, that the MSP game is expected to experience. The responses should be clearly visible for the purpose of game play, but ecologically sensible and realistic, i.e. not excessive. The system should be able to tolerate moderate pressures in the long run, and intense pressures for short amount of time. It should be able to recover in reasonable time-frame (compared to the gameplay and to the time scale of the model), and it should show complete collapse and lack of recovery for long periods of time only when the intensity and duration of environmental pressures exceed realistic limits.

The model's performance and behaviour was tested against realistic and extreme level of pressures, alone and in combination. Initial settings were modified were needed, until the model performance was deemed satisfactory according to the two criteria outlined above and after testing the model performance upon linking with MSP Platform Edition interface. Finally, the model was tested using the MSP start-up layers, included in Ecospace through the MEL-emulator plug-in specifically developed for this purpose (Steenbeek, 2018b). These historical pressure layers include multiple, combined pressures, offering a benchmark to evaluate the model performance under the amount and intensity of stress and impacts it will undergo during game play.

5.1. Model map

The map was designed following the requirement of MSP game in terms of spatial coverage. Selected spatial resolution was a compromise between game play and computational speed (high spatial resolution maps increase computational demand and reduce EwE-MSP game play speed). Some areas not considered useful for gameplay (i.e. outside of the game area, or in fjords and coastal areas), were excluded from computations through the Ecospace 'excluded cells' feature. Following Romagnoni *et al.* (2015), habitats were mainly based on depth. The depth layers were obtained from EUSeaMap. Four habitats are based on depth distribution bands (0-22m, 23-55, 56-115, >115); a fifth habitat, "coastal", includes shallow areas with hard substrate (mostly distributed around the Scottish coastline), while the 0-22m habitat type covers mainly soft substrate. Additionally, for the purpose of MSP gameplay, an "artificial habitat" was included in the map. At initialisation, no cell is assigned to this habitat, which is instead placed by action of players. The resulting map is shown in figure 5.

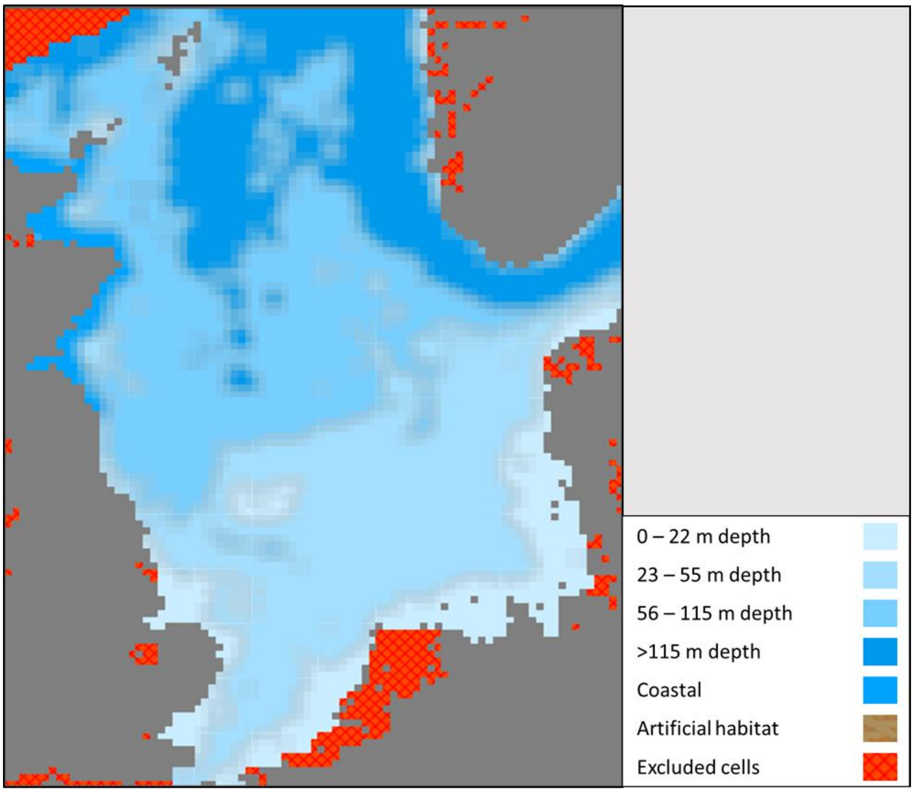


Figure 5. Ecospace map showing habitats by colour. Artificial habitat (not shown in the map as no initial artificial habitat was included in the base map) and Excluded cells, areas of either transitional land-sea habitat or otherwise out of the game area.

5.2 Ecospace parameterisation and initial settings

The main step in Ecospace model parameterisation is to populate the species habitat preferences matrix. These were initially based on literature information about species distribution and ecology. Artificial habitat was similarly set. Among the Ecospace parameters, Dispersal rate is the most important one (Romagnoni *et al*., 2015) so it was the only one modified.

5.2.1. Habitat

The species habitat preferences matrix assigns a value for each species/habitat pair between 0 and 1, where 0 means minimal preference for the habitat and 1 means strong affinity for the habitat (Christensen *et al.*, 2014). All groups were initially set with equal affinity for all habitats (value of 1, assuming all species are distributed everywhere). This value was gradually modified, reducing the proportion of foraging arena in habitats for those species which are known to be absent or uncommon, in certain areas. The distribution was based on ICES maps for fish and other commercially harvested or by-caught species available through the ICES FishMap portal as species fact sheets (ICES, 2018a). These maps are based on data obtained during the ICES International Bottom Trawl Survey (IBTS) (ICES, 2013). For species and groups were maps are lacking, distribution was complemented with the ICES Marine Data Map (ICES, 2018b). For Cetaceans, seals and the two seabird groups, the distribution was based on data from Emodnet biology portal (EMODnet, 2017).

- Cetaceans were distributed everywhere, based on their most important species, harbour porpoise, which is widespread.
- Seals were distributed mainly on the southern and western coast along English and in particular Scottish coast, and up to the Shetland. Windfarm avoiding seabirds are distributed more or less everywhere (although less abundant in habitat 0-22 m depth so this group was assign 0.8 in this habitat and 1 in all other habitats. Surface feeding seabirds are distributed more or less everywhere (although less abundant further from the coast) so they were given full preference to all habitats.
- Cod, based on ICES maps is slightly less abundant in the habitat 23- 55 m depth and in the coastal habitat.
- For commercial gadoids, maps for haddock, saithe and whiting showed that this group is distributed widely (especially whiting) but with a strong gradient and larger abundance in the northern area.
- Demersal predators are mainly composed of hake and monkfish. Hake is only distributed in deepest habitat 4 (Baudron and Fernandes, 2015); Monkfish is distributed in habitats 56-115 m depth, >115 m depth and coastal. This group was therefore excluded from the shallower parts of the basin (Tasker, 2008).
- For the demersal predators, only data for spurdog was available in the ICES FishMap portal. Spurdog is distributed mainly in the central and north. The distribution of other species from the ICES Ecosystem Data Map confirm this distribution.
- Pelagic small gadoids are distributed mainly in the central and northern part: the ICES FishMap portal reports a map only for Norway pout which was used as proxy for the whole group distribution. ICES Ecosystem Data Map confirm this distribution for blue whiting.

- Herring is widespread in the North Sea, and distributed more or less everywhere, with higher abundance in southern and central areas.
- Sandeel and sprat are mainly distributed in the southern part, especially sprat. Sandeel is also abundant around the west coast, according to the ICES Ecosystem Data Map.
- For flatfish, the ICES FishMap portal reports maps only for sole and plaice. These two species have a strong gradient being present exclusively in the southern part of the basin. Other species however are present also in the northern part, as confirmed by the ICES Ecosystem Data Map. The distribution was therefore initially assumed homogeneous.
- Large crabs are basically absent in the northernmost area according to the ICES Marine Data Map.
- For all other groups, a widespread homogeneous distribution was assumed.

Table 14. Habitat preference matrix at initial setting.

	Group \ habitat #	***All***	***0-22 m***	***23-55 m***	***56-115 m***	***>115 m***	***Coastal***	***Artificial habitat***
1	Cetaceans	0	1	1	1	1	1	0
2	Seals	0	1	0.7	1	1	1	0.3
3	Windfarm avoiding seabirds	0	0.8	1	1	1	1	0.2
4	Windfarm indifferent seabirds	1	0	0	0	0	0	0
6	Cod	0	0.3	0.5	1	1	1	0
8	Commercial gadoids	0	0.2	0.4	0.9	1	1	0
9	Demersal predators	0	0.1	0.2	1	1	1	0.2
10	Pelagic small gadoids	0	0.1	0.3	1	1	1	0
11	Herring	1	0	0	0	0	0	0
12	Sandeel and Sprat	1	0	0	0	0	0	0
13	Mackerel	1	0	0	0	0	0	0
14	Small pelagic fish	1	0	0	0	0	0	0
15	Flatfish	1	0	0	0	0	0	0
16	Large demersal fish	1	0	0	0	0	0	0
17	Small demersal fish	1	0	0	0	0	0	0
18	Squid & cuttlefish	0	1	1	1	1	1	0.3
19	Zooplankton	1	0	0	0	0	0	0
20	Large crabs	0	1	1	1	0.2	1	0.8

21	Large benthic invertebrates	0	1	1	1	1	1	0.6
22	Small benthic invertebrates	0	1	1	1	1	1	0.3
23	Microflora (incl Bacteria protozoa)	0	1	1	1	1	1	0.2
24	Phytoplankton	1	0	0	0	0	0	0
25	Detritus and discards	1	0	0	0	0	0	0

5.2.2. Dispersal

Dispersal in Ecospace is measured in km/year and is a measure of average swimming speed. It can be set between 0 and infinite and has a default value of 300 km/year. Dispersal is a measure of how fast a group will redistribute toward other areas as a result of pseudo-random movement. Its effect is particularly visible when the abundance of a group decreases or increases in a particular area, e.g. as a result of setting a MPA or a particularly suitable habitat. Organisms with high dispersal rates tend to arrive sooner in other areas, with limited visible effect of the MPA and high spill-over. Groups with low dispersal, conversely, will become locally abundant as result of local replenishment and limited spill-over. These settings are broadly reflecting the different effects of scale-specific ecological characteristics of different organisms: for example, large pelagic fish will benefit only marginally of a small, local protected area, but sedentary organisms will show large, albeit localised, benefit. Dispersal acts as the speed of immediate response to a disturbance (i.e. the speed to which organisms will relocate away from an impact, or colonise a new habitat, or disperse from a protected area where carrying capacity is reached). It can be a measure of body size for fish, or of dispersal of a species for sessile organisms. While cetaceans or fish will physically swim away from a disturbance within minutes, days or weeks, sessile benthic organisms will take few generations to actually move away, as a species, from an impacted area.

Dispersal in the model was initially set according to the a subjective criterion based on estimated movement capabilities, following Romagnoni et al. (2015): lowest for sessile and infaunal organisms (3), higher (30) for bottom dwelling organisms or for fish with limited movement and size, 300 for organism moving further such as some fish, and 600 only for large fish like cod and gadoids. Seabirds and cetacean were set to 1000 to reflect their capability of moving across the system. Seals were set to 300 because of their connection to land for resting in colonies.

The spatial and temporal dynamics with dispersal and other values at initial setting, with and without historical fishing pressure (Fig. 6-9) show that the ecosystem is well balanced. The dynamics of herring was however higher, if stable, than all other groups. For this reason, the dispersal of herring was modified from initial value of 30 to 300 after sensitivity tests. This change produced flat dynamic (Fig. 7) consistent with other groups and smoother spatial distribution consistent with data. Historical fishing pressure led to moderate changes in biomass which reach stability after few years (Figs. 8,9).

Table 15. Dispersal rate (in km/year) at initial setting.

	Group name	Dispersal rate
1	Cetacean	1000
2	Seal	300
3	Windfarm avoiding seabirds	1000
4	Windfarm indifferent seabirds	1000
5	Cod	600
6	Commercial gadoids	600
7	Demersal predators	600
8	Pelagic small gadoids	30
9	Herring	30
10	Sandeel and Sprat	30
11	Mackerel	300
12	Small pelagic fish	30
13	Flatfish	30
14	Large demersal fish	30
15	Small demersal fish	30
16	Squid & cuttlefish	30
17	Zooplankton	300
18	Large crabs	3
19	Large benthic invertebrates	3
20	Small benthic invertebrates	3
21	Microflora (incl Bacteria protozoa)	3
22	Phytoplankton	300
23	Detritus and discards	10

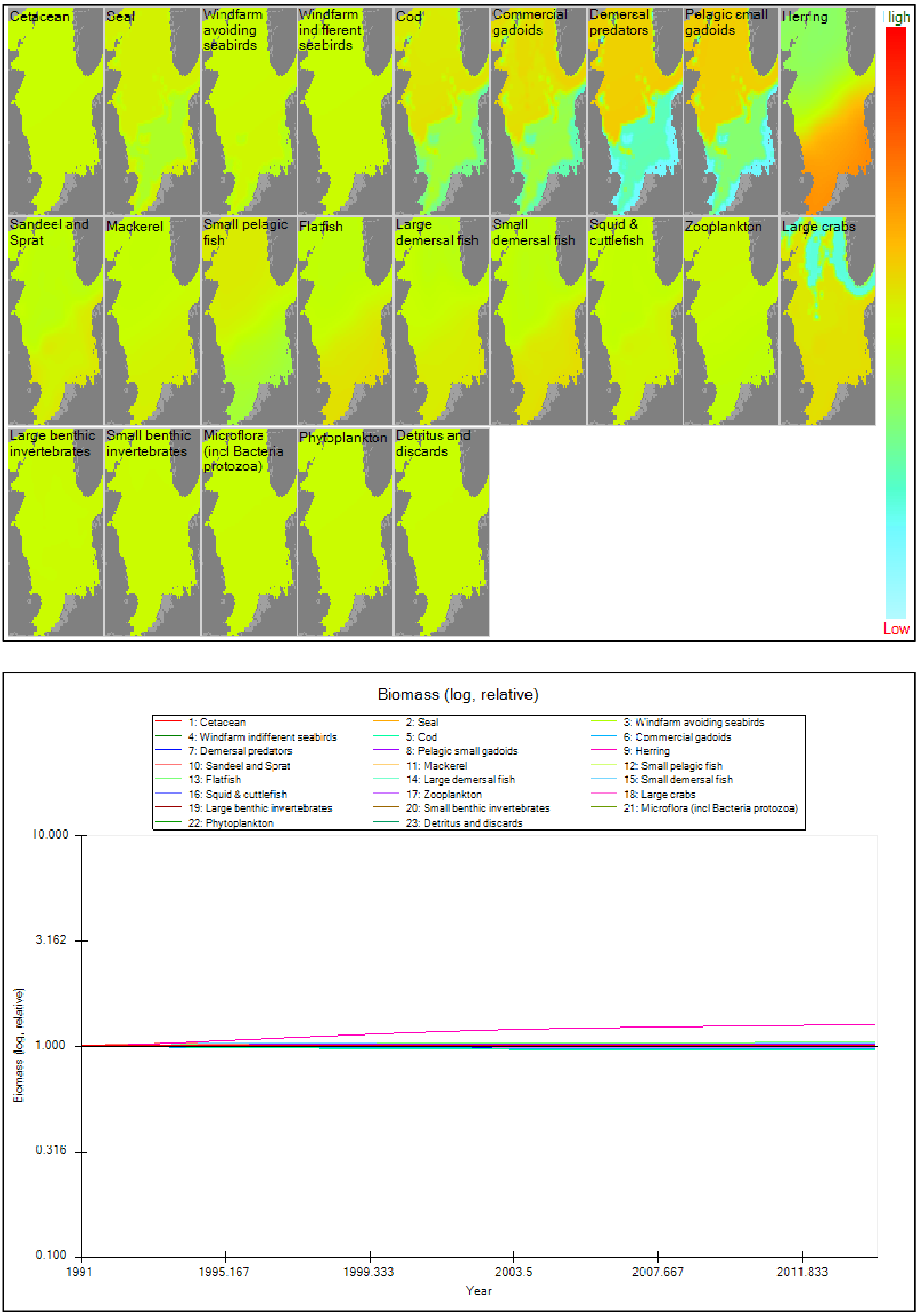


Figure 6. Spatial (top) and temporal (bottom) dynamics at initial setting, no impacts included.

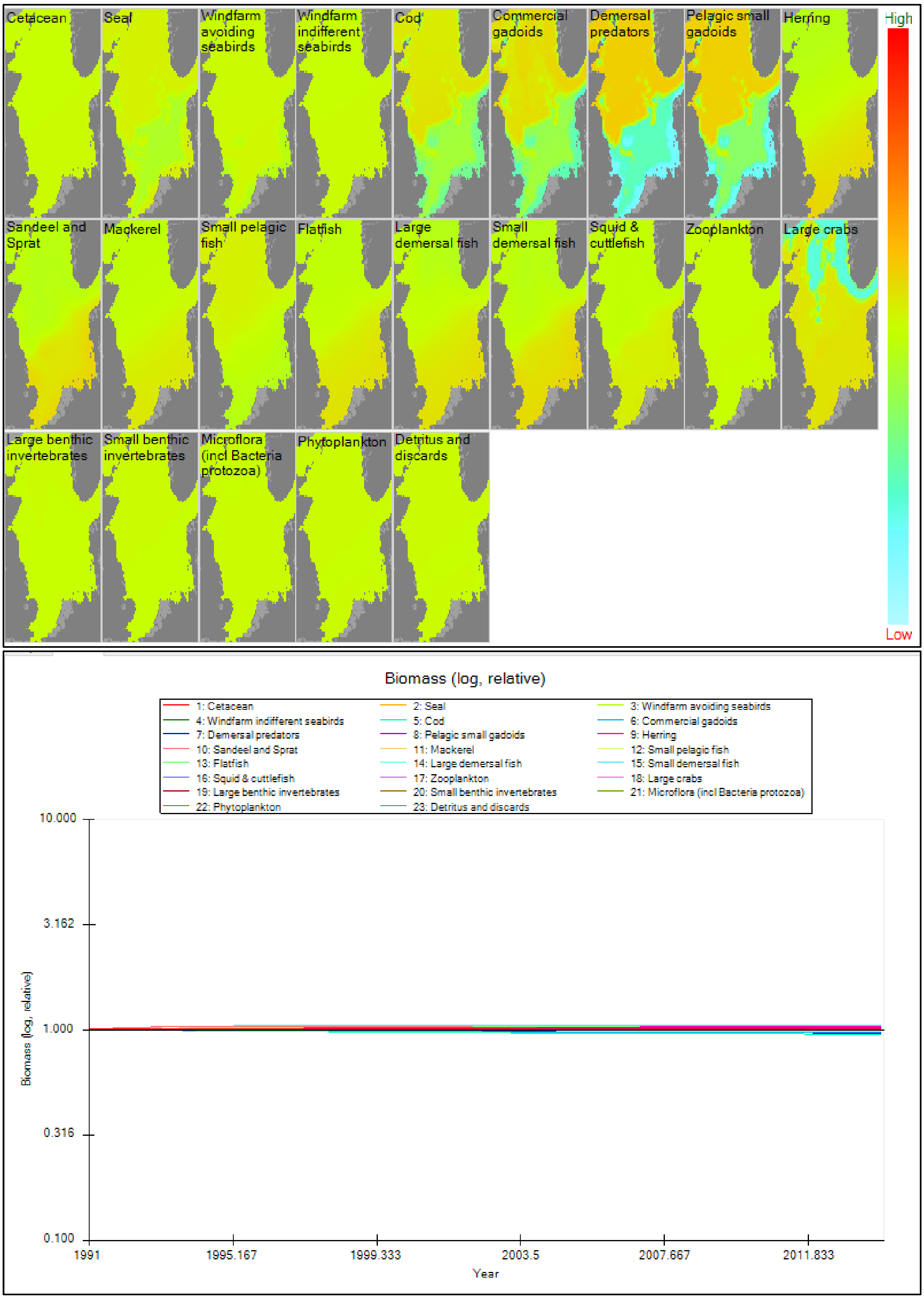


Fig. 7. Spatial (top) and temporal (bottom) dynamics at initial setting after herring dispersal was changed from 30 to 300. No impacts included.

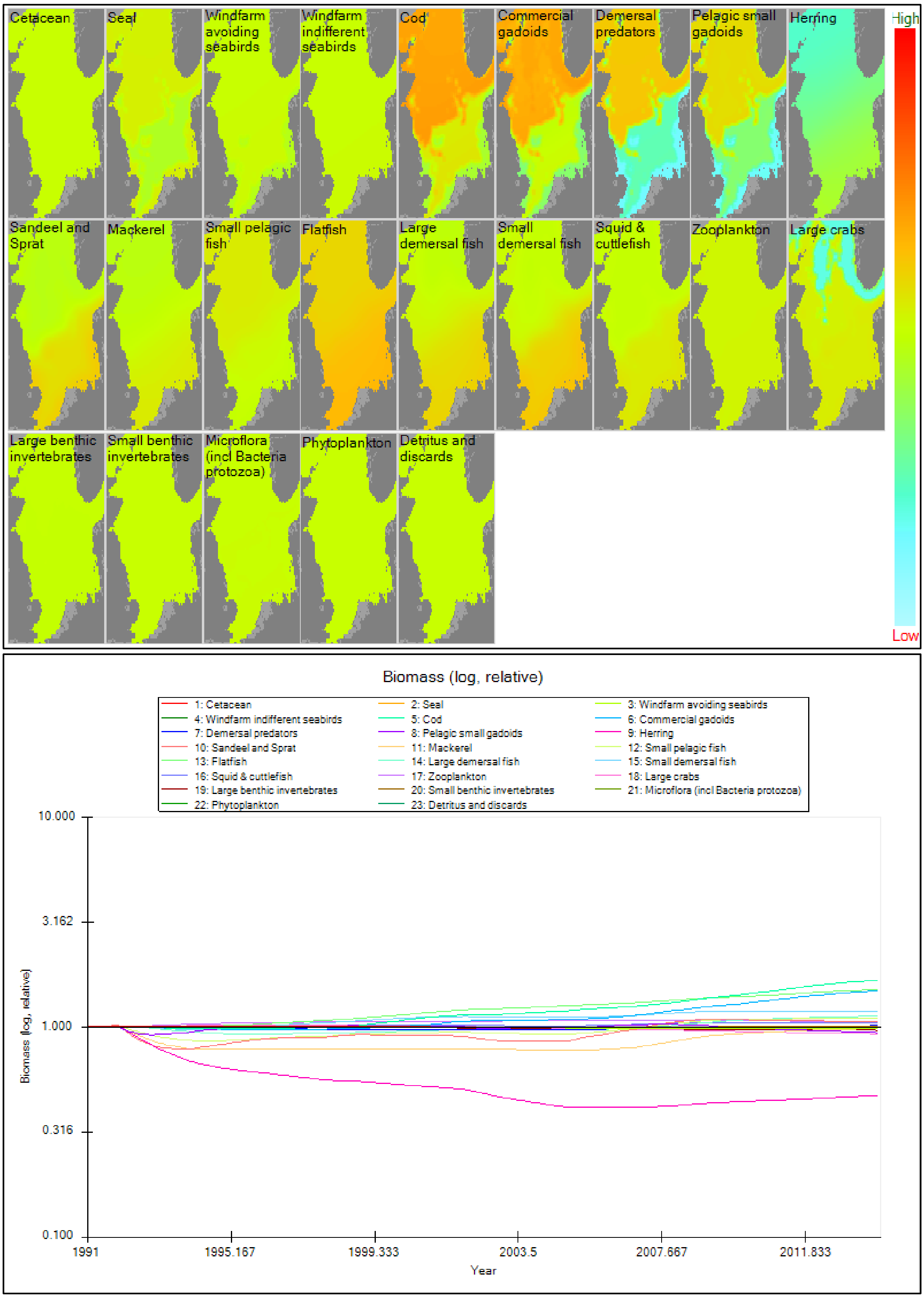


Fig. 8. Spatial (top) and temporal (bottom) dynamics at initial setting with historical time series of fishing effort

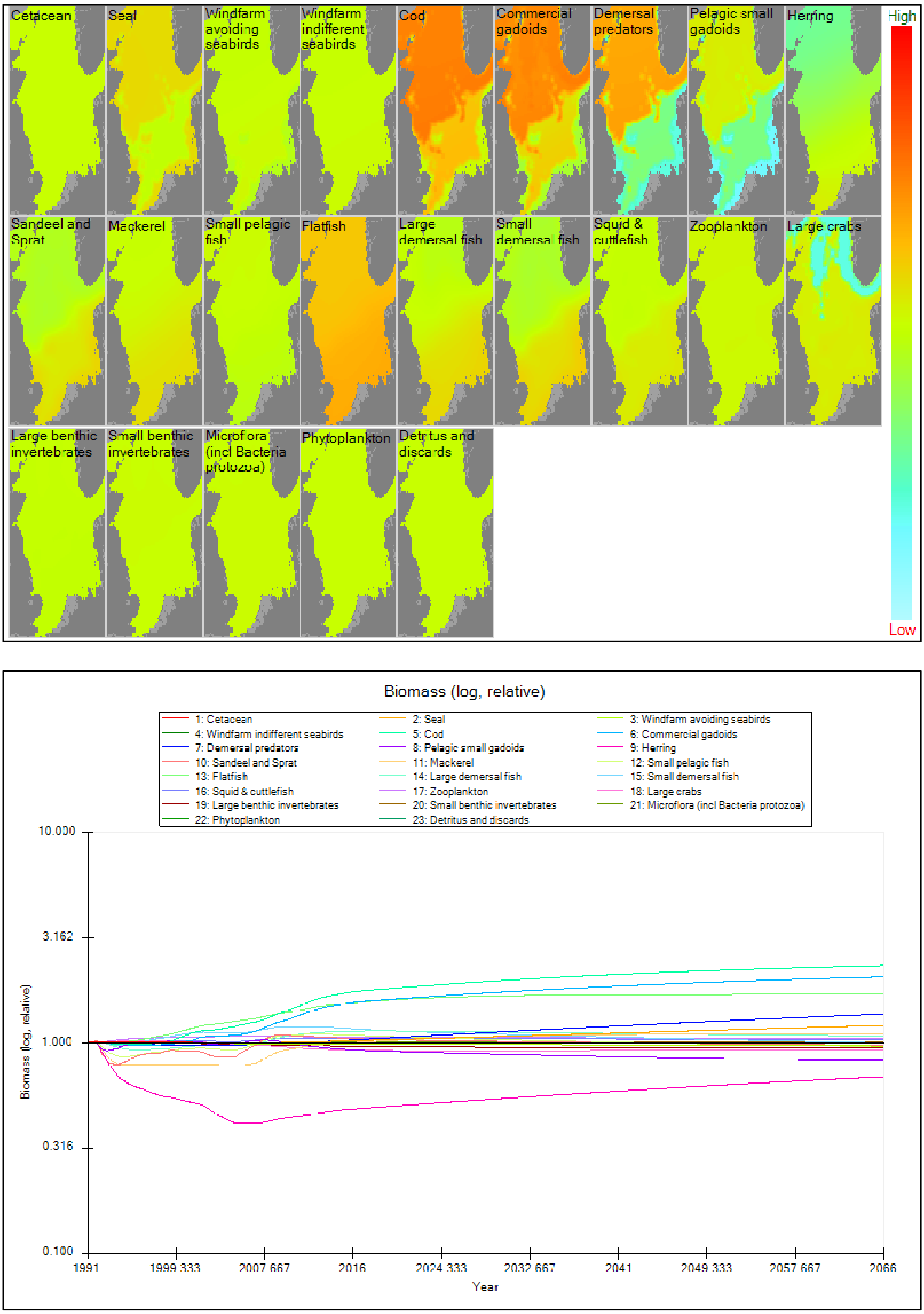


Fig. 9. Spatial (top) and temporal (bottom) dynamics at initial setting with historical time series of fishing effort prolonged for 75 years. Fishing effort kept at constant level after the end of time series.

5.3. MSP Challenge pressures and Ecospace responses

In MSP gameplay, players can plan and implement activities (e.g. setting windfarms, dredging, fishing, etc.). These are translated into a limited number of pressures through an activity-pressure matrix (table 16). Each activity corresponds to a level between 0 and 1 of each of the pressures included in the game. The values, quantified by experts within the MSP Platform Edition team, represent the impact in terms of pressure that would be applied to a cell if the activity occupied the whole cell area. Of course most activities occupy much smaller areas than the Ecospace cell (10 by 10 km), thus the pressure level in a given cell is weighted by the proportion of the area effectively impacted.

Pressures include:

- artificial habitat;
- protection from fishing (one layer for each fishing fleet) for simplicity called MPAs;
- fishing effort (one multiplier of base effort for each fishing fleet);
- noise;
- surface disturbance;
- bottom disturbance.

*Table 16. Activity pressure matrix. Pressures (taking into account 10*10 km cells) for each activity are given as a value from 0 to 1, where 0 means no impact and 1 means extremely high impact for a particular pressure. Each activity can be set as either open or close to fishing through the protection layers (one for each fleet). Protection is set as a 0-1 value.*

Activity	***Artificial habitat***	***Noise***	***Bottom Disturbance***	***Surface Disturbance***	***Protection Bottom trawl***	***Protection Pelagic trawl***	***Protection Drift and fixed nets***
Aquaculture	**0.1**	**0**	**0**	**0.1**	**0**	**0**	**0**
Anchorages	**0**	**0**	**0.1**	**0.1**	**0**	**0**	**0**
Gravel Extraction	**0**	**0.3**	**1**	**0**	**0**	**0**	**0**
Electricity Cables	**0.1**	**0**	**0.1**	**0**	**1**	**0**	**0**
Telecom Cables	**0.1**	**0**	**0.1**	**0**	**1**	**0**	**0**
Unused Cables	**0.1**	**0**	**0**	**0**	**0**	**0**	**0**
Electricity Cables *(construction phase)*	**0**	**0.5**	**0.1**	**0**	**1**	**1**	**1**
Telecom Cables *(construction phase)*	**0**	**0.5**	**0.1**	**0**	**1**	**1**	**1**
Oil & Gas Instalations	**0.2**	**0.2**	**0.1**	**0.2**	**1**	**1**	**1**
Ports	**0.8**	**0.8**	**0**	**0.8**	**1**	**1**	**1**

Pipelines *(construction phase)*	0.1	0.5	0.5	0.3	1	1	1
Pipelines	0.1	0	0.05	0	1	0	0
Recreational Areas	0	0.1	0	0.2	0	0	0
Dredging Deposit Areas *(only open areas)*	0	0	0.8	0	0	0	0
NS Shipping Intensity	0	1	0	1	1	1	1
Tidal Farm *(construction phase)*	0.2	0.5	0.5	0.5	1	1	1
Tidal Farms	0.2	0.1	0	0.1	1	1	1
Wave Farm *(construction phase)*	0.1	0.5	0.5	0.5	1	1	1
Wave Farms	0.1	0.1	0	0.1	1	1	1
Wind farm *(construction phase)*	0.4	0.8	0.6	0.5	1	1	1
Wind Farms	0.4	0.2	0	0	1	1	0
Military Areas *(dumping areas only)*	0	0	0.4	0	1	1	1

- Artificial habitat represents areas of sea where hard structures are built. This includes for example oil platforms or windfarms, but also underwater cables, oil pipes, harbour structures, and so on. These hard surfaces are often attractive for numerous organisms such as encrusting invertebrates (blue mussel oysters, corals and sponges) and other organisms, including fish, that find food and shelter in these areas.

- Protection from fishing, or MPAs (Marine Protected Areas), is assigned as a 0-1 value: each cell is either open or close to fishing. Some areas might be open to only one type of fishing but not to others therefore the protection is set for each fleet independently. In MSP, the term “protection” is used, encompassing actual MPAs set for conservation purposes, technical fishing closures as well as areas closed to fishing to avoid interaction with other activities, e.g. shipping lanes, areas with cables, windfarms or oil and gas extraction platforms. As the effect for all of these is a restriction to fishing effort, specified by fleet type, these protection layers are all converted into Ecospace MPAs. Fishing boats are not allowed to enter MPAs. The assigned effort (driven in MSP by fishing effort multiplier, see below) must therefore be redistributed to the areas still open to fishing, leading to an increased effort in the remaining areas.

- Fishing effort is a multiplier of the default fishing effort value in the model. In the game, players can modulate the fishing effort individually, with the option to decrease effort from default to 0, or to increase to the maximum effort allowed (a ceiling corresponding to the level of effort causing a collapse of the target groups). The effort of each player is summed up to the total, which is used as a multiplier. This corresponds to the Total Effort Multiplier (TEM), a multiplier of Ecosim fishing effort, used in Ecospace to tweak the fishing pressure intensity.

- Noise includes, for example, activities such as windfarm pile driving, shipping traffic, recreational use of marine space and others.

- Surface disturbance includes for example pollution such as discharge from human activities and infrastructure, small-scale oil spills, marine litter, marine micro and macroplastics, and so on.

- Bottom disturbance includes physical damages to the seafloor such as those resulting from dredging or construction of oil and gas platforms and windfarms, pollution of the seafloor, and so on.

These last three pressure layers, called environmental drivers, represent some among the most impacting effects of the various activities exerted in the marine space by human use, thus they were included explicitly. However, their definition and effects on the system are maintained very broad (for example, no distinction between physical and chemical disturbance is drawn, nor between noise frequencies and intensities). The impact outlined should be intended as proxies of multiple impacts that fall within each of these categories. There is still limited understanding about the biological and ecological mechanisms through which all of these impacts affect the ecosystem and its components. Broad and general impacts therefore serve the purpose of the game better than detailed but incomplete and uncertain pressure layers.

Functional groups in Ecospace can exhibit individual preferences and tolerances to these environmental drivers through functional responses (Christensen *et al*., 2014). The habitat foraging capacity model dynamically evaluates the foraging capacity of each functional group across the grid, reducing local foraging capacity when environmental conditions worsen to the tolerances of a specific group. In order to capture the impact of player-induced environmental change on different functional groups, three functional response curves were initially defined: low negative impact, high negative impact, positive impact (figure 10). These are simple linear functional responses, where a given pressure value (determined by the pressure layer) corresponds to a response value being a multiplier of the habitat capacity, which translates in turn in “attractiveness” of each Ecospace cell for the group in question. The function has a base value =1 for pressure at zero; and a lower or higher value for pressure increasing to its maximum of 1. In the used response function, low negative impact corresponded to a decrease of 10% habitat capacity at pressure of 1, and high negative impact corresponded to a decrease of 50%. Positive impact corresponded to an increase of 20%.

5.3.1. Functional responses setting

Responses were set based on known biological responses:

- Cetacean are mainly affected by surface disturbance (e.g. pollution; Baulch and Perry, 2004), and by noise (Middel and Verones, 2017), which heavily affects their behaviour, so these two pressures were set as "low impact" and "high impact" respectively.

- Seals are similarly affected by surface disturbance and by noise (Lindeboom *et al.*, 2011; Russell *et al.*, 2016), although noise could be less distressing than for cetaceans, so their response was set as "low impact" for both.

- Seabirds can be sensitive to noise so both groups were set as "low impact". Surface disturbance might have a negative, but also a positive aspect: in fact, seabirds are known to be attracted by e.g. fishing boats, and can scavenge on discarded fish. For this reason, they were set as "positive impact" for surface disturbance.

- Large crabs, large benthic invertebrates and small benthic invertebrates are all assumed to be highly impacted by bottom disturbance, and were all set to "high impact" (Stronkhorst et al., 2003).

- All other groups were initially set as no impact.

Table 17. Functional responses by pressure (noise, surface disturbance, bottom disturbance) as assigned for each group in the ecosystem, at initial settings.

	Group name	***Noise***	***Surface disturbance***	***Bottom disturbance***
1	Cetacean	High	Low	
2	Seal	Low	Low	
3	Windfarm avoiding seabirds	Low	Positive	
4	Windfarm indifferent seabirds	Low	Positive	
5	Cod			
6	Commercial gadoids			
7	Demersal predators			
8	Pelagic small gadoids			
9	Herring			
10	Sandeel and Sprat			
11	Mackerel			
12	Small pelagic fish			

13	Flatfish	
14	Large demersal fish	
15	Small demersal fish	
16	Squid & cuttlefish	
17	Zooplankton	
18	Large crabs	High
19	Large benthic invertebrates	High
20	Small benthic invertebrates	High
21	Microflora (incl Bacteria protozoa)	
22	Phytoplankton	
23	Detritus and discards	

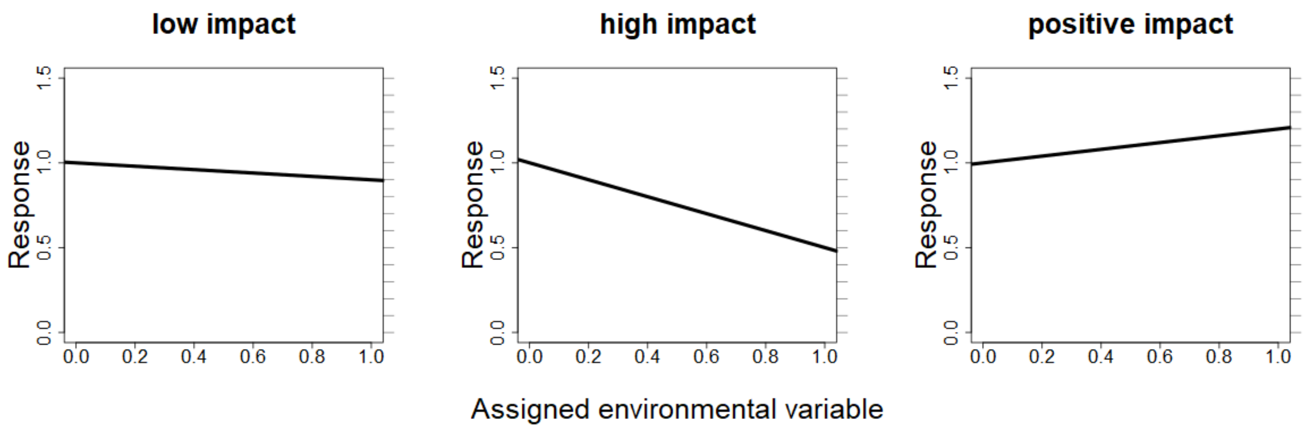


Figure 10. Functional responses for low impact, high impact and positive impact to environmental variables, i.e. pressures.

5.3.2. Artificial habitat and MPAs

MSP artificial habitat offers additional substrate to groups with a preference to this type of habitat, increasing niche suitability in each cell where artificial habitat is present (Christensen *et al.,* 2014). Potential negative effects from artificial habitat have to be dealt with through functional responses. Values included in artificial habitat affinity account for additional feeding benefits for a given functional group, where a value of 1 indicates that the cell is fully usable for foraging. Initially, the model has no artificial habitat in the map as this layer will be included during game play.

Group-specific preferences for artificial habitat are included at initialisation, and assignments were based on the fact that some species draw benefit from the presence of man-made structures such as windfarm piles, oil platforms, submerged structures, etc. For example, seals can benefit from using emerged artificial habitats as haul out sites, and seabirds can use them for resting (Dierschke *et al.*, 2016). However, in the MSP game the category of artificial habitat is broad and simplistic, including both emerged and submerged structures, which do not have a clear beneficial effect on these two groups. Therefore, the choice of preference values were compromises between these two aspects.

- Cetaceans, and especially harbour porpoises, are known to gather around artificial substrate (Scheidat *et al.*, 2011; Todd *et al.*, 2016) however it is unclear whether the effect is driven by actual preference for the area, by the higher abundance of food driven by the local closures or by the limited disturbance from shipping (Bergström *et al.*, 2014; Scheidat *et al.*, 2011). Both of the latter effects should be captured by the food web and by the displacement due to shipping; so the preference for artificial habitat for cetaceans was initially set at 0.
- Seals, based on the compromise between benefit and avoidance, and evidence of preference for some artificial habitat areas (Russell *et al.*, 2014) was set at 0.3
- Windfarm avoiding seabirds were set at 0.2 to represent the advantage provided by resting opportunities provided by artificial habitat, while windfarm indifferent seabirds were left at default.
- Cod, commercial gadoids and demersal predators are known to gather around artificial habitats (Løkkeborg *et al.*, 2002; Reubens *et al.*, 2013; Soldal *et al.*, 2002), presumably due to the larger abundance of prey fish (the reef effect), or to find shelter, or simply because these areas are closed to fishing activities thus acting as *de facto* MPAs (Bergström *et al.*, 2014). The benefit from increased prey opportunities in artificial habitat area should be captured by the food-web effect. The increased sheltering opportunities, instead, is not expected to be captured by the food-web effect, and can be included by setting artificial habitat as favourable habitat. For these groups, a value of 0.2 was used.
- Squid and cuttlefish were set at 0.3, under the assumption that, in addition to food and shelter, hard substrate can be important for attaching adhesive eggs.
- Large crabs, large invertebrates, and small invertebrates benefit substantially by artificial substrate (Bergström *et al.*, 2014; Bray *et al.*, 2016; Hooper and Austen, 2014; Krone *et al.*, 2013, 2016), through increased shelter and three-dimensional space. For many hard-substrate dwelling organisms, artificial substrate creates effectively an island of habitable area in the middle of otherwise non-inhabitable soft sediment areas. For this reason, artificial substrate was set at 0.8 for large crabs, 0.6 for large invertebrates, 0.3 for small invertebrates and 0.2 for microflora, which was assumed to also benefit from the increased habitat. All habitat setting at initial stage are reported in table 14.

MPAs are placed where fishing restrictions exist (Walters et al., 1999), either for conservation reasons or where other activities take place that prohibit fishing (e.g. windfarms, oil rigs, shipping routes or cables). Initially, the model has no MPAs as these layers will be included during game play. The effects of MPAs on fish and other organisms are not easy to assess, and largely depend on the spatial and temporal scale of observation, as well as the characteristics of the species and system of observation. In general, one can expect that an MPA will be efficient in protecting given its size, location (also in relation to other MPAs), age (i.e. since its establishment), and the degree of enforcement (Edgar et al., 2014). For the purpose of the MSP game, characteristics of the species such as the increase of biomass within a protected area and its redistribution outside (often called spill-over) were considered in the model parameterisation, and regulated through fine-tuning of the dispersal rates.

5.4. Stress tests

The model was subject to stress tests to assess its performance in terms of providing realistic and robust response to stressors such as the MSP pressures. The parameterisation was modified where needed after the tests.

Stress tests included:

- test of the responsiveness to MPAs;
- test to inclusion of artificial habitat;
- test of individual layers of noise, surface disturbance, bottom disturbance pressures;
- test to combined pressures, realistically simulating activities to be experienced during the game play (e.g. windfarms);
- changes to fishing intensity;
- Additionally, the resilience of the system to extreme and unrealistically high pressure levels was also tested. This exercise was useful to identify the limits of e.g. fishing pressure, and to assess whether reproduced patterns are consistent to the expected ecosystem dynamics under extreme pressures.

In the following, a selection of stress tests examples is provided.

5.4.2. Setting MPAs

After setting MPAs for either all or each individual fleets, the response of spatial distribution of target and non-target species was observed in order to visually assess:

a. whether protected species did benefit from MPA;
b. whether the species protected in the closed areas would propagate through spill-over effect, and whether the spill-over was unrealistically high or low.

The stress test highlighted that some species were dispersing too fast or too slow out of MPAs. In order to obtain more visible dynamics, the dispersal parameters were tweaked for some species. As an example, cod, commercial gadoids and demersal predators' dynamics were tested to the implementation of an MPA set only to restrict demersal trawlers. Dispersal rate for the three groups was decreased from 600 to 300, 100 and 200 respectively, after iterative tests. These setting provided higher concentration within the protected area and slower and more localised spill-over, more realistic compared to the initial setting (Fig. 11). Further reduction of dispersal rates provided excessive effects of MPAs and affected other aspects of the groups' dynamics.

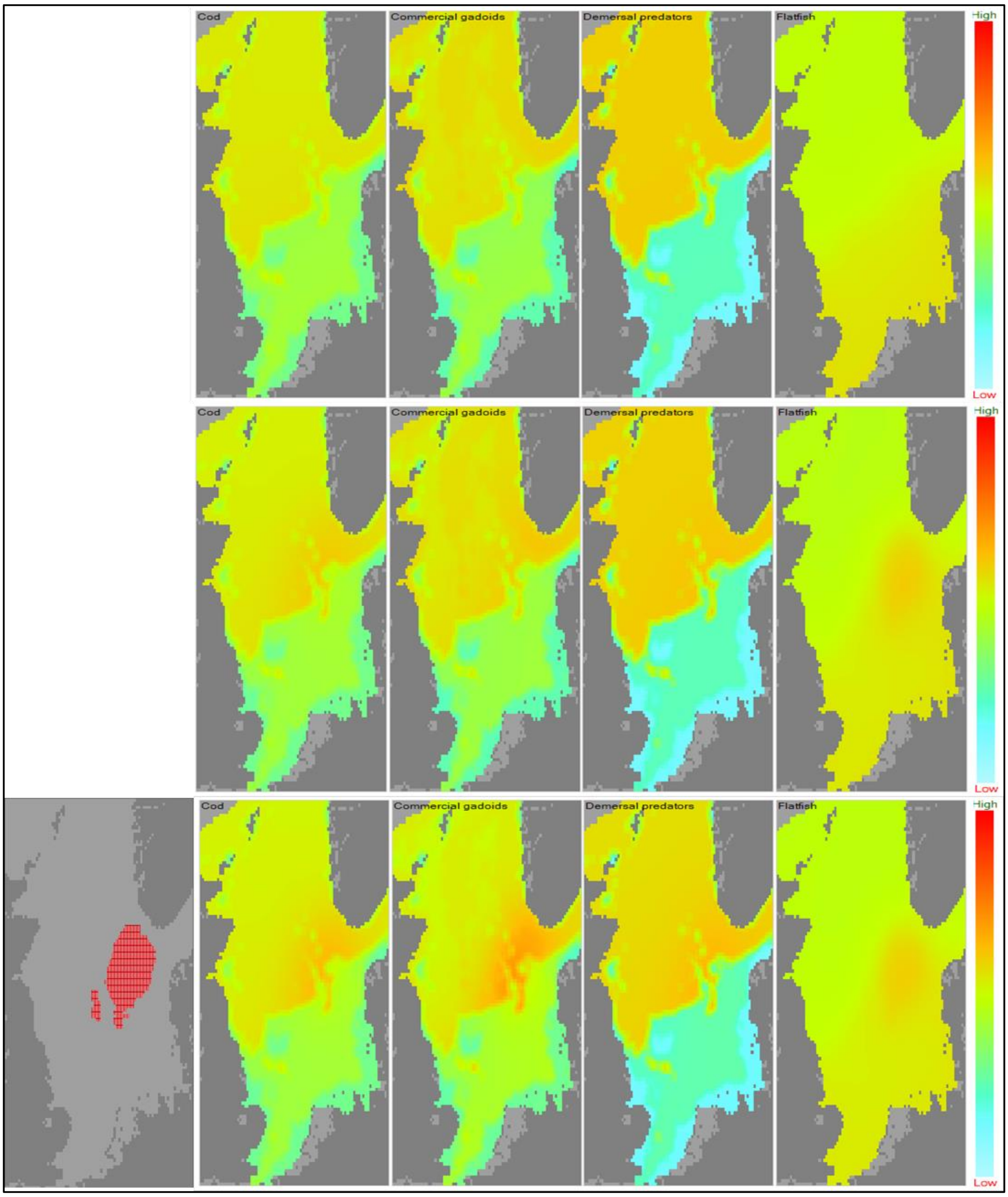


Figure 11. Biomass distribution and MPA (in red, bottom-left panel). Top panel: Biomass distribution before setting MPA; Dispersal for Cod, Commercial gadoids and Demersal predators set at 600 (i.e. initial setting). Central panel: Biomass distribution after setting the MPA. Dispersal for Cod, Commercial gadoids and Demersal predators set at 600 (i.e. initial setting). Bottom panel: Biomass distribution after setting the MPA. Dispersal for Cod, Commercial gadoids and Demersal predators set at 300, 100, 200 respectively. Flatfish (right panel in all three rows) shown for comparison.

5.4.3. Setting Artificial Habitat

The effect of setting small portions of patchy artificial habitat was explored. The effect of setting artificial habitat was assessed looking at the spatial distribution as well as the temporal dynamics of affected groups, which showed patterns related to the redistribution of biomass across the model area. Artificial habitats most strongly impacted large crabs. Inclusion of artificial habitat drives a reduction followed by stabilisation of large crabs' biomass, as well as high increase in biomass concentration in the artificial habitat area and reduced biomass everywhere else (Fig. 12). The reason is that species in Ecospace predicts species distributions, allowing large crabs to gradually move to more favourable habitat conditions created by man-made structures (and thus comparatively reducing biomass in all other areas). Higher large crab biomasses, however, also make these areas more attractive to large crabs' predators and for fisheries (in this example, unrestricted). This is irrespective of the size of the artificial habitat areas.

The dynamics of many other groups required some modifications through this test. Groups including cetacean, windfarm avoiding seabirds, cod and commercial gadoids are known to be attracted by the artificial habitat areas through increased food abundance; however, these results show that the model at initial setting could not capture such phenomenon. For this reason, these groups were assigned a preference for this habitat. Preference for artificial habitat of large crab was reduced from 0.8 to 0.3 because the large attractiveness of artificial habitat drove a general reduction of this group from all other areas, which was considered excessive. Preference of windfarm indifferent seabirds for artificial habitat was increased from 0 to 0.3, based on the fact that artificial habitat can provide resting areas for this group, and especially for cormorant (Dierschke *et al.*, 2016). Preference for cetaceans, cod, and commercial gadoids was increased from 0 to 0.2. These changes resulted in more responsive biomass distribution for these groups and reduced the negative effects on large crabs (Fig. 13).

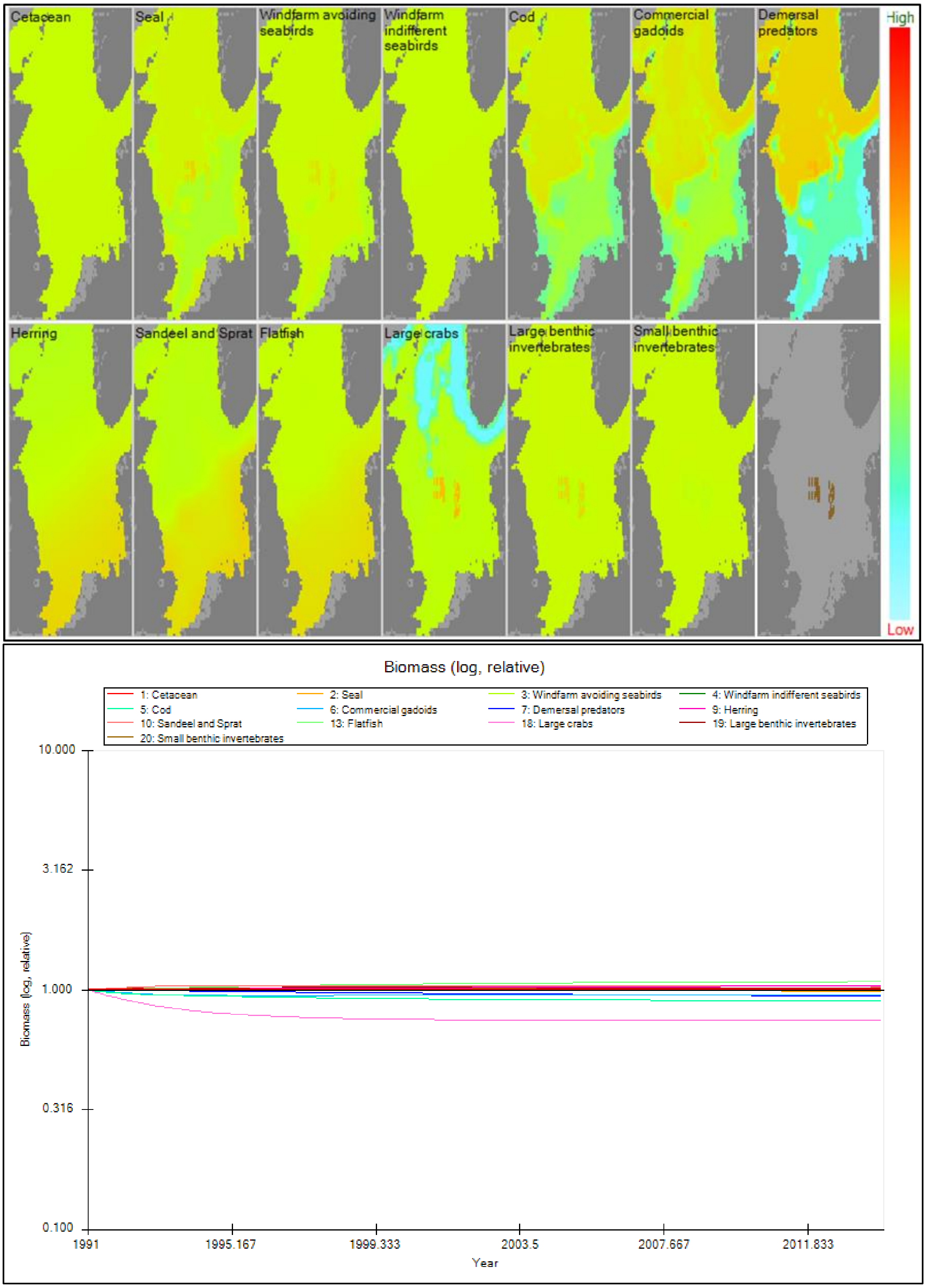


Figure 12. Spatial (top) and temporal (bottom) dynamics after inclusion of a test layer of artificial habitat (layer shown in the last panel, in brown). Large crabs (pink line) suffer slight decrease in biomass with artificial habitat.

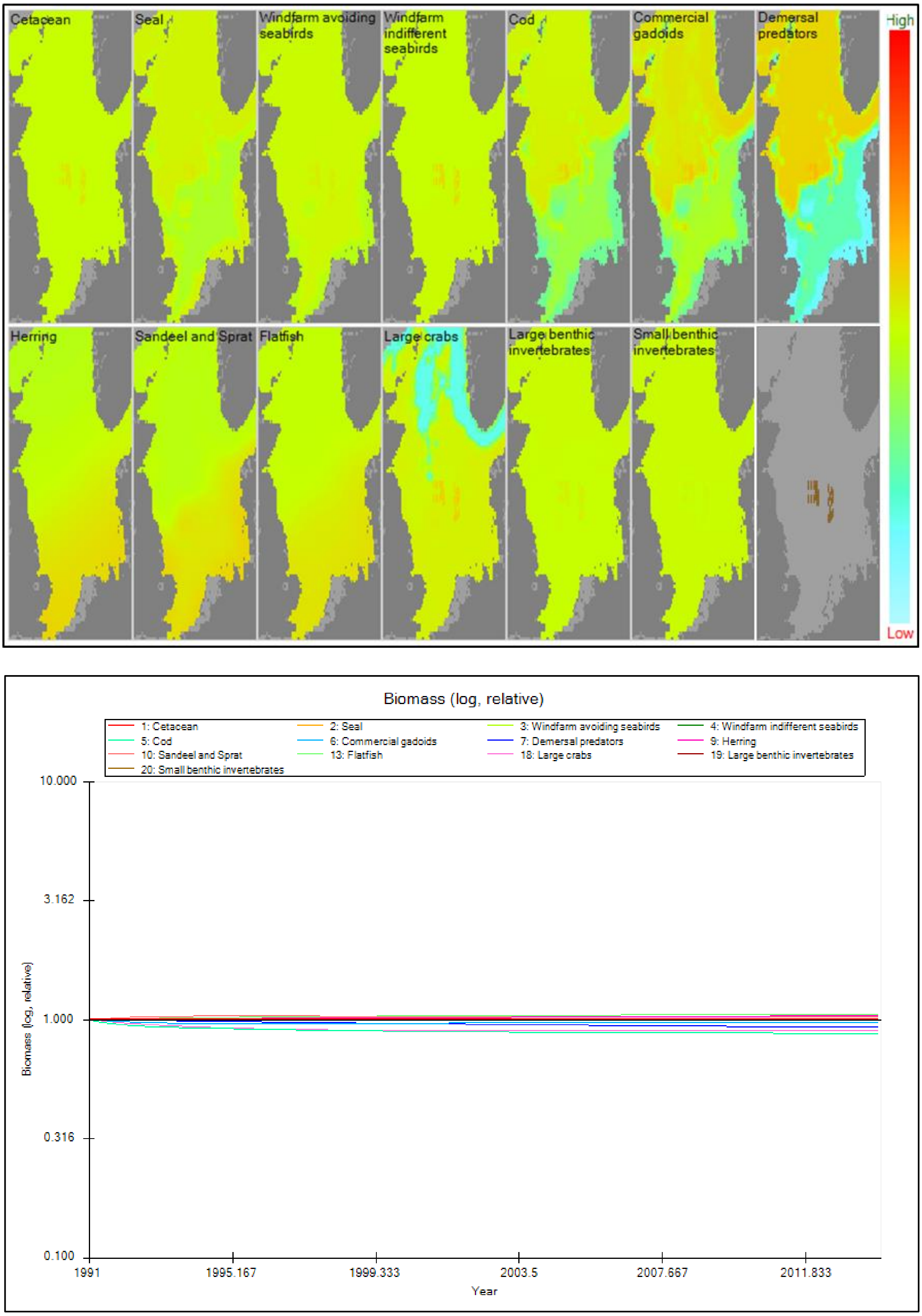


Figure 13. Spatial (top) and temporal (bottom) dynamics after inclusion of artificial habitat. Dynamics after modifying the setting for preference for artificial habitat.

5.4.4. Test of multiple pressures: windfarms

During game play, MSP impacts are not isolated from each other, but rather occur in combination: for example, when players set a windfarm in an area, this is translated into pressure layers of noise, artificial substrate, and MPAs for all fleets (see table 16). Therefore, testing noise or surface or bottom disturbance in isolation can be hard to evaluate and provide an incomplete picture. In order to test for a realistic behaviour of the model, the combined pressures of, for example, windfarm construction and operational phases must be tested. Windfarm construction phase include artificial habitat, noise (at high level), bottom disturbance and surface disturbance, while windfarm operative phase includes artificial habitat and noise (at milder level, see Table 16). Both phases include (in this example)[2] restriction to all fishing gears. The expectation is that construction leads to strong negative effects on cetaceans, seals, windfarm avoiding seabirds and windfarm indifferent seabirds; and that the operation phase leads to moderate increase in cetacean, seals, windfarm indifferent seabirds, large and small benthic invertebrates and large crabs, and negative effect on windfarm avoiding seabirds. Effect on fish species could be positive or negative due to the mixed effects of protection and of increased predation.

Figures 14 to 16 show the resulting spatial distribution of selected groups after placing randomly distributed windfarm patches. The results are mostly as expected: at construction (Figs. 14, 15), with high noise, surface and bottom disturbance, there is a visible negative impact on cetaceans and seals. There is also a negative impact on large crabs and a moderate negative impact on large and small benthic invertebrates. At the operative phase of the windfarm (Fig. 16), cetaceans, seals and windfarm indifferent seabirds are mildly attracted; cod, commercial gadoids, demersal predators and large crabs are strongly attracted, and large and small benthic invertebrates mildly attracted. These patterns reflect most of the expected changes that the main groups should display upon construction and operational phases of windfarms. Windfarm avoiding seabirds showed however a positive response to windfarms rather than the expected negative response. Their preference for artificial habitat was thus reduced from 0.2 to 0, following indication that windfarm avoiding seabirds (such as the species included in this group) do not benefit from windfarms but will actually be displaced from these areas (Dierschke *et al.*, 2016).

[2] In the final version of the MSP game, the setnet and driftnet fleet was allowed to fish in windfarms during the operational phase.

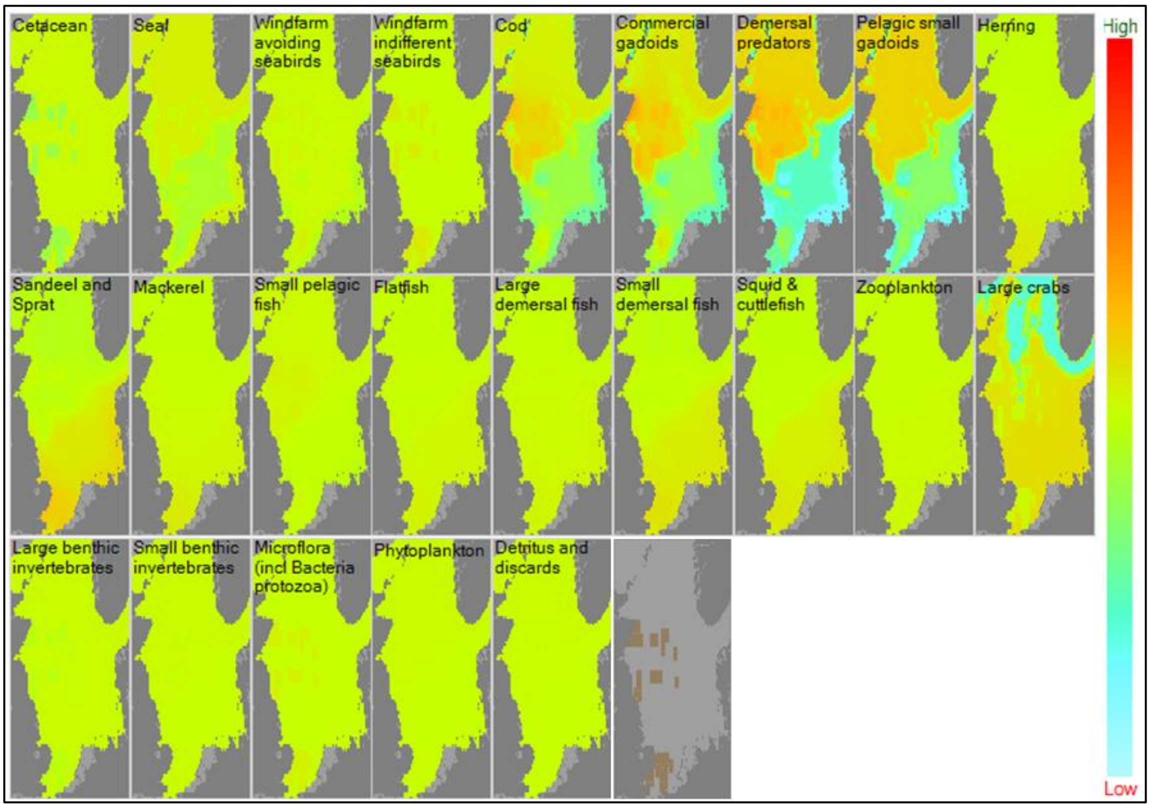


Figure 14. *Spatial distribution of all groups under the impact of a set of pressure layers corresponding to the impact of windfarm during construction phase.*

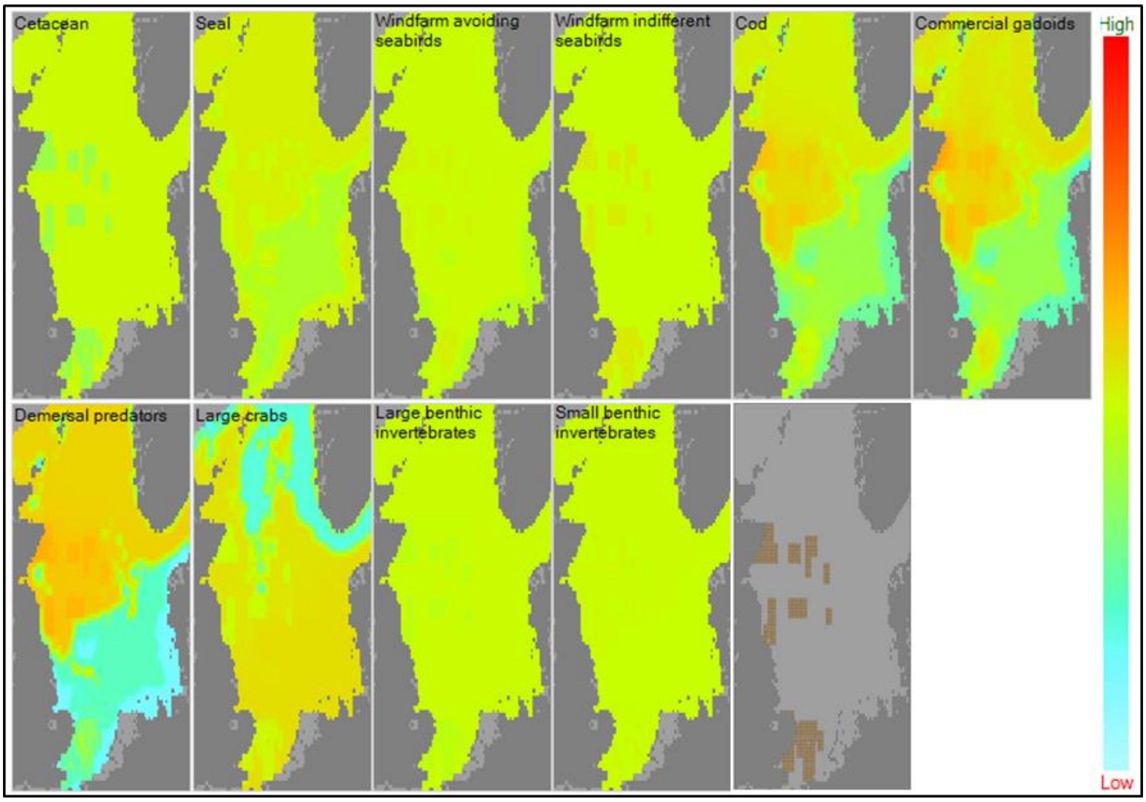


Figure 15. Same as figure 14, selected groups

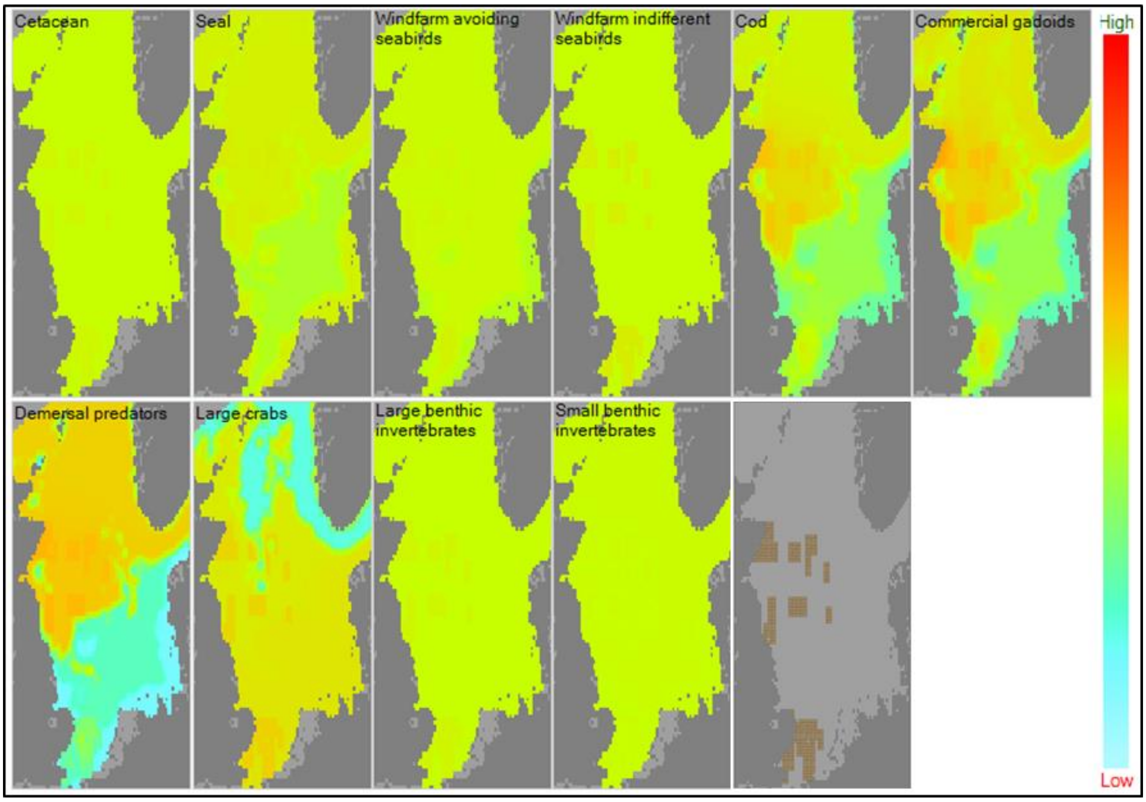


Figure 16. Spatial distribution of all groups under the impact of a set of pressure layers corresponding to the impact of windfarm during operation phase.

5.4.1. Changes to fishing intensity

Fishing is the most important driver of species biomass in the system, as it is the only factor effectively causing mortality. Fishing can result in direct reduction in biomass through catches and discards, as well as in indirect effects through the food-web. Increase or decrease of fishing is modulated through Total Effort Multiplier (TEM), used in Ecospace to tweak the fishing pressure intensity. Table 18 summarizes the species affected the most by each fishing fleet, i.e. those which suffer the highest fishing mortality (which is not necessarily the same as species for which catches are highest). Note that these species are those directly affected by fishing. Other species are also indirectly influenced through predator-prey relationships. Note that in absolute terms the mortality caused by Drift and Fixed Nets is at least one order of magnitude lower than the other two fleets, as the landing of this fleet is much lower than then the other fleets (table 6). In the game, effort of this fleet can be increased to a higher level compared to the other two, before collapse of any group occurs.

Discards are an important component of fishing activities, explicitly included in EwE as a proportion of catches for each fleet (table 18). Bottom trawler is the fleet with largest discards, followed by Industrial and pelagic trawler (table 7). Change in the TEM will result in proportional change to discards, which affect organisms feeding on them such as windfarm-avoiding seabirds. Note that seabirds, although relying on discard as a source of food, will not be affected substantially by this change as their broad diet will allow to turn to other food sources.

Table 18. species affected the most by each fishing fleet, i.e. those which suffer the highest fishing mortality. The groups are listed in order of importance, with the group suffering highest fishing mortality as first.

Fleet	***Most impacted species***	***other impacted species***
Bottom trawl	Cod, commercial gadoids, demersal predators, small demersal fish, flatfish	large demersal fish, squid and cuttlefish, small pelagic fish, mackerel, large crabs
Industrial and Pelagic trawl	Sandeel and sprat, herring, mackerel, pelagic small gadoids, small pelagic fish	
Drift and fixed nets	Cod, demersal predators, small demersal fish, cetaceans.	

Changes to fishing intensity included two type of tests: static (i.e. constant value) and dynamic modification of fishing intensity. Both tests types examine the robustness of the system to increase and decrease of fishing pressure, focusing on temporal dynamics of selected groups.

Static variation of fishing intensity was based on setting fishing effort at different levels, for each fleet individually and for all fleets combined. This test had the purpose of checking the model realism under fishing pressure level higher or lower than default, but stable in time. Improvement in model performance and robustness were obtained by modifying the dispersal rates of the groups showing unrealistic and excessive patterns.

The examples below (figures 17, 18) show a selection of the tests performed with changes to TEM kept within reasonable limits, e.g. doubling or halving the fishing pressure. Note that doubling or halving fishing effort is not realistic in the real life, where changes to fishing effort between years are generally reduced. The threshold used here are however not unexpected during game play, where players might implement stronger reduction or increase of fishing effort than what is observed in the real life. In the example in figure 17, fishing pressure (all other parameters being at default level) was set to TEM = 2 (doubling fishing intensity). While all groups show gradual changes to biomass, herring and few others show rapid and substantial decline. In particular, commercial gadoids and demersal predators declined sharply to stabilise at low level, while herring declined steadily. It is worth noting that the fishing mortality for these group is relatively high, so a decline is not unexpected. By changing herring dispersal rates from 100 to 300 (allowing faster redistribution of biomass), the decline was reduced to the point that herring did not collapse in the time frame explored (although it reached a low level).

The example in figure 18 shows a test with reduction in fishing pressure using TEM = 0.5. The species dynamics change with an increase in biomass of most species, in particular those with high fishing pressure and fast turnover rate, such as for example herring. The largest increase is observed for demersal predators. This pattern corresponds with the historical observed increase of biomass of demersal predators taking place in parallel to decreasing fishing pressure (see Fig. 8). Tweaking dispersal rate of demersal predator revealed that the value used provided a reasonable compromise, while higher or lower values resulting in unrealistic dynamics.

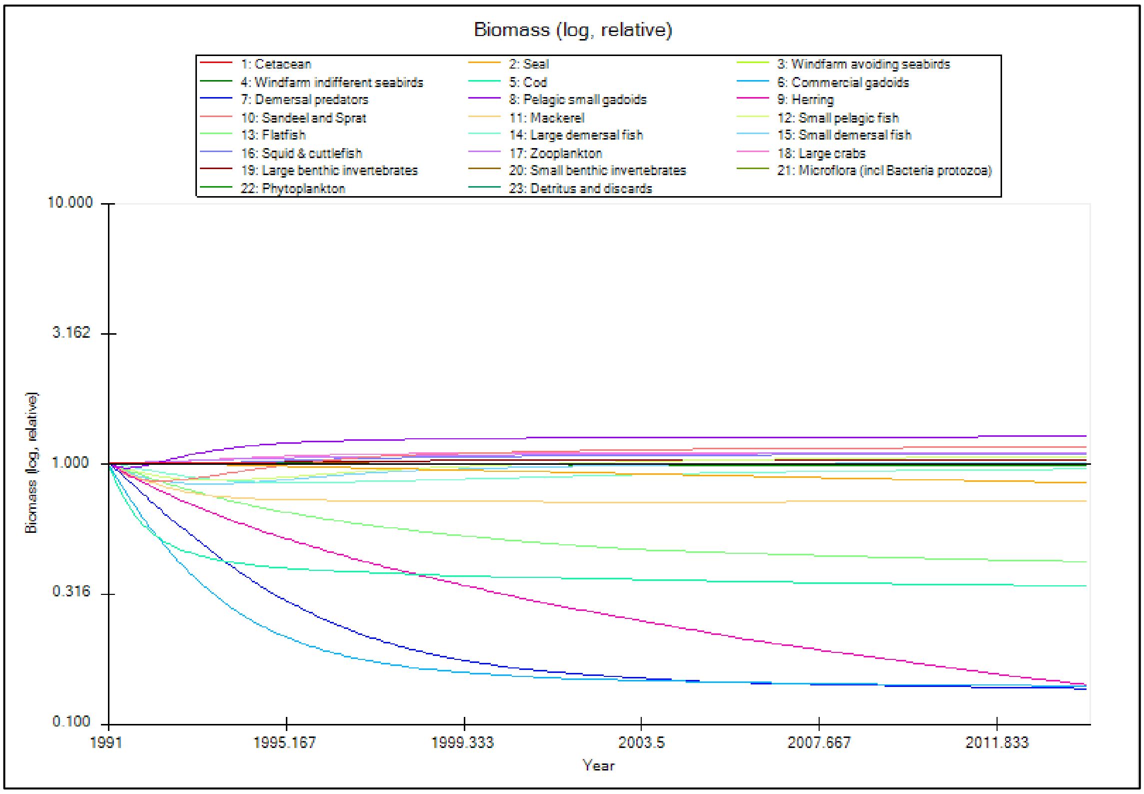


Figure 17. Biomass dynamic after change in fishing pressure setting intensity: doubling fishing pressure (TEM =2).

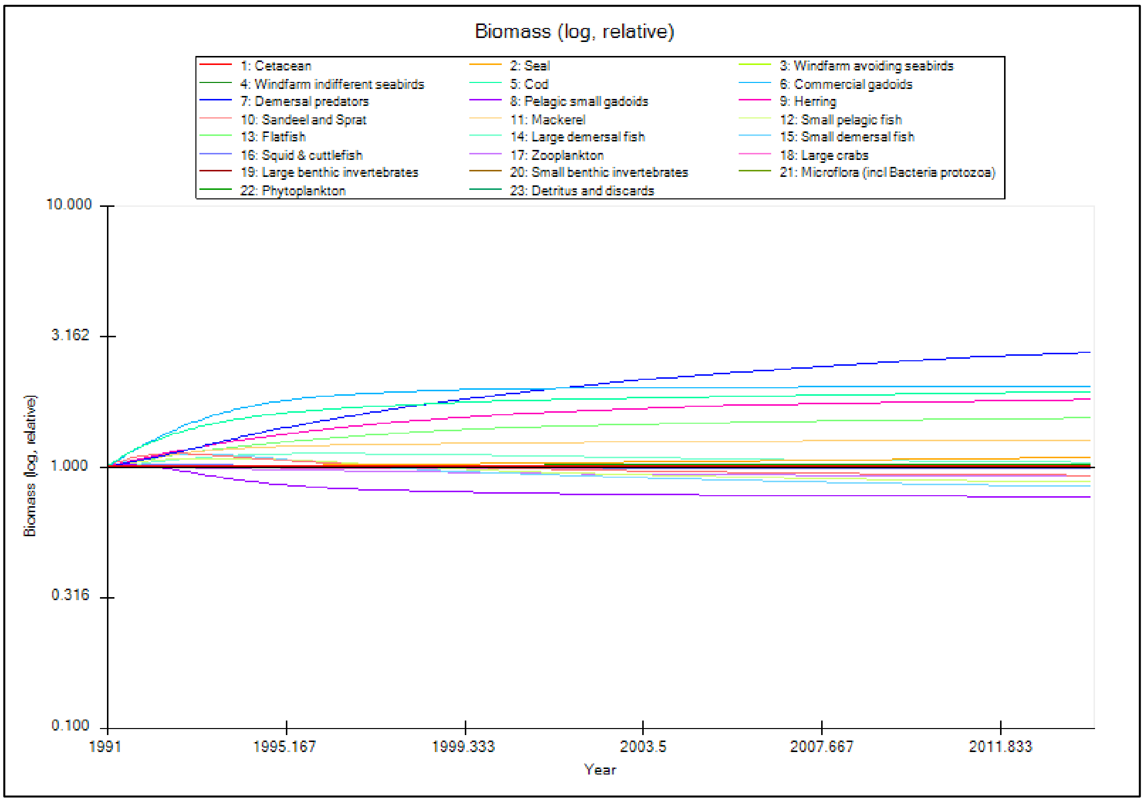


Figure 18. Biomass dynamic after change in fishing pressure setting intensity: doubling fishing pressure (TEM =0.5)

The sensitivity of the system to extreme levels was tested in separate analyses, setting levels approaching TEM = 0.1. In these examples (not reported), as expected, biomass of most species increased or decreased substantially. These patterns were overall realistic reflecting the expected ecosystem changes under extreme fishing scenarios. However, for few species, and especially demersal predators, the increase was considered slightly excessive, and further tweaking of dispersal rate did not allow to reduce these patterns. Further tests were performed on extremely high values of TEM (TEM= 5, 10, 20), revealing (unsurprisingly) that with constant high fishing pressures, the system suffers. Increase of fishing pressures leads to serial collapse of populations with long recovery times, consistently with expected patterns. These scenario represents an extreme case, and it is unlikely that during game play the model will undergo extreme levels of low or high fishing pressure, if not locally and for reduced lengths of time, so this dynamic of demersal predators is not of concern for game play. It is expected that game players will avoid exceeding reasonable limits, and will quickly correct their overestimates during gameplay, avoiding the most dramatic effects on the system. Guidance to game players on the system's level of tolerance to fishing pressure might be appropriate. Notably, the different fleets affect functional groups in different ways, and the system can tolerate higher increase in fishing pressure for e.g. Drift and fixed nets than for Industrial and Pelagic trawlers or Demersal trawlers.

Dynamic variation of fishing intensity was performed on selected species and fleets with the purpose of assessing whether selected organisms did show realistic and expected decline and recovery patterns, and to what extent the speed of recover or lack thereof was related to the intensity of depletion. This test explores the effects on oscillations in fishing intensity with alternatively higher and lower TEM: this pattern reflects the dynamics of the game, when players will set a fishing effort and gradually adjust it through iterative steps, after assessing the consequences of their initial setting. For example, the dynamics of three groups (cod, commercial gadoids and demersal predators) with alternate increase and decrease of fishing intensity is shown below (figures 19, 20). Figure 19 shows how recovery time is relatively fast for cod and commercial gadoids, and slower for demersal predator which seem to also suffer more the increase in fishing pressure. The examples show that the biomass tends to rapidly recover once the intense fishing ceases, approaching the base level for Cod and Commercial gadoids. This pattern is realistic and reflects the fact that, once the main pressure is removed, given otherwise positive conditions (e.g. limited impacts, food availability) Cod and other gadoids species will recover, as historically happened in the North Sea. This observation shows that, for game play purpose, the model is resilient to temporary increase of fishing pressure. Naturally, when interaction with other pressures on the system take place during game play this quick recovery capability might be compromised or reduced. Recovery is instead slower for the demersal predators. This group include slow-growing fish such as e.g. sharks, so the observed pattern is realistic.

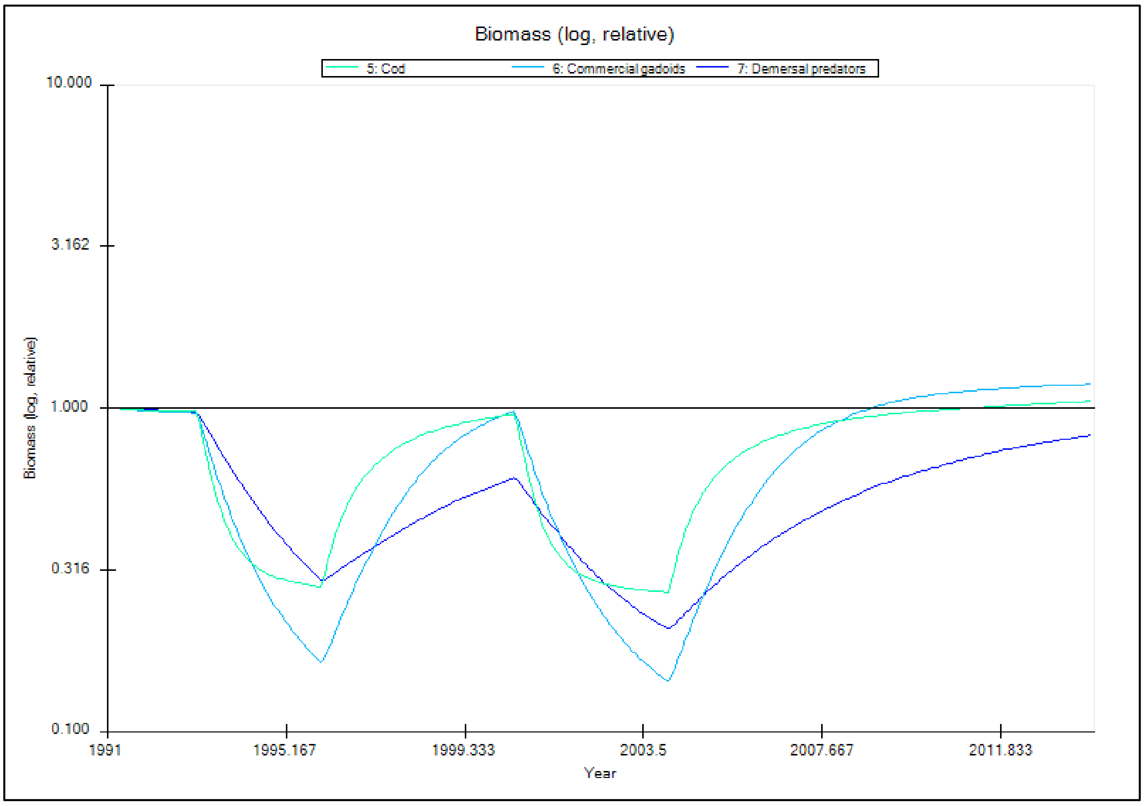


Figure 19. Dynamics of Cod, commercial gadoids and demersal under alternating dynamics. Four subsequent temporal lags were used with TEM = 3, TEM = 0.8, TEM = 3 and TEM = 0.8. Cod declines and recovers fastest, Demersal predator slowest.

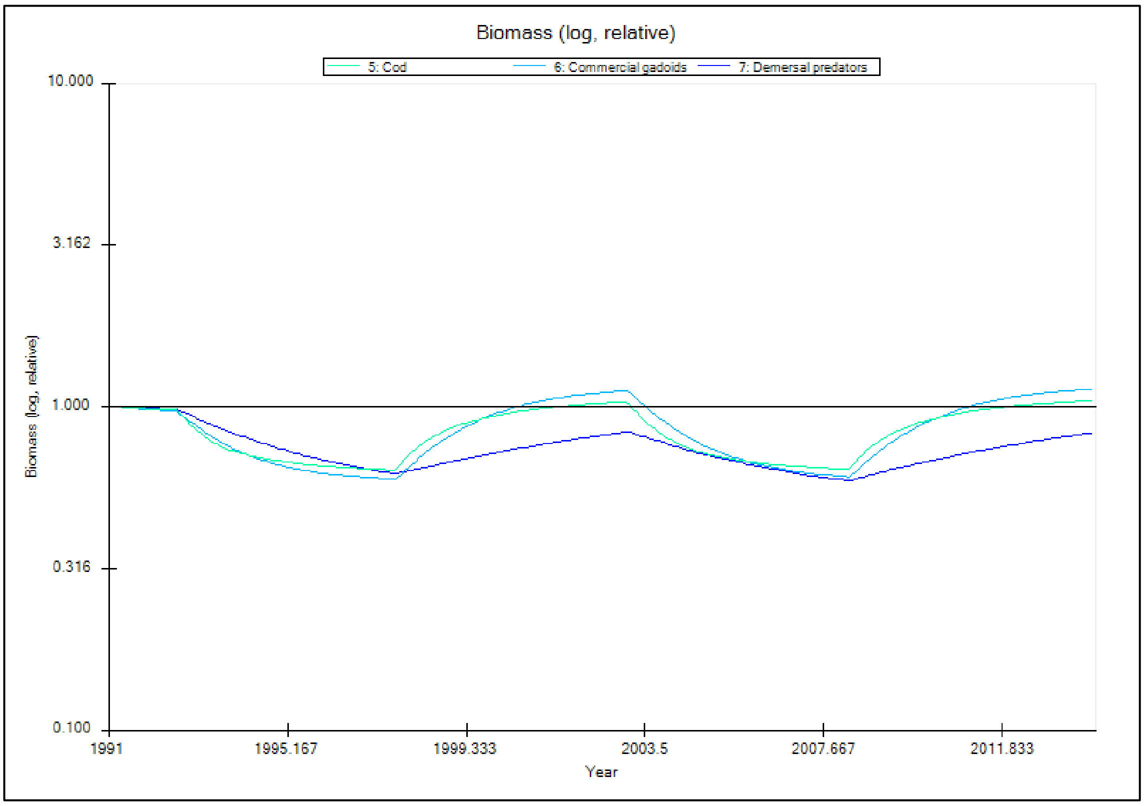


Figure 20. As in figure 19, but with TEM =1.5 followed by TEM =0.8.

Another test, shown in figures 21 and 22, assessed the decline and recovery patterns of charismatic groups: cetaceans, seals, windfarm avoiding seabirds and windfarm indifferent seabirds. Cetacean is the only group impacted directly with small bycatch from Drift and fix net fishery. The other groups are impacted only indirectly by fishing, through effects on their prey species. For this reason, the effects of TEM on these groups is limited: the decline observed in figure 21 is cause by TEM = 20 for Demersal trawl and Industrial and Pelagic trawl, and TEM = 50 for Drift and fix net fleet. All groups declined under very high levels of TEM with, in order of faster decline: cetacean, seals, windfarm avoiding seabirds and windfarm indifferent seabirds. When the effort is reduced to 0.1, cetacean stabilise but do not increase; seals show a very slow, moderate increase; windfarm avoiding seabird have a lagged but sharp increase, driven by similar increase pattern from their prey fish (mainly sandeels); and windfarm indifferent seabirds show a moderate increase. These patterns suggest that cetaceans and seals are highly resistant even to extreme increase in fishing pressures; however, once they start declining, these groups will be very slow or even impossible to recover to their initial extent. Conversely, seabirds seem to be much more resilient with either limited impact or fast recovery. Since the effect on seabirds was almost negligible, and the effect on seals and cetaceans lead to almost impossible recovery, the dispersal rates were modified for all groups, reducing them from 1000, 300, 1000, 1000 to 300, 100, 100, 100 for cetacean, seals, windfarm avoiding seabirds and windfarm indifferent seabirds respectively. For seals and both seabirds group, this change granted more responsive dynamics (Fig. 22).

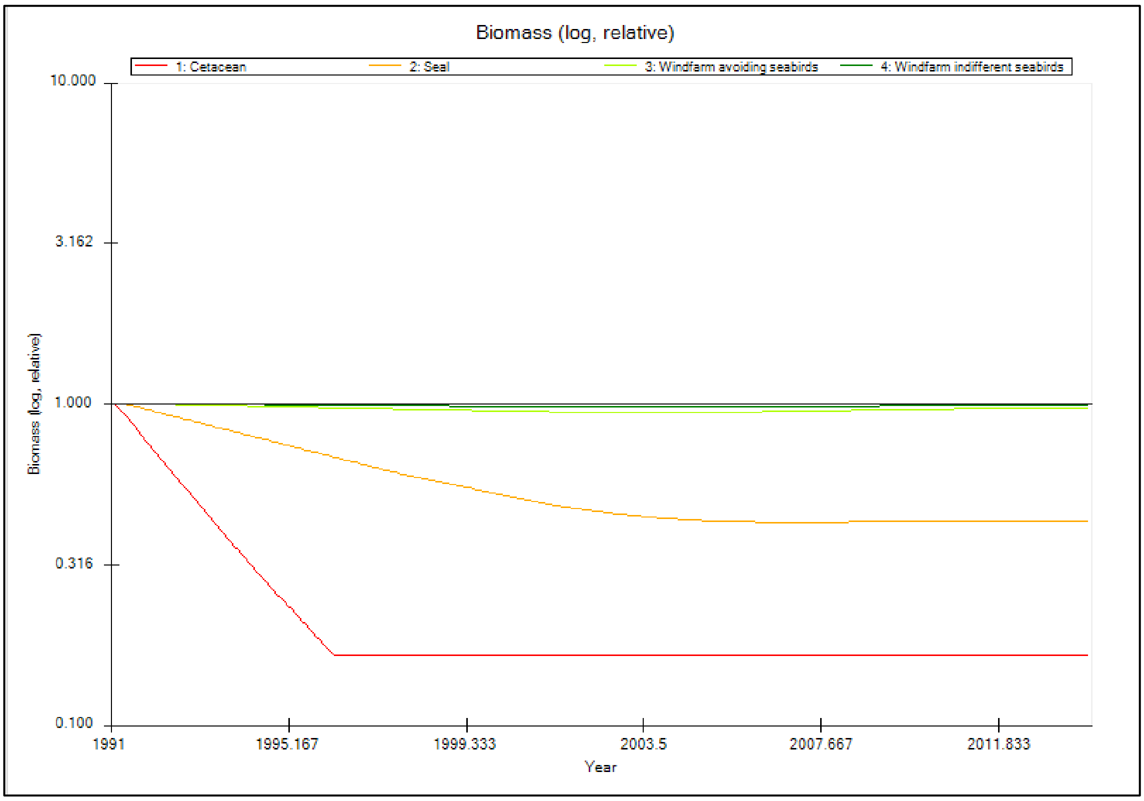


Figure 21. Dispersal rate set at 1000, 300, 1000, 1000 for cetacean, seals, windfarm avoiding seabirds and windfarm indifferent seabirds respectively. TEM =20 (TEM =50 for Drift and fix net fleet). In order of faster decline, cetacean, seals, windfarm avoiding seabirds and shallow seabirds. TEM reduced to 1 for all fleets after some years of simulation. The effect of TEM reduction is immediately visible for cetacean, while its effect is lagged for other groups.

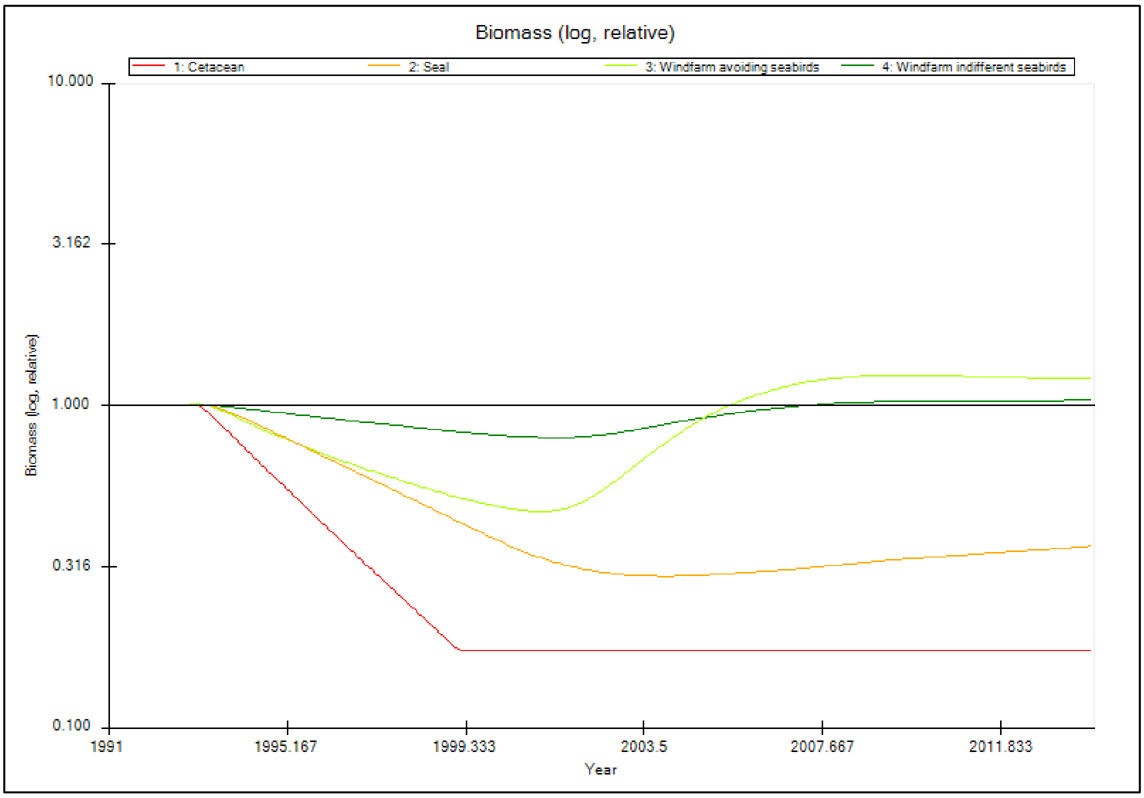


Figure 22. Dispersal rate set at 300, 100, 100, 100 for cetacean, seals, windfarm avoiding seabirds and windfarm indifferent seabirds respectively. TEM =20 (TEM =50 for Drift and fix net fleet). In order of faster decline, cetacean, seals, windfarm avoiding seabirds and shallow seabirds. TEM reduced to 1 for all fleets after some years of simulation. The effect of TEM reduction is immediately visible for cetacean, while its effect is lagged for other groups.

6. Additional changes and final model

6.1. Additional changes

The model described until here provided visible, but not excessive, responses to drivers such as fishing and environmental pressures. The model was successively tested to assess its performance during MSP gameplay. The connection between EwE and MSP across multiple scenarios of impacts and through the MSP user interface revealed some issues, and minor modifications to the Ecospace model were deemed necessary. In particular, the responses to pressures were judged too nuanced for game purpose, and biomass distribution was judged too uniform in space to provide game enjoyableness. Moreover, important habitats for seabirds, key groups for the game, were asked to be emphasized in the Ecospace model. Finally, the model was initialised with a spin-up period of 15 years to allow all groups dynamics to reach stable state before game play start.

Note that the model did not sacrifice realism to accommodate enjoyableness: the foundation Ecopath and Ecosim components were not modified to ensure that the model retained its basic realism. The Ecospace model was made more responsive by fine-tuning the response of functional groups to pressures. These responses are ad-hoc and their realism is hard to assess, lacking empirical data to test against, and because of limited understanding of the individual and synergistic impacts of environmental change due to MSP planning activities. The overall responses are realistic before and also after implementing the changes included in the final model: the same set of rigorous tests were employed to ensure the model performs satisfactorily.

Through iterative changes to model parameters related to response to pressures, a set of changes were implemented into the final model. These include: changes to spatial distribution; changes to response functions; and inclusion of important layers.

6.1.1. Changes to spatial distribution

To make the spatial distribution more dynamic, the distribution of some species was modified. Habitat distribution for some groups was modified to make their distribution less homogeneous and the visual response in the MSP interface more dynamic: habitat preference Cod and Commercial gadoids' preference for habitats "0-22 m", "23-55 m", "56-115 m" was reduced. Similarly, habitat preference was reduced in habitats "23-55 m", "56-115 m" and "> 115 m" for herring, in habitats "56-115 m", "> 115 m" and "Coastal" for small pelagic fish and flatfish, and in habitats "0-22 m" and "23-55 m" for large demersal fish. Also artificial habitat assignment was modified: preference of windfarm-avoiding seabirds for this habitat was reduced to zero (table 19).

Additionally, some groups were constrained to coastal areas through the use of an environmental driver layer based on a function of distance from coastland, slightly modified to account for known spatial distribution of seals (Fig. 23). A specific functional response function was introduced and applied for seals (Fig. 24), with stronger gradient to account for the known preference for coastal areas of this group (Jones *et al.*, 2015). Cetaceans and both seabirds group were constrained close to coast using a "low impact" response to capture their moderate preference for coastal areas (Faijer and van Dam, 2012; Hammond *et al.*, 2017). Additionally, pressures assignment was modified for a number of other groups: In particular, low pressure of noise was included for all fish groups, based on generalised evidence that most fish respond to noise (Bergström *et al.*, 2014). For Herring, the pressure of noise was set to “high”, based on evidence that this species is particularly sensitive to this type of impact (ICES, 2018a). Surface disturbance was included as “low impact” in both groups of seabirds and to all surface-dwelling fish species: pelagic small gadoids, herring, sandeel and sprat, mackerel, small pelagic fish, as well as for zooplankton. These decisions were based on evidence that surface pollution (e.g. persistent organic pollutants from small-scale oil spills; micro and macroplastics) interact negatively with seabirds (Wilcox *et al.*, 2015), fish (Rummel *et al.*, 2016) and zooplankton (Desforges *et al.*, 2015). The group “detritus” (including discards) was assigned a positive impact from surface disturbance, to represent the increase in dead organisms due to surface pollution. Additionally, bottom disturbance was assigned to bottom-dwelling fish such as cod, demersal predators, sandeel and sprat, flatfish, large demersal fish, small demersal fish.

Table 19. Habitat assignation in the final model

	Group \ habitat #	***All***	***0-22 m***	***23-55 m***	***56-115 m***	***>115 m***	***Coastal***	***Artificial habitat***
1	Cetaceans	0	1	1	1	1	1	0.2
2	Seals	0	1	0.7	0.8	0.2	1	0.1
3	Windfarm avoiding seabirds	0	1	1	1	1	1	0
4	Windfarm indifferent seabirds	0	1	1	1	1	1	0.3
6	Cod	0	0.6	0.3	0.8	1	0.8	0.2
8	Commercial gadoids	0	0.2	0.3	0.6	1	0.7	0.2
9	Demersal predators	0	0.1	0.2	1	1	1	0.2
10	Pelagic small gadoids	0	0.1	0.3	1	1	1	0
11	Herring	0	1	0.9	0.9	0.4	0.8	0
12	Sandeel and Sprat	0	1	1	0.8	0.2	1	0
13	Mackerel	1	0	0	0	0	0	0
14	Small pelagic fish	0	1	1	0.8	0.7	0.8	0
15	Flatfish	0	1	1	0.8	0.7	0.8	0
16	Large demersal fish	0	0.8	0.9	1	1	1	0
17	Small demersal fish	1	0	0	0	0	0	0
18	Squid & cuttlefish	1	0	0	0	0	0	0
19	Zooplankton	1	0	0	0	0	0	0

20	Large crabs	0	1	1	1	0.2	1	0.3
21	Large benthic invertebrates	0	1	1	1	1	1	0.2
22	Small benthic invertebrates	0	1	1	1	1	1	0.2
23	Microflora (incl Bacteria protozoa)	0	1	1	1	1	1	0
24	Phytoplankton	1	0	0	0	0	0	0
25	Detritus and discards	1	0	0	0	0	0	0

Table 20. Dispersal rate setting in the final model.

	Group name	***Dispersal rate***
1	Cetacean	300
2	Seal	100
3	Windfarm avoiding seabirds	100
4	Windfarm indifferent seabirds	100
5	Cod	300
6	Commercial gadoids	100
7	Demersal predators	200
8	Pelagic small gadoids	30
9	Herring	300
10	Sandeel and Sprat	30
11	Mackerel	100
12	Small pelagic fish	100
13	Flatfish	30
14	Large demersal fish	30
15	Small demersal fish	30
16	Squid & cuttlefish	30
17	Zooplankton	30
18	Large crabs	3
19	Large benthic invertebrates	3
20	Small benthic invertebrates	3

21	Microflora (incl Bacteria protozoa)	3
22	Phytoplankton	300
23	Detritus and discards	10

6.1.2. Changes to response functions

To make the response of all groups more pronounced, the response functions were modified with a steeper slope, providing more pronounced response to high impacts (Fig. 25). In the new response function, low negative impact corresponded to a decrease of 40% habitat capacity at pressure of 1, and high negative impact corresponded to a decrease of 80%. Positive impact corresponded to an increase of 20%.

6.1.3. Inclusion of important seabird areas

To account for important habitats of seabirds, a seabird habitat layer was included (fig. 23), based on literature describing important feeding grounds and hotspots of migratory routes (Faijer and Van Dam, 2012), were abundance might be higher and impact of e.g. windfarms could be more pronounced (Stienen *et al.*, 2007). In particular, important habitats were included in areas around Shetland and Scotland as well as in the Southern Bight were important migrations occur along the Dutch and Belgian coast, as well as toward England (Faijer and Van Dam, 2012). The habitat layer was connected to seabirds through a positive impact response function (Fig. 25).

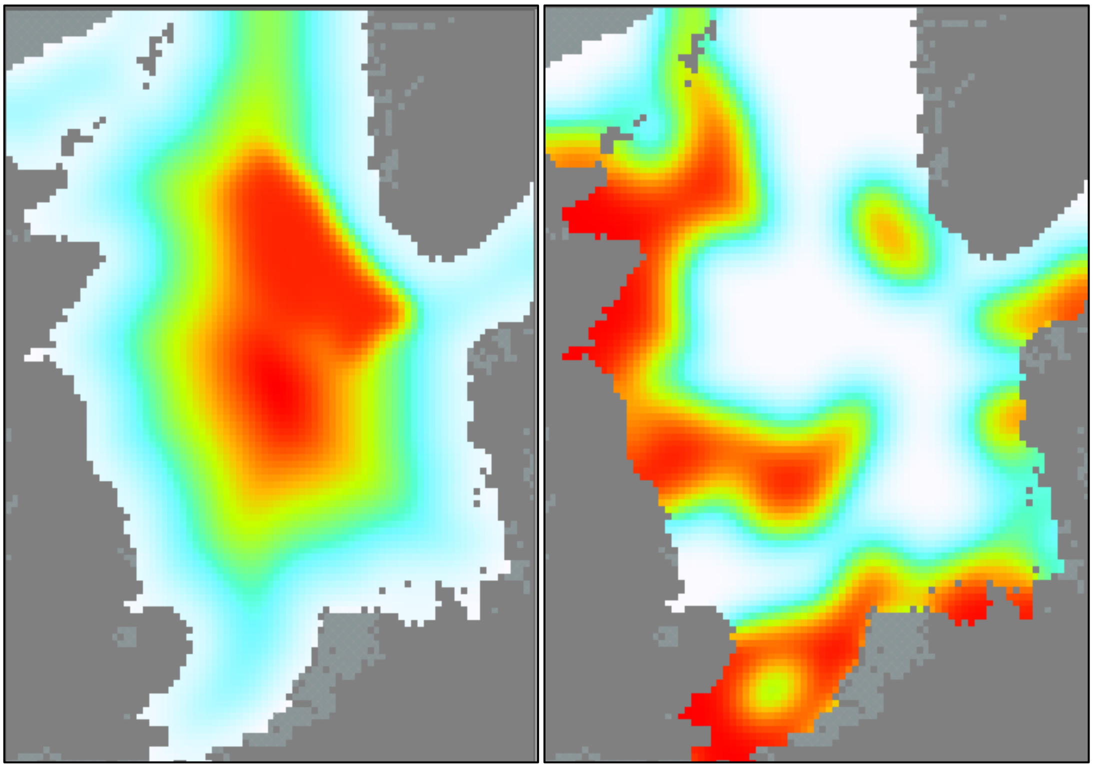


Figure 23. Left: Distance from land layer, modified to include ecological knowledge about seals, and used to drive the seal distribution through the functional response "seal distance from land". The layer was also used to drive cetaceans and both seabird groups distribution through a "low impact" functional response. Right: seabird important habitat layer, based on known important feeding grounds and migratory routes hotspots, and used to drive both seabirds groups through the "Seabirds habitat" functional response.

Table 21. Functional responses by pressure (noise, surface disturbance, bottom disturbance) for each group

	Group name	Noise	Surface disturbance	Bottom disturbance
1	Cetacean	High	Low	
2	Seal	High	Low	
3	Windfarm avoiding seabirds	High	Low	
4	Windfarm indifferent seabirds	High	Low	
5	Cod	Low		Low
6	Commercial gadoids	Low		

7	Demersal predators	Low		Low
8	Pelagic small gadoids	Low	Low	
9	Herring	High	Low	
10	Sandeel and Sprat	Low	Low	Low
11	Mackerel	Low	Low	
12	Small pelagic fish	Low	Low	
13	Flatfish	Low		Low
14	Large demersal fish	Low		Low
15	Small demersal fish	Low		Low
16	Squid & cuttlefish			
17	Zooplankton		Low	
18	Large crabs			High
19	Large benthic invertebrates			High
20	Small benthic invertebrates			High
21	Microflora (incl Bacteria protozoa)			
22	Phytoplankton			
23	Detritus and discards		Positive	

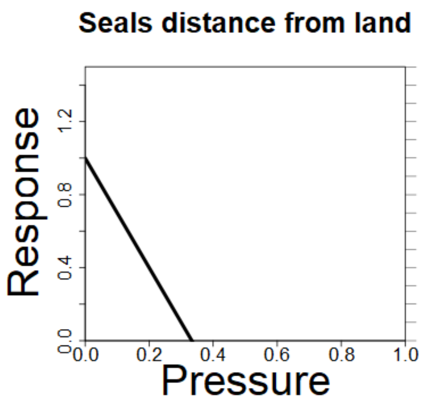


Figure 24. Functional response for Seals distance from land.

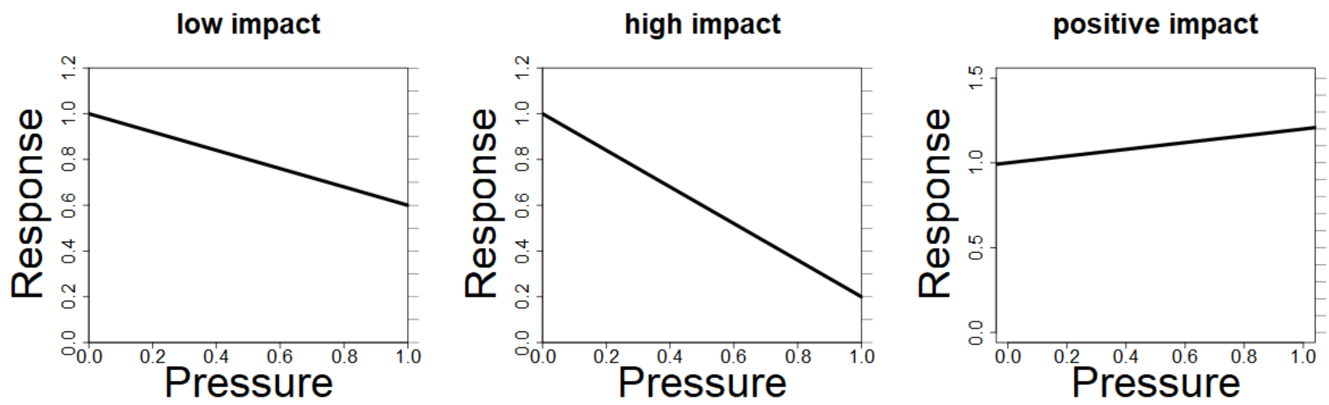


Figure 25. Functional response for low and high impact used in the final version of the model.

6.2. Final model

After these changes, the model showed higher reactivity and therefore game enjoyableness (Fig. 26, 27). The model (labelled version 3.3.2) provided visible, but not excessive, responses to drivers such as fishing and environmental pressures. For example, responses to fishing are more intense than with the initial values (confront figures 8 and 27); however the model without any pressure runs flat (Fig. 26).

After these changes were included, additional stress tests were performed on the modified model. The TEM tests provided very similar results to previous version and are summarised below. Effects of inclusion of windfarms, MPAs and artificial habitats are reported below. Finally, the model was tested to inclusion of all the start-up layers. All tests confirmed the positive results of the final model which was not further modified.

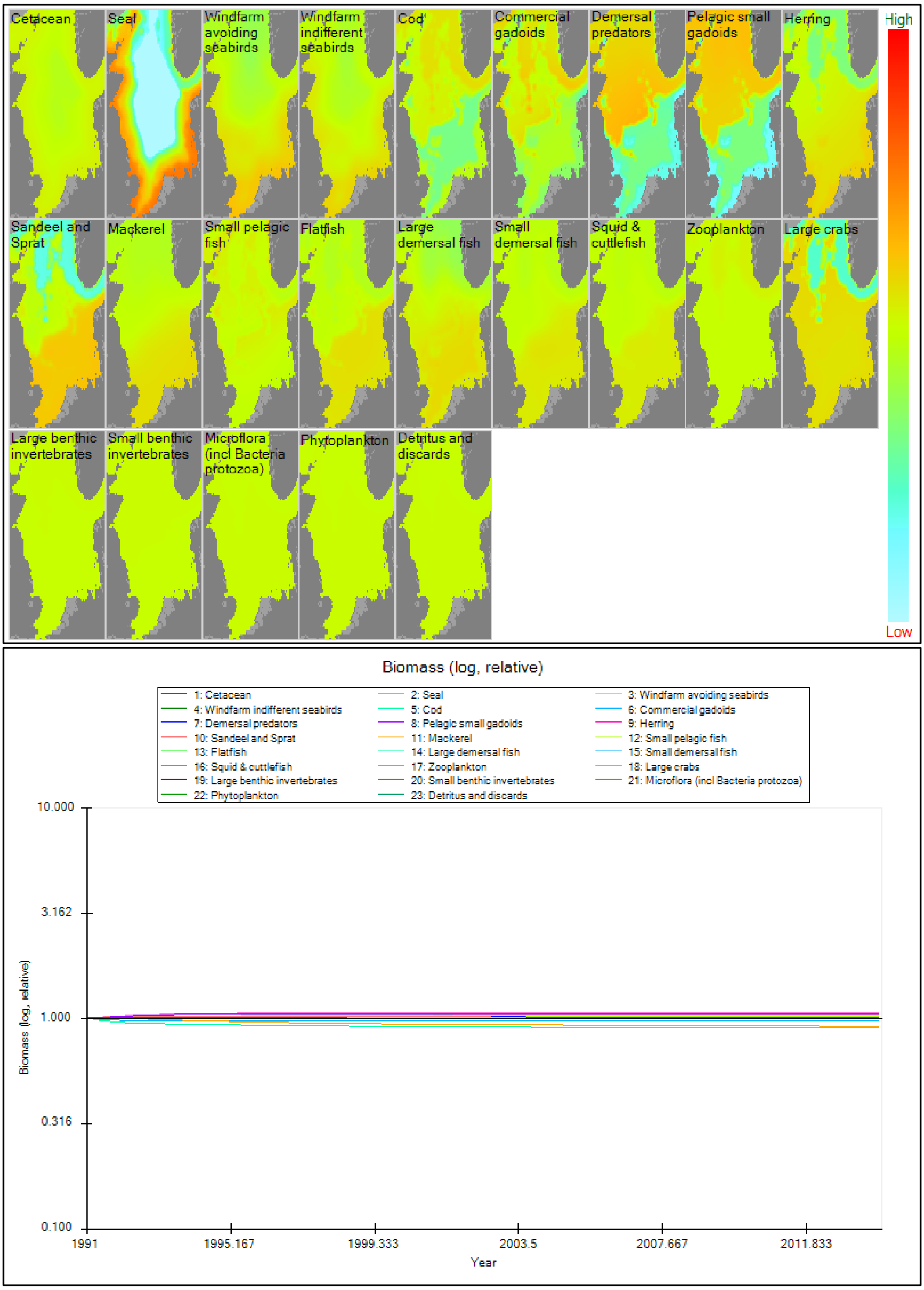
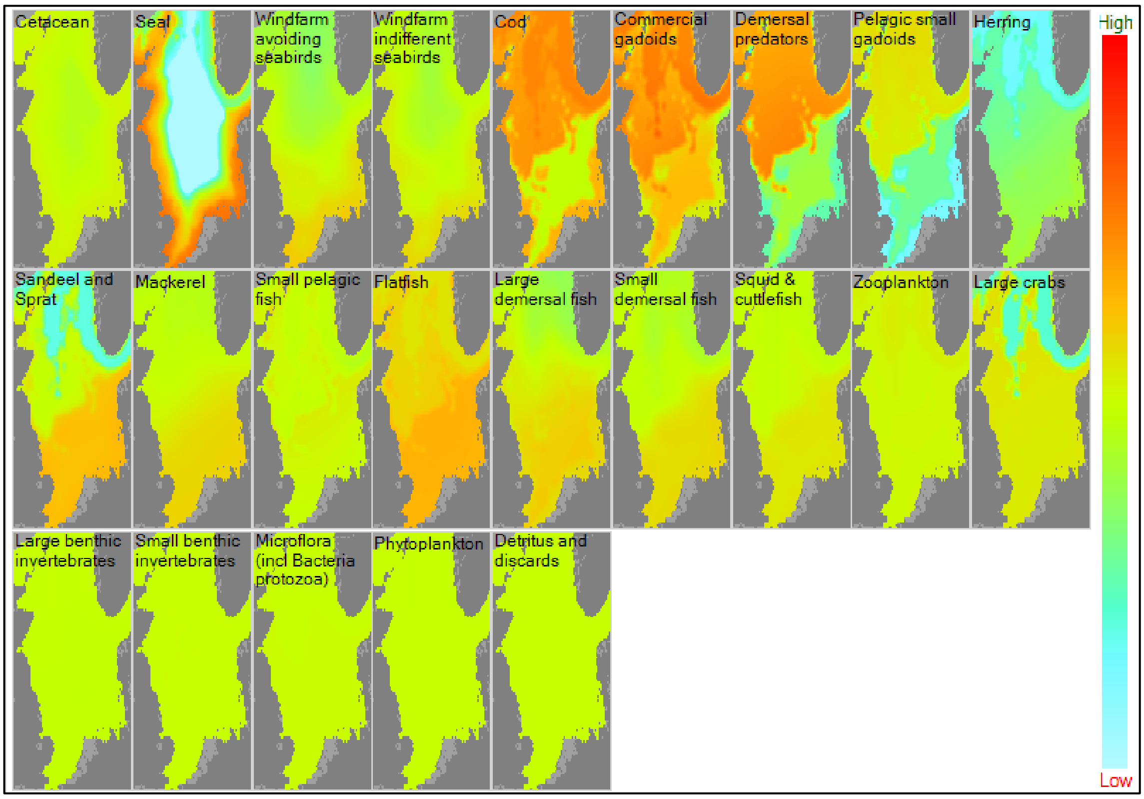


Figure 26. Spatial (top) and temporal (bottom) dynamics at final setting



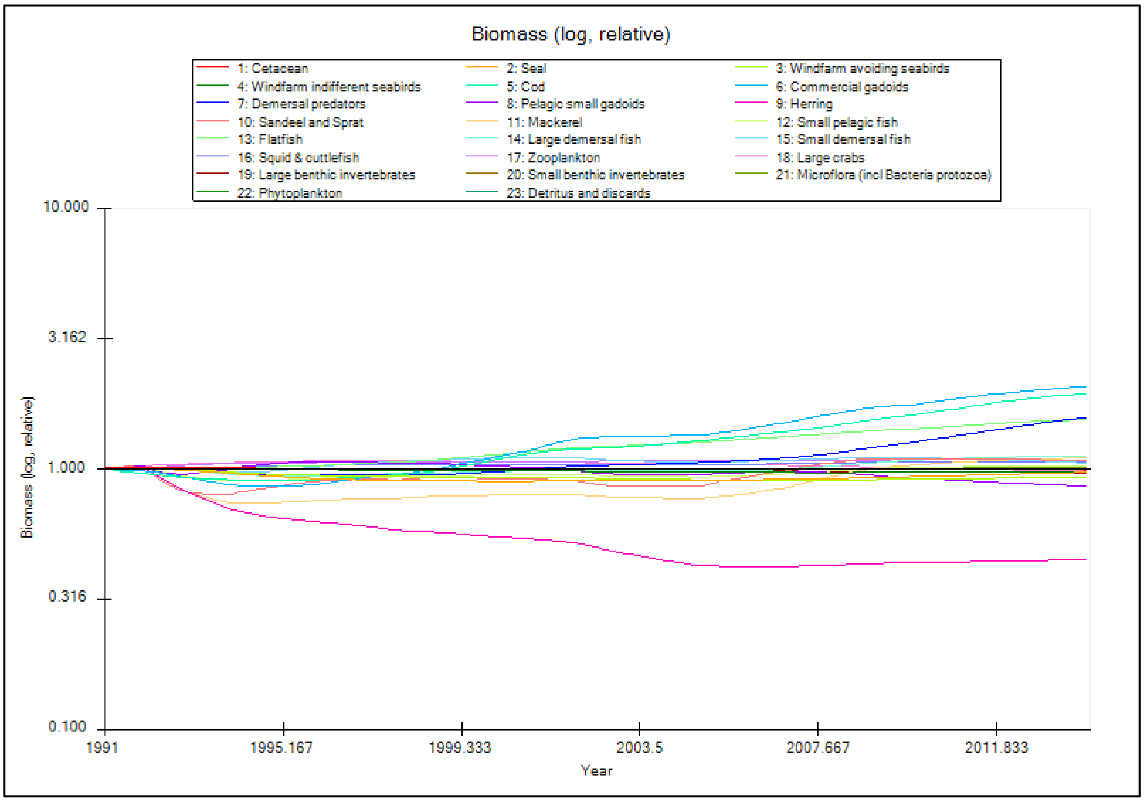


Figure 27. Spatial (top) and temporal (bottom) dynamics at final setting under historical fishing rate

6.3. Stress tests on the final model

6.3.1. Setting MPAs

The effect of restriction of Demersal trawlers on cod, commercial gadoids, demersal predators is similar to the previous version of the model in its intensity and distribution (figure 28, compare with figure 11).

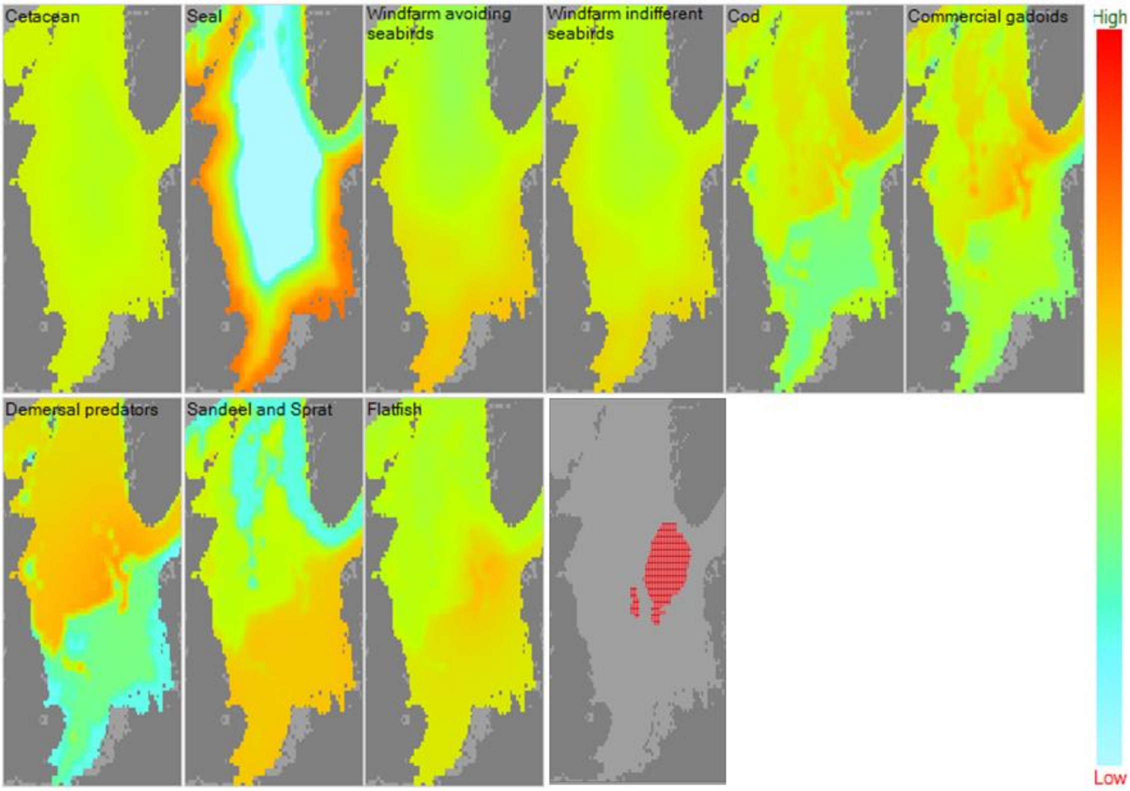


Figure 28. Effect of MPA for Bottom trawler on selected functional groups. The position of the MPA cells is displayed in the last panel, highlighted in red.

6.3.2. Setting Artificial habitat

The effect of artificial habitat is now more pronounced for most groups, although it is hardly visible for Seals. No effect for Windfarm avoiding seabirds is visible, as expected (Figure 29).

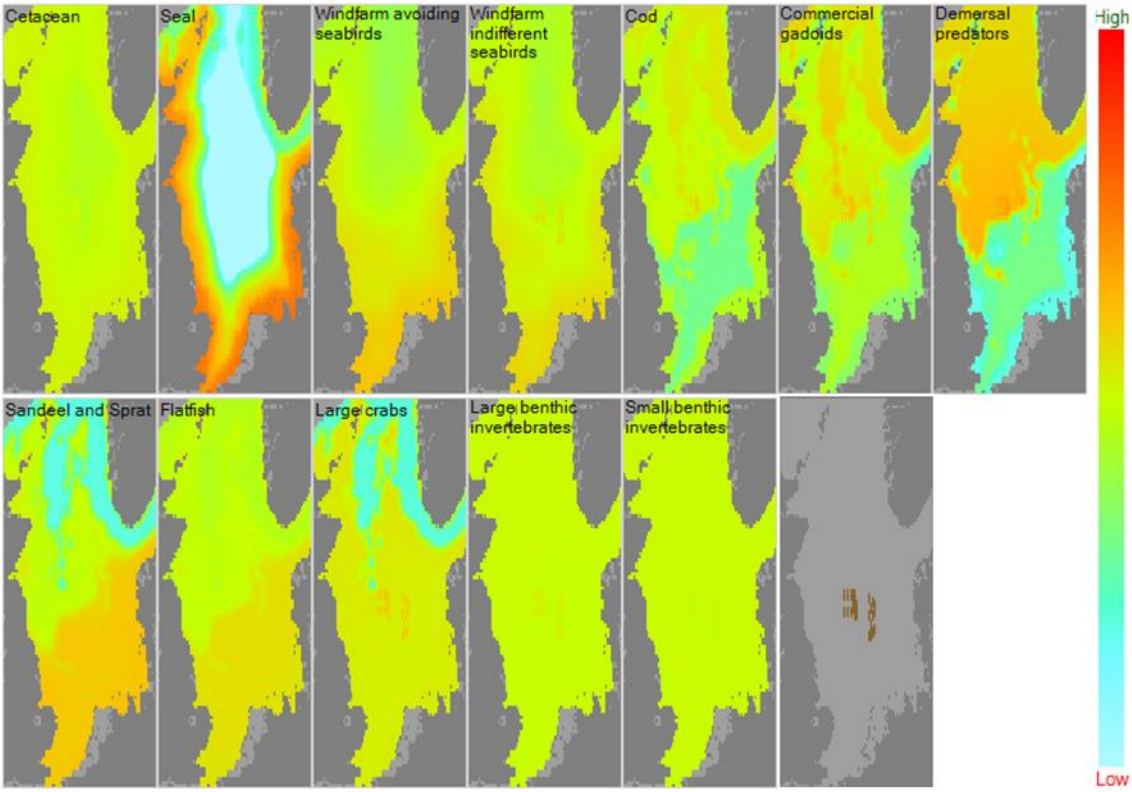


Figure 29. Effect of Artificial habitat placement on selected functional groups. The position of the artificial habitat cells is displayed in the last panel, highlighted in brown.

6.3.3. Test of multiple pressures: windfarms

The results show responses in line with what expected: the effect of placing randomly distributed windfarms is now more realistic, with positive impact on windfarm indifferent seabirds, and stronger impacts, with visible spillover effect, on commercial gadoids, and demersal predators (at least in the southern bight) and moderate positive effect on cod. As desired, the impact on windfarm avoiding seabird is negative (figure 30, 31): this group displays avoidance of the windfarm areas (mostly visible in the southern bight and along the English coast).

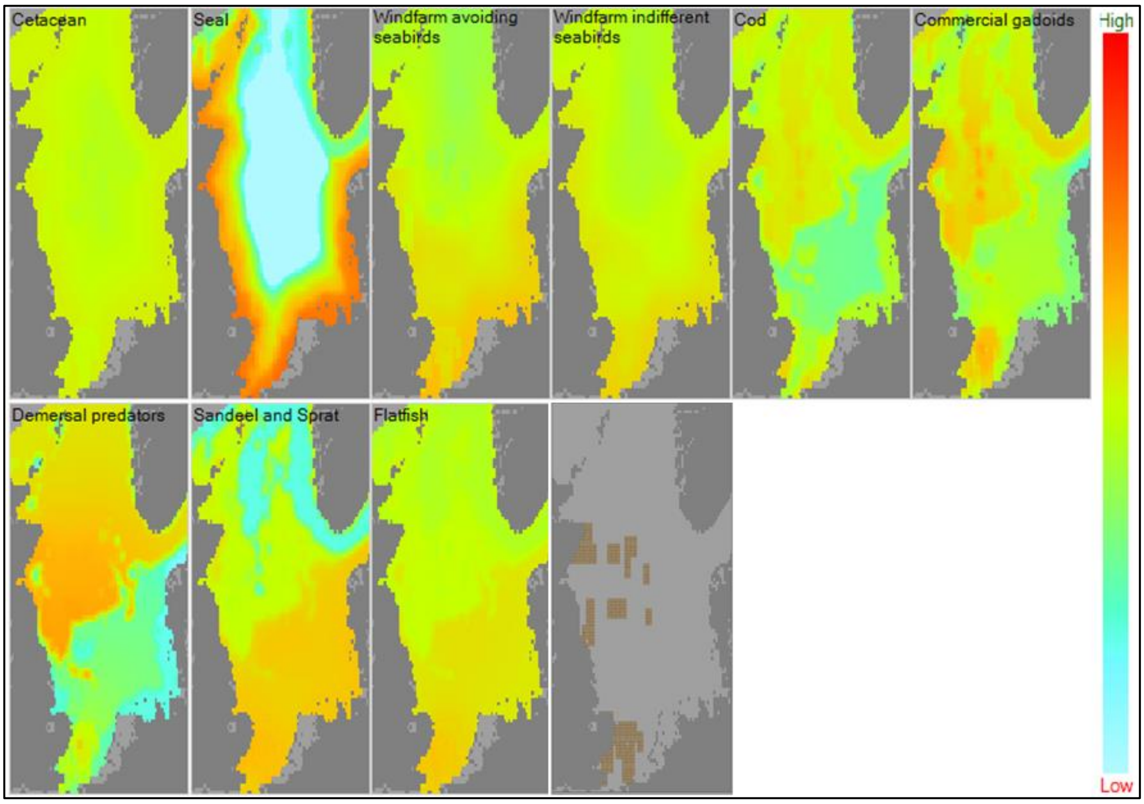


Figure 30. Effect of windfarms during operational phase on selected functional groups. The position of the windfarms cells is displayed in the last panel, highlighted in brown.

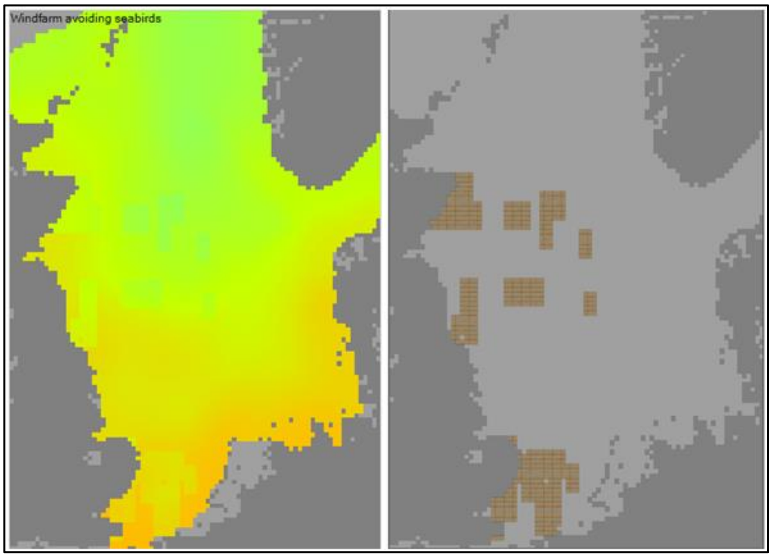


Fig 31: effect on Windfarm avoiding seabirds (left) compared with windfarms. Lower biomass, corresponding to lower preference for these areas, is visible in the Southern Bight and along English and Scottish coast.

6.3.4. Changes to fishing intensity

Tests on fishing dynamics performed similarly to the former version. Increase to TEM =2 and decrease to TEM =0.5 (Figs. 32, 33) provide very similar dynamics to those of figures 17 and 18 relative to the previous version of the model. Additional tests for oscillation in TEM provided equally similar results to the previous version and are hereby not reported.

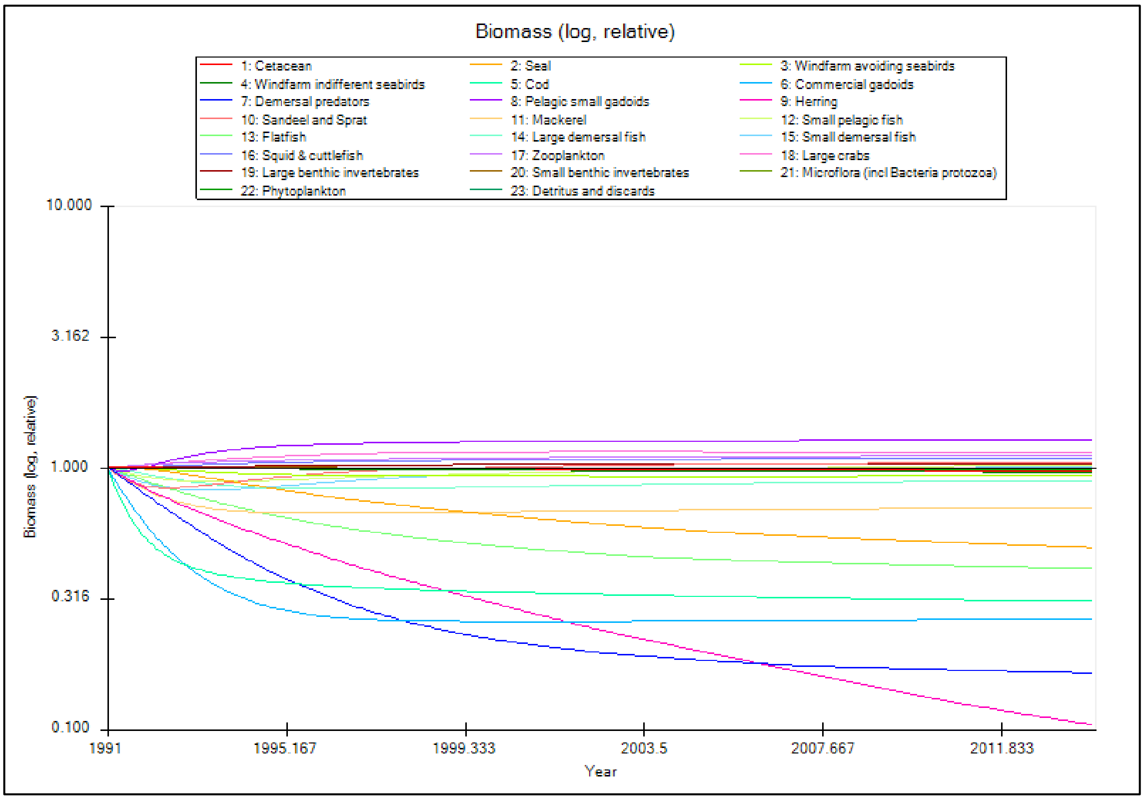


Figure. 32. Changes in fishing pressure setting intensity relative to stable state (TEM =1) doubling fishing pressure (TEM =2).

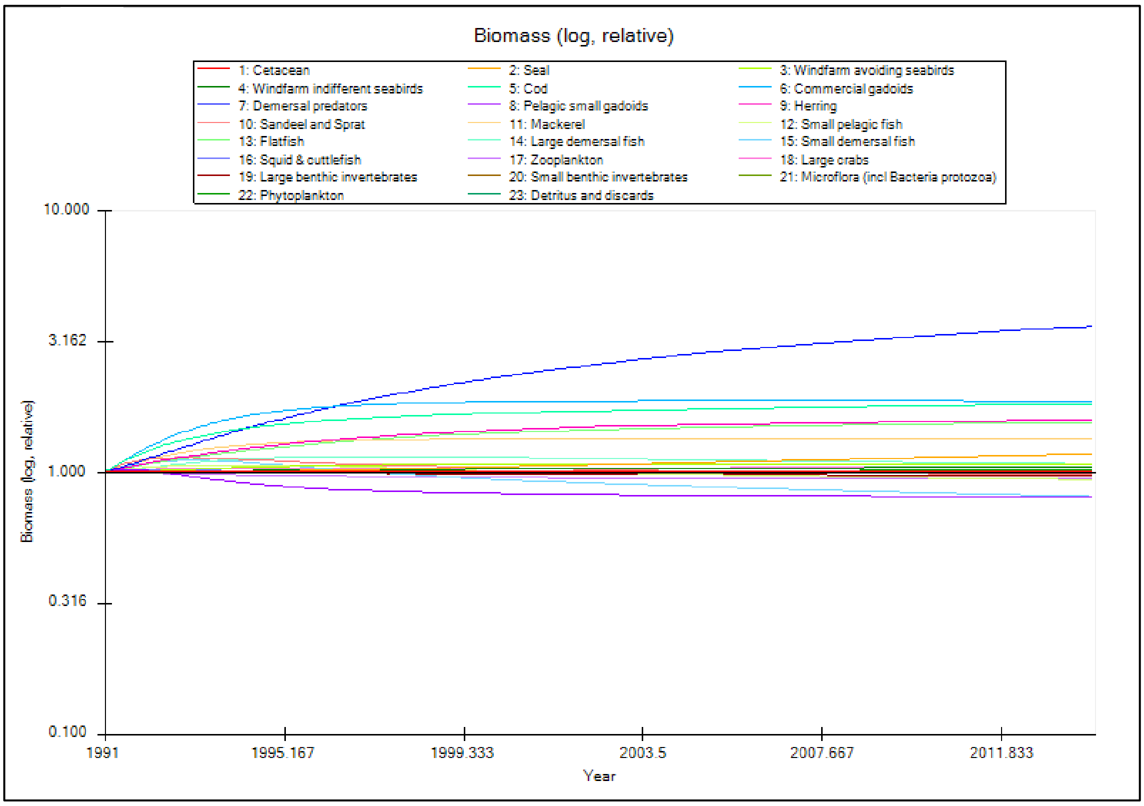


Figure 33: Changes in fishing pressure setting intensity relative to stable state (TEM =1) halving fishing pressure (TEM =0.5).

6.4. Test with MSP start-up layers

The model was finally tested against the combined, continuative impacts of multiple pressures. The MSP start-up layers were used for this test. These pressure layers are derived from MSP activities present in the game at start-up, which reflect the state of the North Sea in the year 2016. Logically, the Ecospace model must initialize and run flat to these start-up conditions. Here, these layers were used as a test to offer realistic combined pressures. Layers for Artificial habitat, Noise, Surface disturbance, Bottom disturbance are shown in figure 34. Note that the layers show similar spatial patterns because most impacts occur together. Shipping lanes, for example, are characterised by relatively high noise and surface disturbance; windfarms by high noise and artificial habitat patches. The distribution of MPAs is almost identical for the three fleets, thus only MPAs for Bottom trawl is shown.

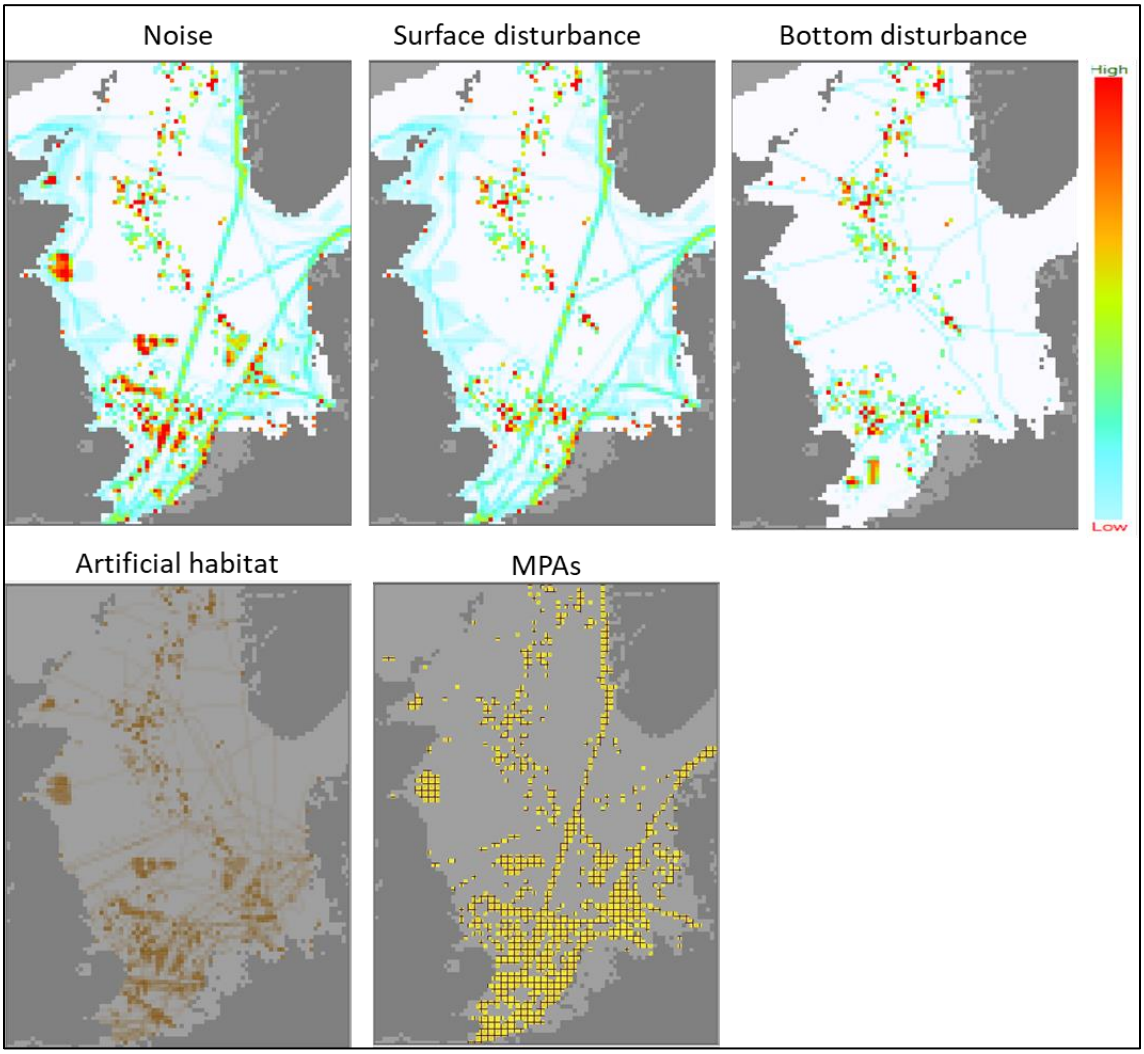


Figure 34: distribution of the start-up layers of Noise, Surface disturbance, Bottom disturbance, Artificial habitat and MPAs for Bottom trawl (reflecting also MPA layers for the other two fleets).

Under the start-up layers pressures, the model shows visible and intense impacts for most species. The model, after the changes implemented and described in chapter 6, provides satisfactory dynamics in space and time. Analyses of the model spatial and temporal performance under constant fishing (TEM = 1) and historical fishing are shown below in figures 35 to 37. Spatial distribution of most groups under TEM = 1 are more dynamic than in the previous version of the model: there are areas of high pressure (e.g. the Southern Bight) with reduced biomass of most groups, including charismatic species, commercially important species, and others (Figs. 35, 36). The dynamics of groups in time does not show fluctuation, as expected: the pressures have an effect on displacement but no direct mortality on the groups (Fig. 35). The spatial distribution of fishing fleets (figure 37) shows displacement, due to the closure of areas which are occupied by other activities. This displacement of fishing effort might have an effect on the distribution of targeted fish. The spatial and temporal dynamics with MSP start-up layers with historical fishing pressure show that the model reacts to changes in fishing pressure with biomas oscillation and redistribution. The temporal patterns show that the model is resilient to combined impacts of fishing and other pressures with flattening of the biomass dynamics in the short (Fig. 38) and in the long period (up to 75 years, Fig. 39).

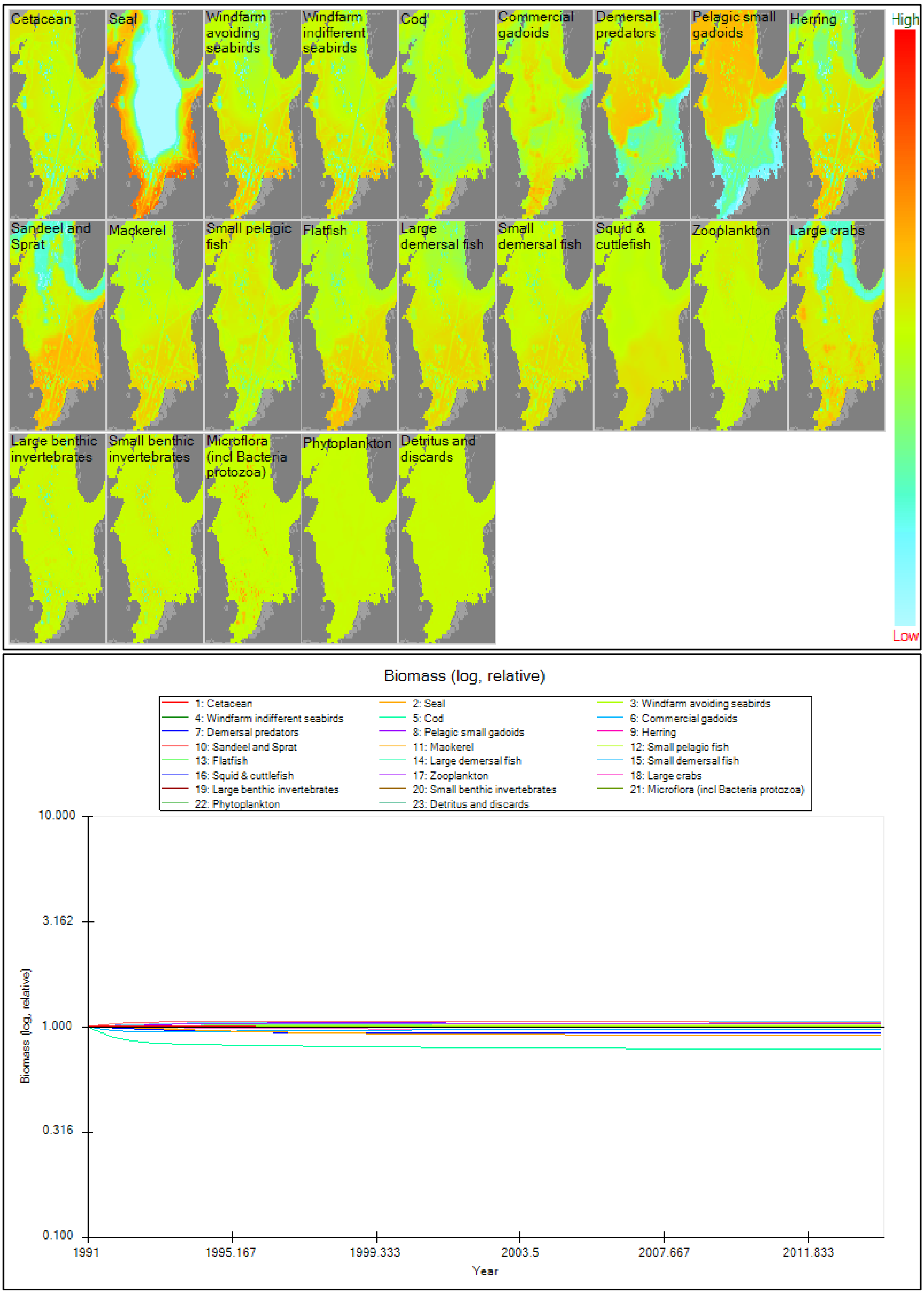


Figure 35. Spatial (top) and temporal (bottom) dynamics with MSP start-up pressure layers

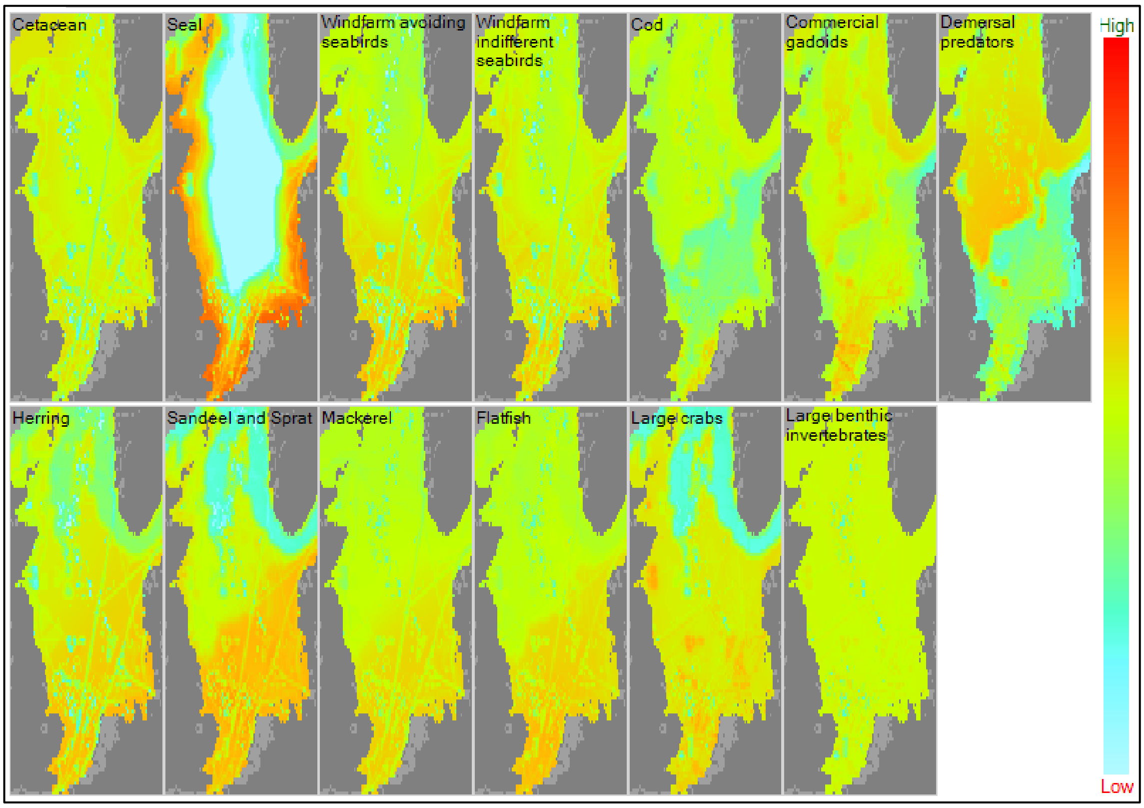


Figure 36. Spatial dynamics with MSP start-up pressure layers, selected species

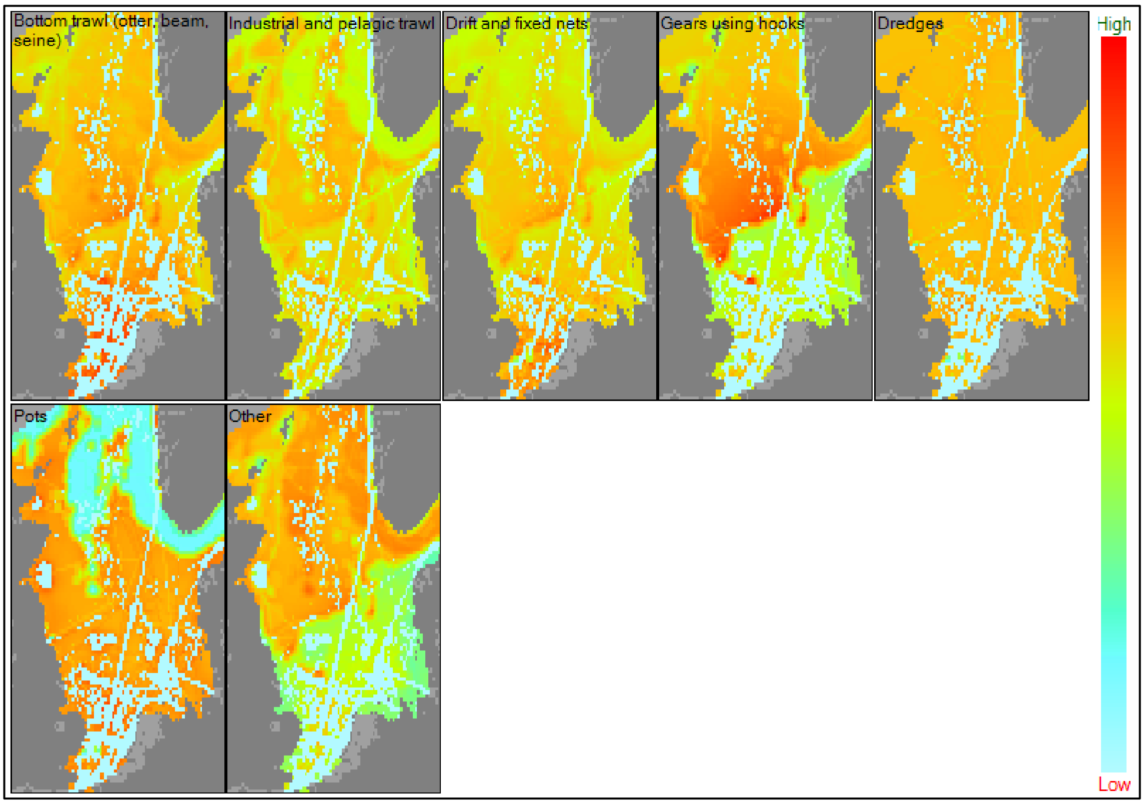


Figure 37. Spatial dynamics of fishing fleets effort with MSP start-up pressure layers

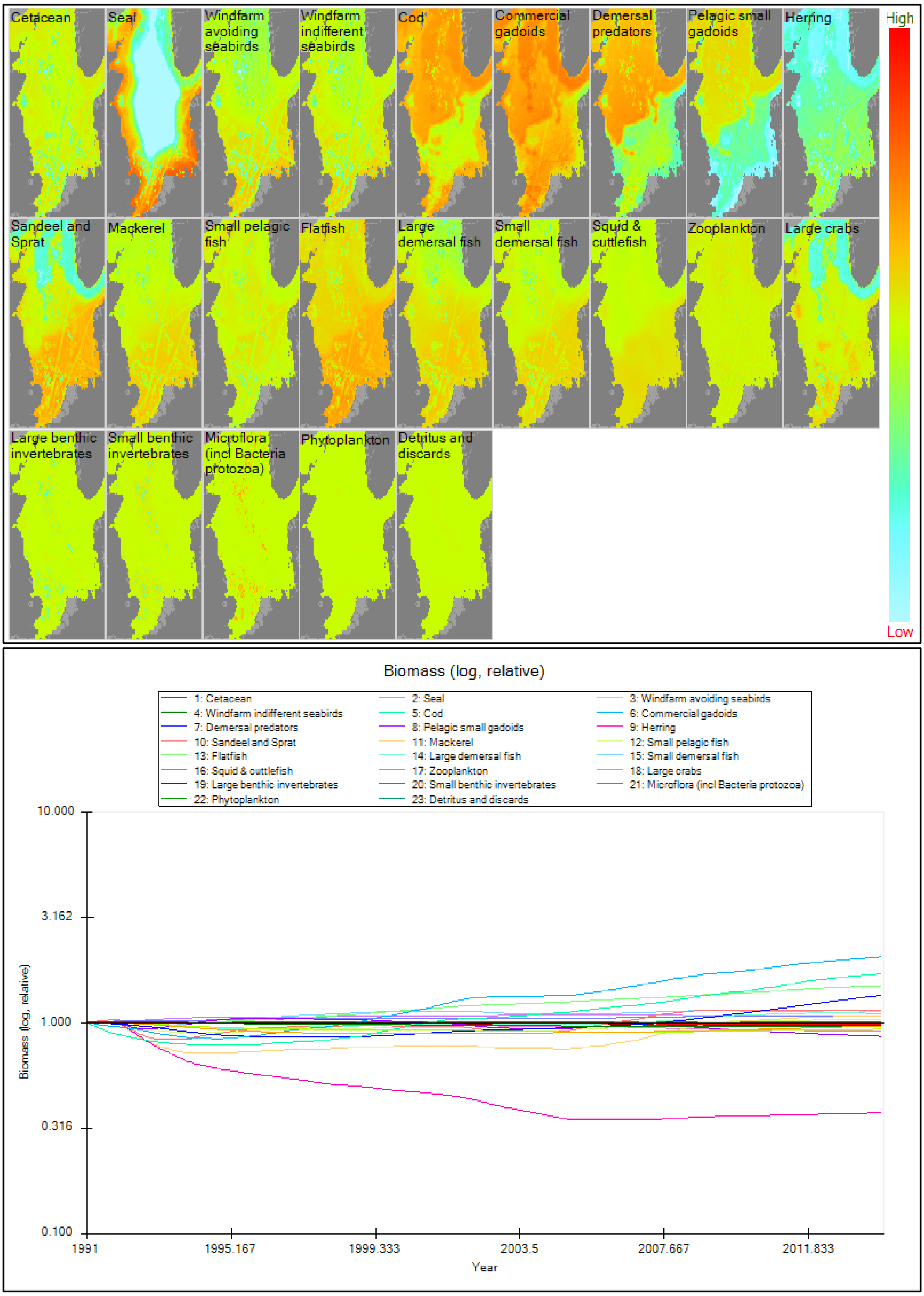


Figure 38. Spatial (top) and temporal (bottom) dynamics with MSP start-up pressure layers with historical fishing effort.

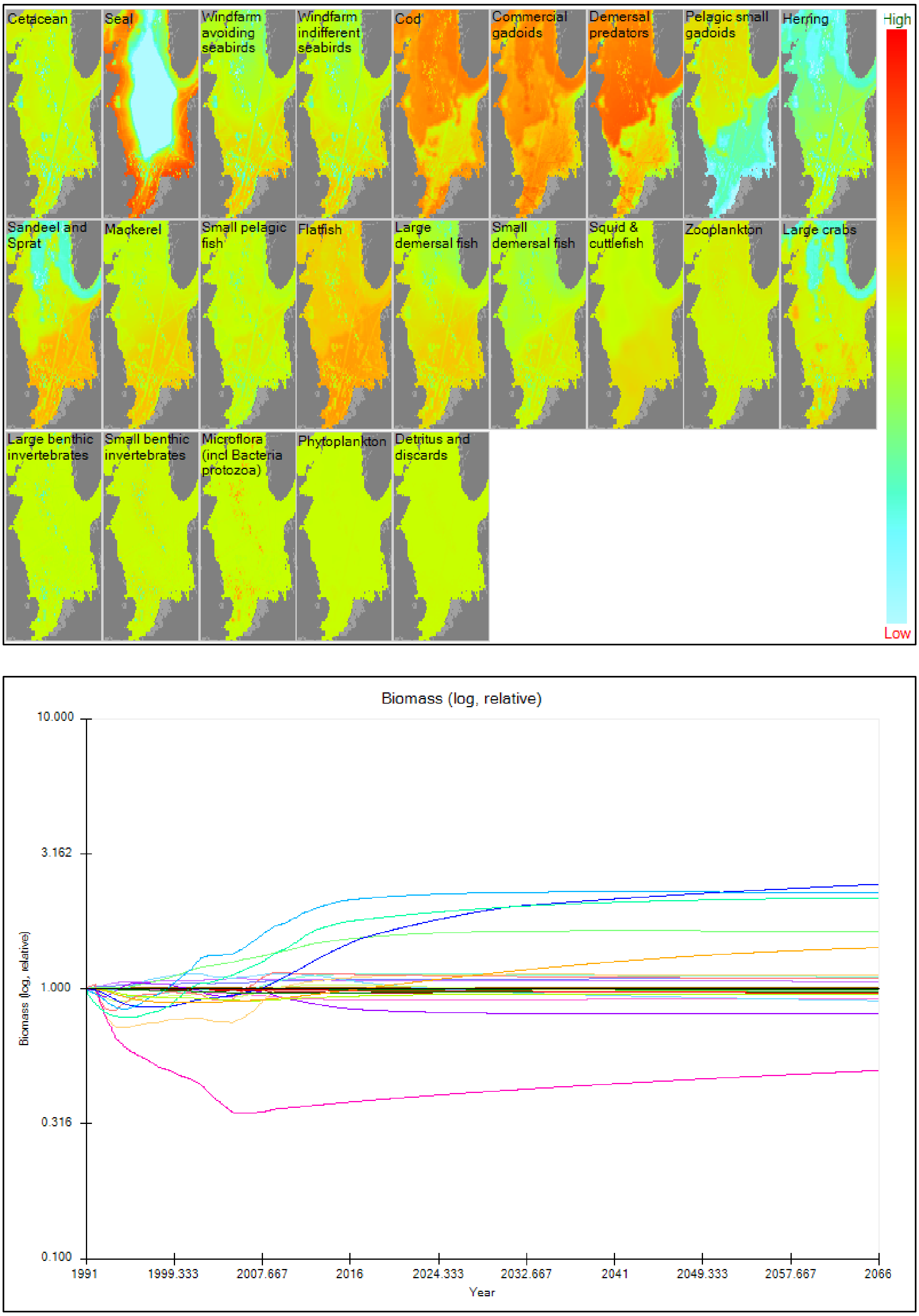


Figure 39. Spatial (top) and temporal (bottom) dynamics with MSP start-up pressure layers and historical fishing effort maintained for 75 years.

6.5. Comments about the final model

After the changes required by the commissioner, the model is considered to have higher reactivity and therefore game enjoyableness. The model is in a stable state when no pressures are applied, and it responds realistically to individual and combined pressures, with temporal and spatial patterns that reflect ecologically realistic patterns expected in this system. The dynamics are more visually appealing, with higher spatial dynamism and more realistic responses after the changes required by the user. For example, responses to fishing are more intense than with the initial values (confront Figs. 8 and 38); however, the model without any pressures runs flat (Fig. 35). Moreover, the responses to pressures are more realistic: for example, cetaceans and seals seem to avoid areas with large impact of noise and disturbance (Fig. 36); windfarm indifferent seabirds seem to be attracted by areas of artificial substrate while windfarm avoiding seabirds show neither attraction nor avoidance (Figs. 29, 36), and show instead avoidance of windfarms (Figs. 35 and 36). Most bottom fish show attraction to the artificial habitats, and benthic invertebrates show a combination of attraction from artificial habitat and displacement from bottom disturbance (Figs, 29, 36).

Additional suggestions for future versions of the EwE-MSP model include refining the selection of pressure layers. In the specific case, one of the requirements of the model commissioners was the inclusion of the negative effects of windfarms on seabirds. The challenge was that windfarm's impacts are quite mild, with only noise and artificial habitat influencing the system. Impacts of windfarms rotors are not well captured directly, and seabirds impact had to be modulated as a function of noise, which did the job satisfactorily. A more appropriate, and recommended, way to do this would be with a specific layer of blade hazard, which could drive some seabird groups away. Additionally, in Ecospace the impacts merely affect the distribution, without causing mortality. It could be an advantage, in the case of windfarms and the collision with seabirds, if in addition to displacement there was a way to include mortality. Development of this aspect could benefit the model and the MSP-EwE integration greatly.

Note that, as mentioned above, the model did not sacrifice realism to accommodate enjoyableness: the model remains scientifically sound, and the changes to response pressures provide a model which is still realistic and scientifically robust. However, it is important to highlight that patterns shown by the model are not necessarily perfectly matching expected spatial dynamics of the real world. The model results rather aim to be realistic under a hypothetical scenario, i.e. the set of impacts that game players will plan and implement in the game. Game players should be aware of the fact that the model includes simplifications related to game enjoyableness: players should not get the impression that everything is possible by taking mitigating or compensating measures (MPA, artificial substrate, etc). Furthermore, stochastic factors and real-life events and dynamics not included in the model might result in different outcomes than what the model represents. The players should remember that this is a game, although scientifically based.

7. Delivering ecological information back to MSP

The MSP software requires EwE to deliver 'outcomes' back to the game for dissemination to game players. Outcomes summarize aspects of the state of the ecosystem for MSP players (Steenbeek 2018), and encompass trends in spatial distribution and intensity in functional group biomass, fishing fleet catches, fishing fleet effort, and a small set of commonly accepted biodiversity indicators such as the Shannon diversity indicator (Shannon, 1948) and the Kempton's species diversity index (Kempton, 1979). The number of EwE outcomes is technically unlimited, but it needs to be as low as possible to keep the MSP game running fast (Steenbeek 2018).

Although the North Sea EwE model contains 23 functional groups and 7 fishing fleets, only those functional groups and fleets relevant to NorthSEE project objectives were included. Sixteen outcomes were defined: 11 biomass outcomes, 3 catch outcomes, and 2 ecological indicators (Table 22). Functional groups relevance for inclusion was based on commercial interest (cod, herring, mackerel, sandeel), ecological relevance (benthic invertebrates, demersal fish) and conservation concern (cetacean, seals, both seabird groups). Main fishing activities were captured by the spatial distribution of catches of the three major fishing fleets (bottom trawl, drift- and fixed nets, and industrial and pelagic trawl). The Large Fish Indicator (LFI) and Shannon diversity indicator were included because they provide robust diagnostics when food webs contain a relative low number of components. The LFI was custom-built, based on available biomass outcomes. The index is calculated as the ratio of total biomass of large fish groups over the total biomass of all fish groups (Engelhard et al., 2015). Figure 40 shows how this outcome was configured in MSP tools.

Table 22 – Ecological outcomes of the NorthSEE EwE model

Category	***Outcome name***	***# components***	***Components***
Biomass (group)	Benthic invertebrates	3	Large crabs; large benthic invertebrates; small benthic invertebrates
	Cetacean	1	Cetacean
	Cod	1	Cod
	Demersal fish	2	Commercial gadoids; demersal predators
	Flatfish	1	Flatfish
	Herring	1	Herring
	Mackerel	1	Mackerel
	Sandeel	1	Sandeel and sprat

	Seal	1	Seal
	Windfarm avoiding seabird	1	Windfarm avoiding seabirds
	Windfarm indifferent seabird	1	Windfarm indifferent seabirds
Catch (fleet)	Bottom trawl	1	Bottom trawl (otter, beam, seine)
	Drift and fixed nets	1	Industrial and pelagic trawl
	Pelagic and industrial trawl	1	Drift and fixed nets
Indicator (group)	Large Fish Indicator	11	Cod; Commercial gadoids; Demersal predators; Pelagic small gadoids; Herring; Sandeel and Sprat; Mackerel; Small pelagic fish; Flatfish; Large demersal fish; Small demersal fish
	Shannon diversity indicator	1	-

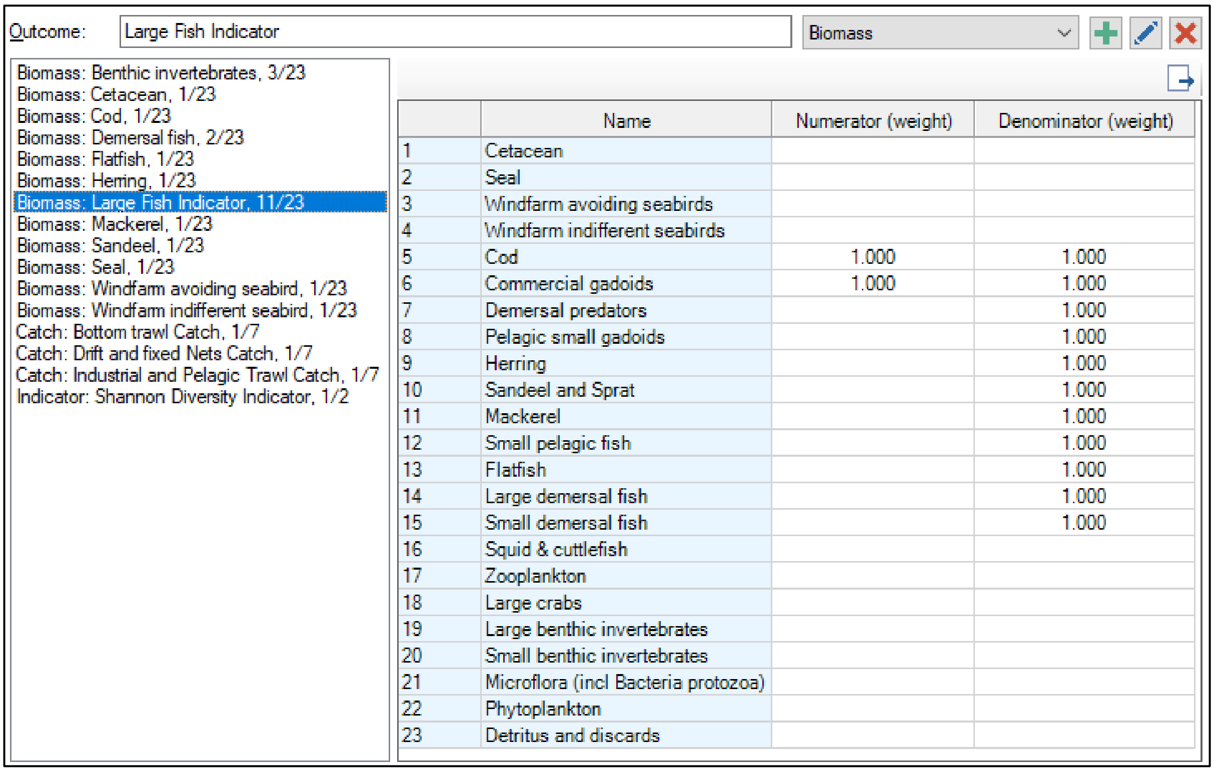


Figure 40. Screenshot of MSP tools, showing the Outcome configuration panel. All defined outcomes are listed here. The Large Fish Indicator is currently selected, and it is configured as a division of the biomass of large fish (cod and commercial gadoids) over the total biomass of all fish in the EwE model.

8. Final notes

The simplification of an existing EwE model for use for MSP is not an easy task. The example reported here was among the first attempts, and one of the goals of this report is to highlight the challenges and potential issues encountered, hopefully benefitting future modellers involved in a similar task.

One of the main problems was the compromise between realism and game requirements: as discussed above, the model needs to stay realistic in order to be scientifically sound. A definition of what is "realistic" is entirely subjective. One important starting point would be the possibility to calibrate, fit and validate the Ecospace model with spatial-temporal time series of data. To the day of writing this report there is no consistent and easy way for this; calibration is performed manually, and validation by visual comparison to data and external expert's opinion. For this report, feedback from senior modeller Steve Mackinson and from other ecologists were very helpful (see Appendix). Additionally, the translation from action to impact on groups was not straightforward. Knowledge of impacts on many organisms is incomplete and, in most cases, relates to one specific action rather than its individual pressures. Pressures can be hard to disentangle on the field, where control tests are not always available and confounding factors can mask real effects. A spatial-temporal fit to time series would be particularly useful to assess the robustness of the assumptions used. For the future, a more structured classification of impacts/pressures (e.g. Bergström *et al.*, 2014) rather than the *ad-hoc* method used for this model, or combination/integration with existing frameworks for integrated impact assessment (e.g. Symphony, Hammar *et al.*, 2018). Notwithstanding, the model performs very satisfactorily. This result can be attributed to the reliability of the underlying EwE model and to high availability of data for the North Sea which makes of this system an ideal case study.

Given the subjectivity and assumptions involved in the model building, the user might justifiably wonder what aspects then should the players 'trust' as meaningful? In order to answer this question, it is important to recall that the ultimate goal of the game is that players learn something useful. Players should take home an understanding of (or at least a grasp about the existence of) unexpected feedbacks from the ecosystem, such as non-linear behaviour and trophic cascades. Ecospace in general, and this model in particular, provide realistic ecosystem dynamics and this is exactly what the players should trust as meaningful. The overall dynamics and spatial-temporal effects of the combination of anthropogenic impacts and predator-prey relationship are realistic and meaningful.

Finally, the process of model refinement benefitted greatly by the feedbacks from the final user and by the tests with MSP software. This highlights the need for continuous feedback between ecological modeller and users when developing custom-designed models such as the simplified Ecospace model described here, and calls for planning repeated tests and allow sufficient time for addressing emerging issues.

9. Appendix

List of external experts consulted, including the expert panel outlined by Rijkswaterstaat, scientific and technical support from Ecopath experts, model performance validation from a senior Ecopath ecologist and author of the original model, and ecological advice and model evaluation from Rijkswaterstaat internal ecologists.

Name	institute	Role
Marcel van der Tol	Rijkswaterstaat	Ecological advice - expert panel
Ralf van Hal	Wageningen University & Research	Ecological advice - expert panel
Wouter Gotje	Witteveen+Bos	Ecological advice - expert panel
Merijn Houge	WWF	Ecological advice - expert panel
Jeroen Steenbeek	Ecopath International Initiative	Technical EwE support
Sheila Heymans	Scottish Association for Marine Sciences	Scientific EwE support
Steve Mackinson	Scottish Pelagic Fishermen Association	Model performance evaluation
Maarten Platteeuw	Rijkswaterstaat	Ecological advice, model performance evaluation
Inger van den Bosch	Rijkswaterstaat	Ecological advice, model performance evaluation

References

Baudron, A. R., and Fernandes, P. G. 2015. Adverse consequences of stock recovery: European hake, a new 'choke' species under a discard ban? Fish and Fisheries, 16: 563–575.

Baulch, S., and Perry, C. 2014. Evaluating the impacts of marine debris on cetaceans. Marine Pollution Bulletin, 80: 210–221. Elsevier Ltd. http://dx.doi.org/10.1016/j.marpolbul.2013.12.050.

Bergström, L., Kautsky, L., Malm, T., and Rosenberg, R. 2014. Effects of offshore wind farms on marine wildlife — a generalized impact assessment. Environmental Research Letters, 9: 034012.

Bray, L., Reizopoulou, S., Voukouvalas, E., Soukissian, T., Alomar, C., Vázquez-luis, M., Deudero, S., *et al.* 2016. Expected Effects of Offshore Wind Farms on Mediterranean Marine Life. journal of marine science and Engineering, 4: 18.

Burnham, K. P., and Anderson, D. R. 2002. Model Selection and Multimodel Inference. A Practical Information-Theoretic Approach. 2nd edition. Springer, New York.

Christensen, V., Coll, M., Steenbeek, J., Buszowski, J., Chagaris, D., and Walters, C. J. 2014. Representing Variable Habitat Quality in a Spatial Food Web Model. Ecosystems, 17.

Christensen, V., and Walters, C. J. 2004. Ecopath with Ecosim: Methods, capabilities and limitations. Ecological Modelling, 172: 109–139.

Desforges, J. P. W., Galbraith, M., and Ross, P. S. 2015. Ingestion of Microplastics by Zooplankton in the Northeast Pacific Ocean. Archives of environmental contamination and toxicology, 69: 320–330. Springer US.

Dierschke, V., Furness, R. W., and Garthe, S. 2016. Seabirds and offshore wind farms in European waters : Avoidance and attraction. Biological Conservation, 202: 59–68. http://dx.doi.org/10.1016/j.biocon.2016.08.016.

Edgar, G. J., Stuart-Smith, R. D., Willis, T. J., Kininmonth, S., Baker, S. C., Banks, S., Barrett, N. S., *et al.* 2014. Global conservation outcomes depend on marine protected areas with five key features. Nature, 506: 216–20. http://www.ncbi.nlm.nih.gov/pubmed/24499817.

EMODnet. 2017. Seabed habitat data 'Broad-scale habitat map (EUSeaMap)'. http://www.emodnet-seabedhabitats.eu/default.aspx?page=1953 (Accessed 19 April 2017).

Engelhard, G. H., Lynam, C. P., García-Carreras, B., Dolder, P. J., and Mackinson, S. 2015. Effort reduction and the large fish indicator: Spatial trends reveal positive impacts of recent European fleet reduction schemes. Environmental Conservation, 42: 227–236.

Faijer, M. J., and van Dam, P. 2012. Cumulative ecological effects of Offshore Wind Farms in the North Sea. Discussion report. 57 pp.

Garthe, S., Sonntag, N., Schwemmer, P., and Dierschke, V. 2007. Estimation of seabird numbers in the German North Sea throughout the annual cycle and their biogeographic importance. Vogelwelt, 128: 163–178.

Hammar, L., Schmidtbauer Crona, J., Kågesten, G., Hume, D., Pålsson, J., Aarsrud, M., Mattsson, D., *et al.* 2018. Integrerat planeringsstöd för statlig havsplanering utifrån en ekosystemansats Havs- och vattenmyndighetens rapport 2018:1.

Hammond, P., Lacey, C., Gilles, A., Viquerat, S., Börjesson, P., Herr, H., MacLeod, K., *et al.* 2017. Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys.

Heymans, J. J., Coll, M., Link, J. S., Mackinson, S., Steenbeek, J., Walters, C., and Christensen, V. 2016. Best practice in Ecopath with Ecosim food-web models for ecosystem-based management. Ecological Modelling, 331: 173–184. http://dx.doi.org/10.1016/j.ecolmodel.2015.12.007.

Hooper, T., and Austen, M. 2014. The co-location of offshore windfarms and decapod fi sheries in the UK : Constraints and opportunities. Marine Policy, 43: 295–300. http://dx.doi.org/10.1016/j.marpol.2013.06.011.

ICES. 2013. NS-IBTS indices calculation procedure Contents. ICES Data Cetre - DATRAS: 12.

ICES. 2015. ICES WGSAM REPORT 2015 Multispecies Assessment Methods (WGSAM) Report of the Working Group on International Council for the Exploration of the Sea.

ICES. 2016. Greater North Sea Ecoregion – Ecosystem overview. 1-22 pp.

ICES. 2018a. ICES FishMap - Species fact sheets. http://www.ices.dk/marine-data/maps/Pages/ICES-FishMap.aspx (Accessed 23 February 2018).

ICES. 2018b. Marine Data Map. http://ecosystemdata.ices.dk/Map/index.aspx?Action (Accessed 24 June 2018).

Jones, E. L., Mcconnell, B. J., and Smout, S. 2015. Patterns of space use in sympatric marine colonial predators reveals scales of spatial partitioning. Marine Ecology Progress Series, 534: 235–249.

Kempton, R. A. 1979. The structure of species abundance and measurement of diversity. Biometrics: 307–321.

Krone, R., Dederer, G., Kanstinger, P., Krämer, P., Schneider, C., and Schmalenbach, I. 2016. Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after de- ployment - increased production rate of Cancer pagurus. Marine Environmental Research, 123: 53–61. http://dx.doi.org/10.1016/j.marenvres.2016.11.011.

Krone, R., Gutow, L., Joschko, T. J., and Schröder, A. 2013. Epifauna dynamics at an offshore foundation e Implications of future wind power farming in the North Sea. Marine Environmental Research, 85: 1–12. http://dx.doi.org/10.1016/j.marenvres.2012.12.004.

Lindeboom, H. J., Kouwenhoven, H. J., Bergman, M. J. N., Bouma, S., Brasseur, S., Daan, R., Fijn, R. C., *et al.* 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone ; Environmental Research Letters, 6: 035101.

Løkkeborg, S., Humborstad, O., Jørgensen, T., and Soldal, A. V. 2002. Spatio-temporal variations in gillnet catch rates in the vicinity of North Sea oil platforms. ICES Journal of Marine Science, 59: 294–299.

Mackinson, S., and Daskalov, G. 2007. An ecosystem model of the North Sea to support an ecosystem approach to fisheries management: description and parameterisation. Science Series Technical Report, 142: 196 pp.

Mackinson, S., Platts, M., Garcia, C., and Lynam, C. 2018. Evaluating the fishery and ecological consequences of the proposed North Sea multi-annual plan. PLoS ONE, 13: e0190015.

Middel, H., and Verones, F. 2017. Making Marine Noise Pollution Impacts Heard : The Case of Cetaceans in the North Sea within Life Cycle Impact Assessment. Sustainability, 9: 1138.

Pauly, D., Christensen, V., and Walters, C. 2000. Ecopath, Ecosim, and Ecospace as tools for evaluating ecosystem impact of fisheries. ICES Journal of Marine Science, 57: 697–706. http://icesjms.oxfordjournals.org/cgi/doi/10.1006/jmsc.2000.0726.

Plagányi, É. E., and Butterworth, D. S. 2004. A CRITICAL LOOK AT THE POTENTIAL OF ECOPATH WITH ECOSIM TO ASSIST IN PRACTICAL FISHERIES MANAGEMENT. African Journal of Marine Science, 26: 261–287.

Polovina, J. J. 1984. Model of a Coral-Reef Ecosystem .1. the Ecopath Model and Its Application To French Frigate Shoals. Coral Reefs, 3: 1–11.

Reubens, J. T., Pasotti, F., Degraer, S., and Vincx, M. 2013. Residency , site fidelity and habitat use of Atlantic cod (Gadus morhua) at an offshore wind farm using acoustic telemetry. Marine Environmental Research, 90: 128–135. http://dx.doi.org/10.1016/j.marenvres.2013.07.001.

Romagnoni, G., Mackinson, S., Hong, J., and Eikeset, A. M. 2015. The Ecospace model applied to the North Sea: Evaluating spatial predictions with fish biomass and fishing effort data. Ecological Modelling, 300: 50–60. http://dx.doi.org/10.1016/j.ecolmodel.2014.12.016.

Rummel, C. D., Löder, M. G. J., Fricke, N. F., Lang, T., Griebeler, E. M., Janke, M., and Gerdts, G. 2016. Plastic ingestion by pelagic and demersal fish from the North Sea and Baltic Sea. Marine Pollution Bulletin, 102: 134–141. http://dx.doi.org/10.1016/j.marpolbul.2015.11.043.

Russell, D. J. F., Brasseur, S. M. J. M., Thompson, D., Hastie, G. D., Janik, V. M., Aarts, G., Mcclintock, B. T., *et al.* 2014. Marine mammals trace anthropogenic structures at sea. Current Biology, 24: 638–639.

Russell, D. J. F., Hastie, G. D., Thompson, D., Janik, V. M., Hammond, P. S., Scott-hayward, L. A. S., Matthiopoulos, J., *et al.* 2016. Avoidance of wind farms by harbour seals is limited to pile driving activities. Journal of Applied Ecology, 53: 1642–1652.

Scheidat, M., Tougaard, J., Brasseur, S., Carstensen, J., Van Polanen Petel, T., Teilmann, J., and Reijnders, P. 2011. Harbour porpoises (Phocoena phocoena) and wind farms: A case study in the Dutch North Sea. Environmental Research Letters, 6: 025102.

Scott, E., Serpetti, N., Steenbeek, J., and Heymans, J. J. 2015. A Stepwise Fitting Procedure for automated fitting of Ecopath with Ecosim models. SoftwareX, 5: 25–30.

Shannon, C. E. 1948. A mathematical theory of communication. The Bell System Technical Journal, 27: 379–423, 623–656.

Soldal, A. V., Svellingen, I., Jørgensen, T., and Løkkeborg, S. 2002. Rigs-to-reefs in the North Sea: Hydroacoustic quantification of fish in the vicinity of a 'semi-cold' platform. ICES Journal of Marine Science, 59: S281–S287.

Steenbeek, J. 2018a. EwE model guidelines for MSP gameplay. figshare. https://doi.org/10.6084/m9.figshare.5897185.v1.

Steenbeek, J. 2018b. Integrating Ecopath with Ecosim into the MSP software - conceptual design. https://doi.org/10.6084/m9.figshare.5849634.

Stienen, E. W. M., Waeyenberge, V., Kuijken, E., and Seys, J. 2007. Chapter 3 TRAPPED WITHIN THE CORRIDOR OF THE SOUTHERN NORTH SEA : THE POTENTIAL IMPACT OF OFFSHORE WIND FARMS ON SEABIRDS. *In* Birds and wind farms: risk assessment and mitigation, Quercus. Ed. by M. . De Lucas and G. F. E. . F. Janss.

Stronkhorst, J., Ariese, F., Hattum, B. Van, Postma, J. F., and Kluijver, M. De. 2003. Environmental impact and recovery at two dumping sites for dredged material in the North Sea. Environmental Pollution, 124: 17–31.

Tasker, M. L. 2008. The effect of climate change on the distribution and abundance of marine species in the OSPAR Maritime Area. ICES Cooperative Research Report No. 293. 43 pp.

Todd, V. L. G., Warley, J. C., and Todd, I. B. 2016. Meals on Wheels ? A Decade of Megafaunal Visual and Acoustic Observations from Offshore Oil & Gas Rigs and Platforms in the North and Irish Seas. PLoS ONE, 11: e0153320.

Walters, C., Pauly, D., and Christensen, V. 1999. ECOSPACE: prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems, with particular reference to impacts of marine protected areas. Ecosystems, 2: 539–554.

Walters, C., Pauly, D., Christensen, V., and Kitchell, J. F. 2000. Representing density dependent consequences of life history strategies in aquatic ecosystems: EcoSim II. Ecosystems, 3: 70–83.

Wilcox, C., Van Sebille, E., and Hardesty, B. D. 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proceedings of the National Academy of Sciences, 112: 11899–11904. http://www.pnas.org/lookup/doi/10.1073/pnas.1502108112.