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Investigating food web effects due to man-made structures using COupled Spatial Modelling (COSM)

For: INSITE

Christopher Lynam, Paulette Posen, Serena Wright, Clement Garcia, Jeroen Steenbeek, Steven Mackinson, Susana Lincoln and Mark Kirby

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COSM: Investigating food web effects due to man-made structures using COupled Spatial Modelling

Submitted to: Richard Heard, INSITE Programme Director

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Executive summary

Man-made structures (Figure 1) including oil and gas platforms, pipelines, cables, ship wrecks provide additional hard substrate in the largely soft-sediment environment of the North Sea. Structures have been present in the North Sea for many decades and these have been colonised by benthic communities and attract fish, seals and seabirds looking for prey, rest, or refuge from predators. Activities at and around structures may also cause disturbance to the marine environment locally that can result in avoidance by mobile organisms (e.g. through transportation of equipment / personnel to / from them and associated noise). The presence of man-made structures can lead to a shift in the species composition locally and through predator-prey interactions potentially alter the functioning of the marine food web. However, the scientific evidence and tools needed to understand the role of hard substrate provided by oil and gas infrastructure in the North Sea ecosystem and to generate evidence-based approaches for decommissioning has been lacking. This gap was recognised by Oil and Gas UK and the INSITE programme was set up to fund this research.

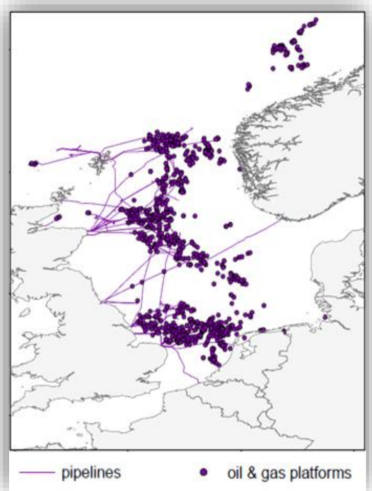


Figure 1. Location of pipelines and platforms

INSITE funded the project entitled “Investigating food web effects due to man-made structures using COupled Spatial Modelling” (COSM) to assess the potential ecosystem effects of man-made structures in the North Sea. This project was led by Cefas (https://www.cefas.co.uk/) with the aim to better understand if the presence of man-made structures might lead to changes locally that can spread through the wider ecosystem through predator-prey interactions and dispersal. This was delivered through the collation of existing data, statistical modelling of data, and the development of a spatial food web model that can be projected through time. The food web model was used to evaluate scenarios: asking the question, what would happen to communities if structures were removed through decommissioning? Which species might be affected? Are any effects important given that climate change and fishing already impact the system greatly?

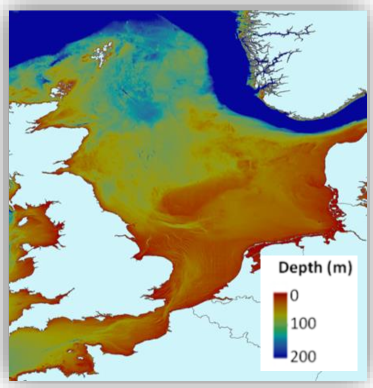


Figure 2. Bathymetry (source: Defra DEM UK EEZ plus EMODnet bathymetry)

Compilation of data was a significant challenge and was done in collaboration with the INSITE EcoConnect project. Data on man-made structures and natural habitats (Figure 2) were compiled and the proportion of different types estimated in quarter degree grid squares across the North Sea. In addition, data were sourced for key environmental layers (temperature, salinity, bathymetry and primary

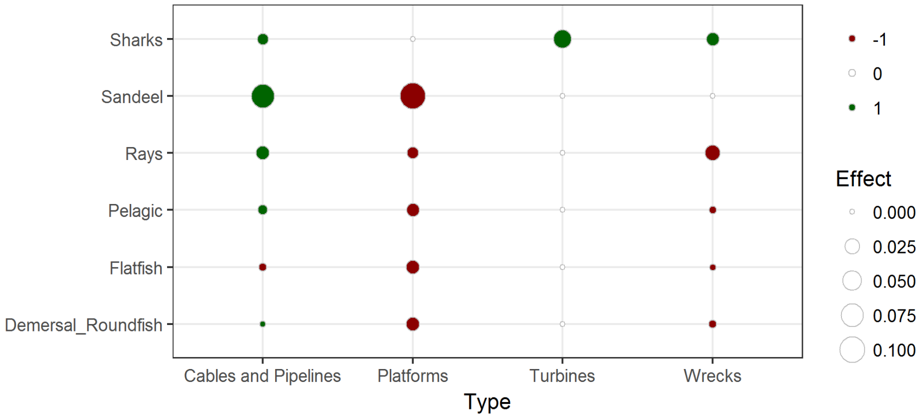


Figure 3. Statistical effects of structures on probability of occurrence of groups in survey data, a green bubble indicates that the likely occurrence is increased through the presence of structures (with larger bubbles indicating larger effect size).

production) and spatial information on fishing effort (in collaboration with the EU BENTHIS project). Statistical modelling of survey data, collected by international fisheries surveys and benthic monitoring, was conducted to identify preferences for fish and benthos for natural substrates and man-made structures in addition to their responses to change in the environment. In general, the survey data indicated that fish, rays and sharks occurred more often near cables and pipelines than expected given their presence in the natural environment (e.g. Figure 3). In contrast, these groups were less likely to be found near oil and gas pipelines than expected. Sharks were more likely to be found near ship wrecks and wind turbines, but many other groups were less often found in survey data near wrecks.

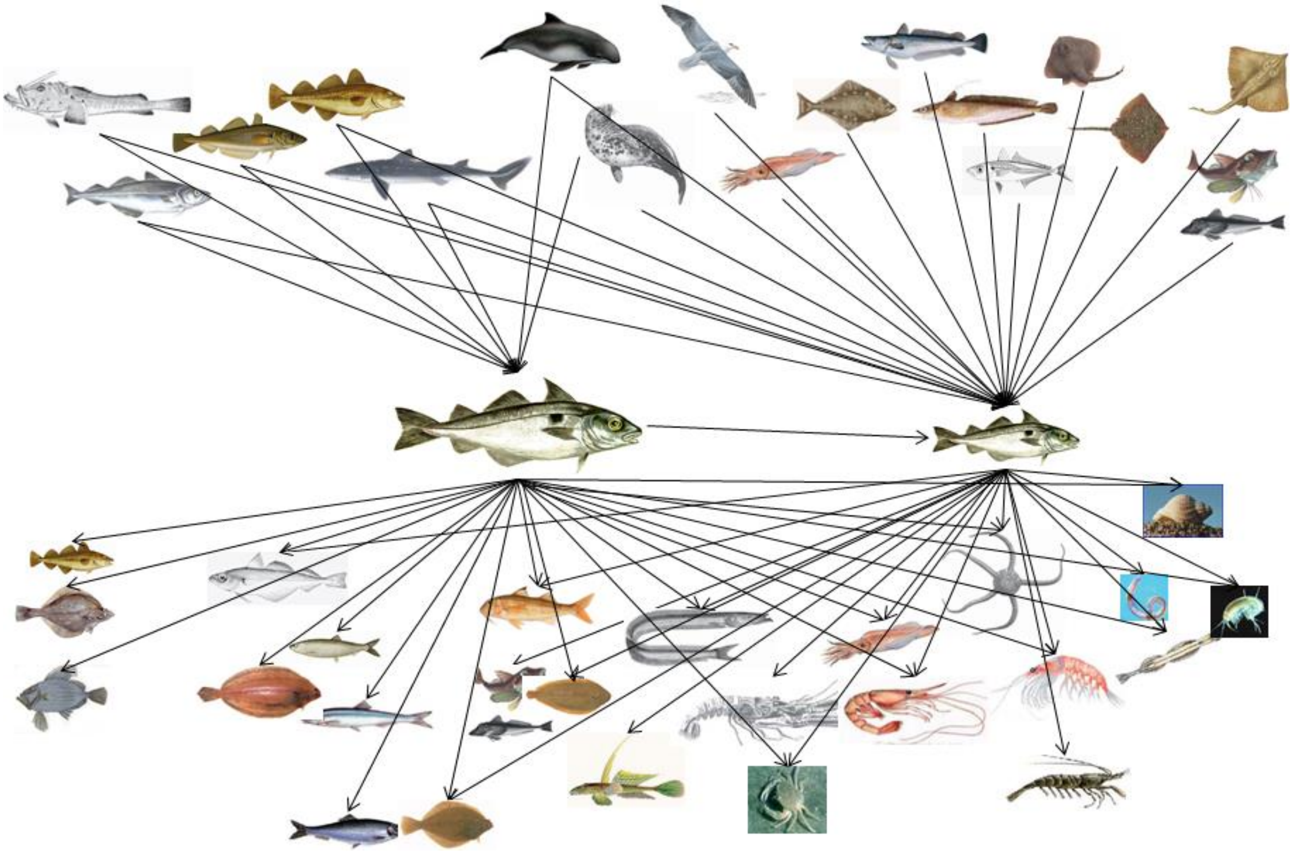


Figure 4. Schematic showing interactions for haddock (adult, left; juvenile, right) with predators above and prey species below.

Decommissioning of man-made structures at the end of their use is generally a condition of the licence to operate. In the North Sea, oil and gas platforms are coming to the end of their life and options for decommissioning structures, ranging from complete removal to leaving in place or dumping at sea, are being considered. As structures are removed from the sea, they will disturb any communities that have become associated with them, which may ripple through the food web to cause ecosystem level effects. To investigate the potential response of the ecosystem, COSM built a spatio-temporal food web model of the North Sea ecosystem (Figure 4 and Figure 5) ranging from phytoplankton to predatory marine mammals that is embedded within a model environment that includes information on seabed habitats (natural and artificial) and the water column (salinity and temperature). This model is then used to test scenarios of change relating to removal of structures, and contrasted to change in the environment and fishing pressure. The impact on the food web of the two extreme decommissioning options (i.e. removal of all structures versus no change) were tested to determine the range of responses that this novel modelling approach could generate.

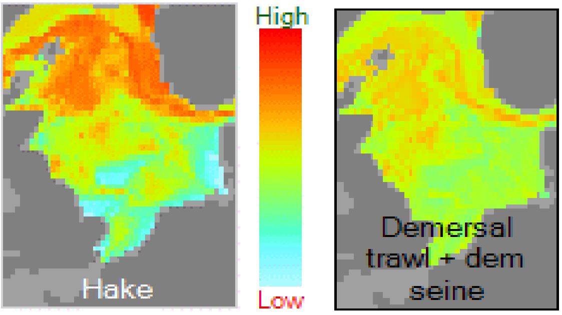


Figure 5. Ecospace modelled relative distribution of hake (left) and the demersal trawl and demersal seine fleet

Care should be taken interpreting the results of this study as many assumptions are needed to build such models.

Although efforts were made to compare the model to scientific data at each step, there is a paucity of available ecological observations at and in the local vicinity of natural and man-made structures.

With additional data, it would be possible to reduce the uncertainty in the modelling results.

With these considerations in mind, the key findings from COSM are as follows:

1. Model simulations indicate that man-made structures have an effect on the local community composition and these effects can disperse throughout the North Sea ecosystem mediated by interactions between species.
2. The removal of oil and gas platforms and pipelines may ultimately contribute to declines in some groups (rays and sand eels), but increases in others (sharks, flatfish and roundfish).
3. The presence of wrecks and wind turbines appears to have a much greater impact than oil and gas infrastructure on rays, sharks, sand eels, flatfish and demersal roundfish.
4. Importantly, all modelled effects of structures are minor compared to the potential effect of other pressures such as an increase in temperature on the ecosystem or increase in fishing effort to historic levels.
5. Although the additional habitat provided by platforms and pipelines may be relatively small, this difference should not be disregarded at this stage for non-commercial species of conservation concern, since natural variability is by its very nature unmanageable and the removal of other structures such as wrecks is unlikely to occur in great amount.

1. Introduction

The Cefas-INSITE project ‘Investigating food web effects due to man-made structures using COupled Spatial Modelling’ (COSM) aimed to: evaluate habitat preferences of key functional groups of species in the North Sea; to combine this knowledge with spatio-temporal maps and food-web dynamics in a state-of-the-art modelling tool; and to explore the role of man-made structures in the system.

Man-made structures including oil and gas platforms, pipelines, cables, ship wrecks provide additional hard substrate in the largely soft-sediment environment of the North Sea. Structures have been present in the North Sea for many decades and these have been colonised by benthic communities and attract fish, seals and seabirds looking for prey, rest, or refuge from predators. Activities at and around structures may also cause disturbance to the marine environment locally (e.g. through noise and transportation to/from them) that can result in avoidance by mobile organisms. The presence of man-made structures can lead to a shift in the species composition locally and through predator-prey interactions alter the functioning of the marine food web.

Decommissioning of man-made structures at the end of their use is generally a condition of the licence to operate (e.g. UNCLOS 1982; OSPAR Decision 98/3; UK Petroleum Act 1998; UK Energy Act 2008). In the North Sea, oil and gas platforms are coming to the end of their life and options for decommissioning structures, ranging from complete removal to leaving in place or dumping at sea, are being considered (Oil & Gas Authority, 2016). As structures are removed from the sea, they will disturb any communities that have become associated with them, which may ripple through the food web to cause ecosystem level effects. To investigate the potential response of the ecosystem, COSM has built a spatio-temporal food web model of the North Sea ecosystem ranging from phytoplankton to predatory marine mammals that is embedded within a model environment that includes information on seabed habitats (natural and artificial) and the water column (salinity and temperature). This model is then used to test scenarios of change relating to removal of structures, and contrasted to change in the environment and fishing pressure. Given that it was unknown whether any change in the food web could be detected by such a novel modelling approach, the project tested extreme options for decommissioning scenarios (i.e. removal of entire categories of structure) to determine the bounds of detection by the model.

The spatio-temporally dynamic model of the food web that COSM developed utilises the Ecopath approach (Christensen and Walters 2004; Christensen *et al.* 2014). In this approach, a base model is built to represent predator-prey interactions between functional groups within a single year and imposes the restriction that the mass and energy input and output of all living groups must balance. The model is based on two main equations, the first relates to the biological production of a functional group, which should be equal to the sum of the group’s mortality from predation and fishing, net migration, and biomass accumulation. In the second key equation, the consumption by a functional group must meet the demand for the group’s production and respiration. The key input parameters are the biomass and fishery catch of each of the modelled groups, their production and consumption rates, and the proportion of each group in the diet of each of its predators. Under the assumption that the system is mass-balanced, Ecopath solves a system of linear equations to estimate any missing parameters.

The foundation for the spatial food web model developed here is the previously published calibrated temporal-only model (Ecopath with Ecosim) that was quality controlled in accordance with guidance by the International Council for the Exploration of the Sea (ICES, 2016). The model includes 69 functional groups from phytoplankton and benthic groups at the base of the food web up to predatory sharks and seabirds. In addition to modelling the predatory mortality between groups the impact of 11 fishing fleets are modelled that represent the international fleets operating in the North Sea. This published model was extended to integrate spatial information using the Ecospace software module, which effectively replicates Ecopath with Ecosim food web dynamics over a spatial grid of cells, which are linked through dispersal of organisms. Additional tools to interrogate the model were developed and will be freely available in future releases of the software. Relationships between functional groups and habitats, including their affinity for particular natural substrates and man-made structures were based on empirical analyses of unbiased, if incomplete, scientific survey data where available.

COSM was funded by the INSITE programme to develop novel science to better understand consequences of the existing man-made structures on the ecosystem, and the effects of removal of man-made structures on structure and function of the North Sea ecosystem. To achieve this, COSM had the following objectives:

1. To collate existing data and knowledge on linkages between hard substrate.
2. To evaluate the habitat preferences of key functional groups of infauna, epifauna and fish in order to link the distribution of each to substrates and environmental data layers.
3. To develop a state-of-the-art modelling tool that links spatio-temporal maps with food-web dynamics, resolved at a resolution that can represent man-made structures, while at the same time evaluate the impacts over wider spatial scales.
4. To explore the role of man-made structures on the food web relative to natural variation and other pressures.

COSM successfully collated spatial information on habitat type (substrates and bathymetry), environment (temperature, salinity, and primary production) and pressure data (fishing) and modelled the distribution of benthic and pelagic ecosystem components from infauna to seabirds. The consumption of prey by functional groups of predators was modelled in relation to their habitat preferences and the subsequent flow of mass through the system to higher predators was examined when man-made structures were present in the system and for a range of scenarios relating to removal of structures. The change in the system level biomass of functional groups was contrasted to modelled change in these groups due to the potential effects of a change in fishing pressure and due to natural variability in sea water temperature.

This report contains a summary of the scientific outputs of COSM, highlights how COSM helped to deliver INSITE objectives, demonstrates how science from COSM can inform on decommissioning strategies, and identifies further research that can improve on the evidence base in support of decommissioning options.

2. Methods

2.1. Data collating and processing

This project drew on a range of physical, chemical and biological data for its analyses, with a strong focus on the compilation and processing of data relating to physical structures in the North Sea, both natural and man-made. Datasets of natural substrates and man-made structures were compiled to support the modelling processes. Different types of substrate and structure have the capacity to support a variety of marine communities, but environmental requirements will differ between species. In many cases it is not merely the presence of a certain type of substrate or structure that will determine the establishment and continued success (or otherwise) of a community, but also the spatial extent and/or connectivity of those features. In order to assess the combined influence of man-made structures and natural substrates on marine communities, it was necessary to examine the spatial relationships between these features. Spatial data were processed using ArcMap v10.1 (http://www.esri.com/) and statistical analyses were conducted in R (version 3.3.2, 2016-10-31).

Data layers were prepared for the statistical modelling and Ecospace set-up for the following features: bathymetry, natural substrates, man-made structures (oil and gas platforms; subsurface structures; wind turbines; wrecks; pipelines; submarine cables), salinity, temperature, primary production, fishing effort and marine protected areas (Figure 6 and Figure 7). A range of spatial resolutions were considered and a compromise chosen (0.25 x 0.25 decimal degree grid) to balance the need to capture the effects of small-scale features while modelling broad scale distributions over the whole North Sea. For full information on data sources and processing see Annex 1 “Data collation, preparation and outcomes”.

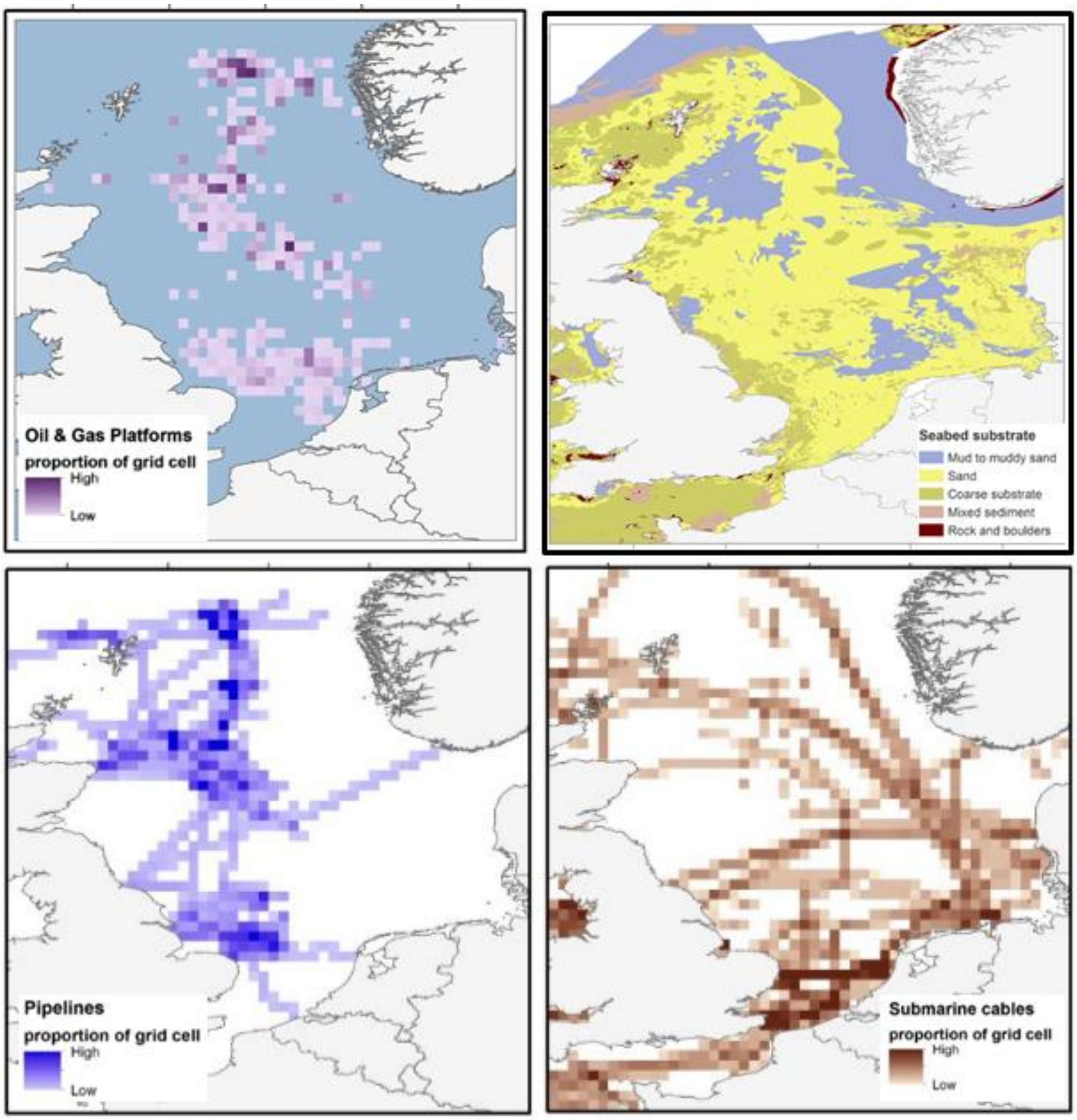


Figure 6. Key data layers prepared for modelling studies showing locations of man-made structures (gridded at 0.25 degree resolution) and natural habitat. For further details see the Annex (Data processing and compilation).

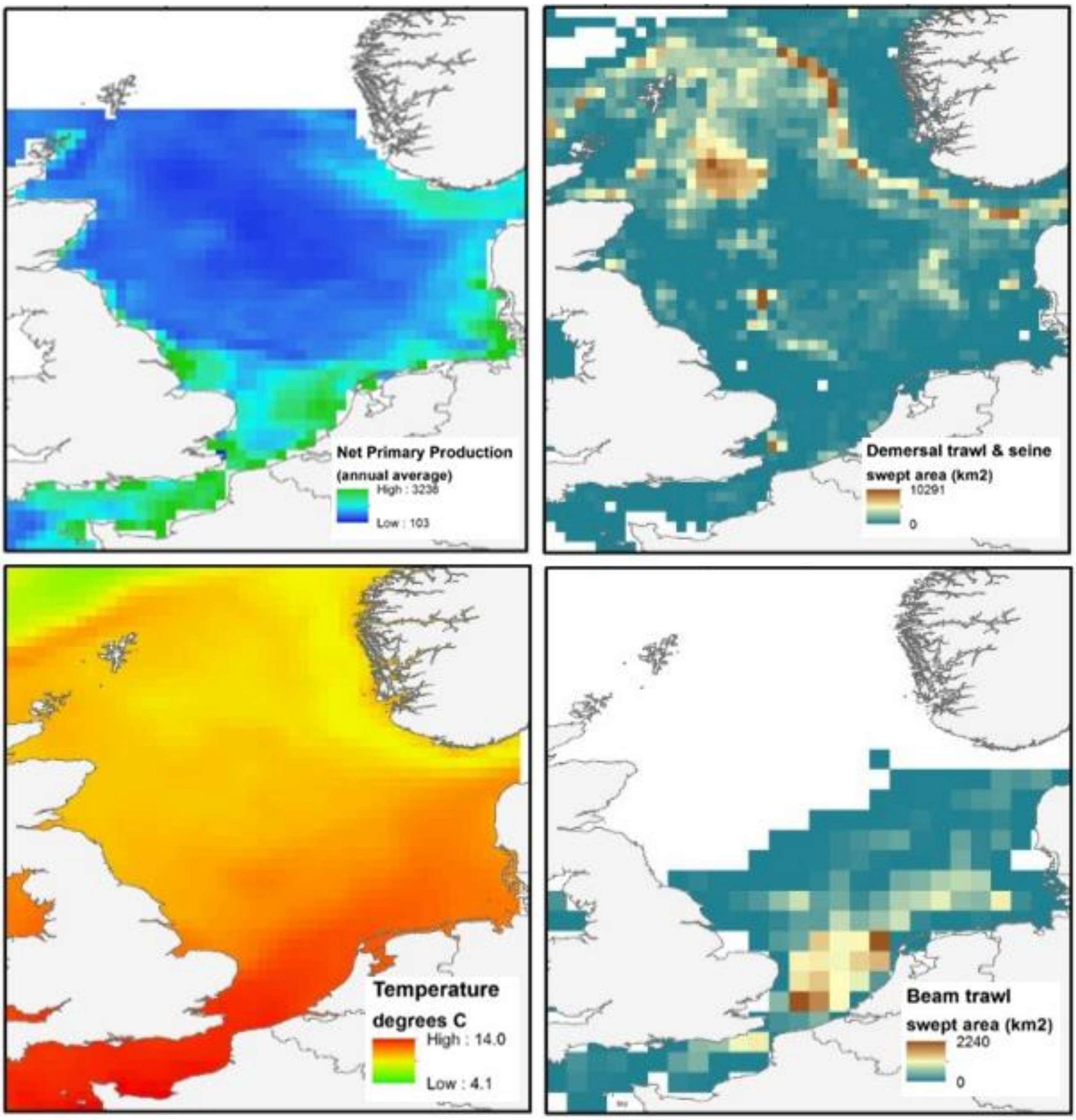


Figure 7. Key data layers prepared for modelling studies showing environmental drivers and fishing effort maps. For further details see Annex 1.

2.2. Statistical Analyses

Firstly, fish abundance from scientific surveys conducted in quarters 1 (since 1983) and quarter 3 (since 1998) were investigated to identify whether fish species were distributed differently spatially within the year. Quarterly distributions were merged when there was no significant difference between them following a Mantel spatial correlation test (with 5% significance level). Environmental and structure information were subsequently linked to the data based on their spatial and temporal co-occurrence. Data were grouped into decadal periods to average out interannual variability due to recruitment and fishing pressure effects and account for the fact that not all structures were present throughout the time series.

Initial data exploration made use of pairwise correlation plots and simple linear models to investigate potential relationships in the data. Correlations between functional groups and the presence of either pipelines and cables were not found to be dissimilar and given the limitations of the data to survey at these locations and the uncertainty regarding the coverage of the structures, the presence data for pipelines and cables were combined in to a single explanatory variable. Generalized Additive Models (GAMs) were chosen to model relationships between fish survey data and explanatory variables since these models are able to capture the non-linear and non-monotonic relationships observed in the exploratory data analyses and allow for flexibility in the error structure chosen. In contrast to simple linear models, GAMs allow the nature of the relationship between the response and the set of explanatory variables to emerge from the data rather than imposing a parametric relationship upon them. However, there is a risk that such data driven models will result in unrealistic relationships when the data underpinning them are highly variable. To mitigate against this risk, the maximum number of knots in each spline was limited at 4 to prevent the GAM over fitting to the noise in the data. As part of a stepwise-deletion approach to the selection of explanatory variables, a shrinkage algorithm was implemented to enable smoothers to be shrunk to zero where possible (Wood 2017). Three model types were subsequently run to assess which predictor variables (environmental and physical) were significantly related to the distribution of fish species using the 'gam' function from the "mgcv" package in R:

M1. A detection/non-detection model (Binomial distribution for errors, logit-link)
M2. An abundance model excluding non-detections (Gamma distribution for errors, log-link)
M3. An abundance with non-detection model (Negative binomial distribution for errors, log-link)

M1 was considered most appropriate for species rarely detected in the survey, while M3 – the most explanatory type – could be used for species that were numerous and occurred frequently. M2 can be combined with M1 in a two-stage modelling process for species that are not numerous in the dataset or are numerous, but do not meet the statistical requirements of the M3 model.

Model goodness of fit was assessed through:

- variance-inflation factors to assess multi-collinearity;
- semi-variograms to assess spatial independence of the residuals;
- partial residual plots for predictors to identify if patterns remain that were not captured by the model and its error structure;
- percentage of deviance explained by the models;
- predictive performance was measured through the Area Under the Receiver Operating Characteristic (ROC) Curve.

Fitted models were used to assess empirically the impact of removing hard structures on the occurrence of species by making predictions across the North Sea grid (all 0.25 x 0.25 degree cells) with all significant terms in the model and with man-made structures removed.

The relationships between response and predictors (i.e. the smoothers) determined from simple detection/non-detection models were retained for input into the Ecospace model to link presence of functional groups directly to the environmental and man-made structure spatial layers (see below).

2.3. Ecospace Model set up and testing

Ecospace is a spatial simulation tool within the Ecopath with Ecosim software environment (EwE - http://www.ecopath.org/). The three main components of the software are: Ecopath - a static, mass-balanced snapshot of the ecosystem; Ecosim - a time dynamic simulation module for policy exploration; and Ecospace – a spatial and temporal dynamic module. EwE has been developed continuously for 30 years and since 2011 the Ecopath Research and Development Consortium has encouraged co-development of the open-source software.

The Ecopath base model represents the system (including biomass and catch) during the base year of 1991. This base model has been projected forward temporally in Ecosim using time-series data (environmental data and fishing mortality) to calibrate the model to biomass data for functional groups and form the model "key run" (ICES 2016). The Ecospace model inherits parameters from the key-run (including Ecosim fitted vulnerabilities), but requires additional input data layers and parameters to generate a consistent spatial model. Here we detail the key data and parameters included in the Ecospace model.

Environmental forcing data and fishing impacts

For multi-stage groups (cod, haddock, whiting, saithe and herring), non-spatialized recruitment time-series (1991-2013) used by Ecosim to drive the interannual production of juvenile groups were retained and, for forward simulations, fixed at their final values. Temporal environmental forcing (i.e. temperature and salinity) functions for producers and consumers were replaced with spatial layers in the Ecospace modules using an average annual map based on spatio-temporal data for the hindcast period. Man-made structures were assumed present throughout the model period. For other data layers (bathymetry, natural substrates, primary production) see Section 1/Annex 1.

Fishing effort time series were retained from the ICES key run so that Ecospace projections were based on the most recent fishing effort levels rather than the Ecopath base values. Spatial patterns of fishing fleets were guided by cost functions based on the inverse of observed fishing effort by fleet (see the Annex) with an additional high penalty for beam trawlers in the northern North Sea since the fleet targets sole and plaice in the southern North Sea only. Ecospace was then allowed to predict the fine scale spatial distribution of fishing effort given the distribution of the target species. Fleets were given the freedom to fish in each substrate type (sand, mud, muddy sand, coarse, mixed) with the exception of *Nephrops* trawlers that do not generally fish in the mixed areas and pots that do not generally operate in mud, muddy sand or sand habitats. Where rocks and boulders were present, only gears using hooks, pots and the “other” category were allowed to fish. Where man-made structures were present demersal trawlers and seiners, drift and fixed nets, gears using hooks, pots and “other” were allowed to fish within the grid cell, but the remaining 6 fleets (dredgers, pelagic trawlers, beam trawlers, industrial trawlers, *Nephrops* trawlers, shrimp trawlers) were generally excluded from fishing in the area. Exceptionally, shrimp trawlers were allowed to fish when pipelines and cables only were present.

Habitat usage and foraging capacity

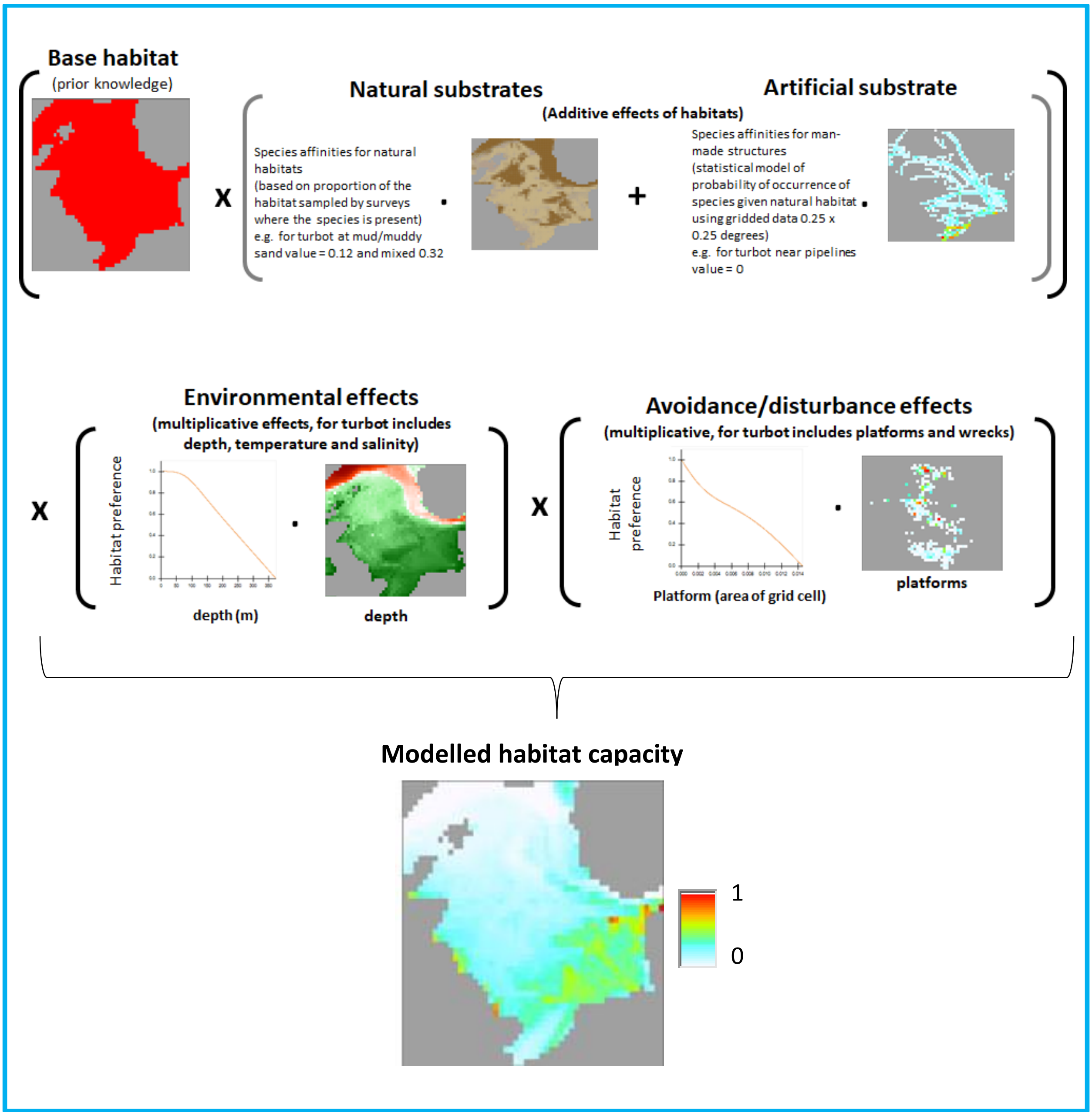
In the EwE Ecospace software, pre-release version 6.6 used for COSM, habitats are linked to functional groups in two ways. Firstly, a base affinity value can be specified (in the Ecospace table “habitat foraging usage”) that represents what proportion of the habitat is potentially directly useful to the functional group. Note that since the publication of Christensen *et al.* (2014) model grid cells can combine fractions of multiple habitats, and species can have fractional affinities for each habitat type. Secondly a habitat capacity function can be supplied to alter the effective foraging arena in the habitat based on a relationship with a third variable (typically an environmental data layer), such that in relatively poor habitats a predator will have a much-reduced ability to forage successfully.

Habitat foraging capacity can thus be determined by combining different hypothesis.

i. Base capacity for each functional group is always defined, and, assuming that no prior conditions exist, is initialized at 1 across the modelled area. This base foraging capacity can be altered to introduce likelihood distributions, optionally through the spatial temporal framework.
ii. Optionally, for selected functional groups, species affinities for habitats (such as natural substrates and man-made structures) across the map can be considered via the original Ecospace habitat foraging usage system. Here, the additive effect of cell habitat coverage and species habitat affinities amount to a habitat capacity multiplier onto the base capacity.
iii. Optionally, for selected functional groups, functional responses to environmental drivers can be included in the modelling approach as described in Christensen *et al.* (2014), acting as a habitat capacity multiplier onto the base capacity, too."

Each of these 3 options were utilised here for fish and benthic groups where data allowed (see below and Box 1). In contrast, functional groups of plankton, meiofauna, microflora, seabirds, seals and whales were not impact positively or negatively by any (natural or artificial) habitat type.

Box 1. Modelling steps to determine habitat capacity of a functional group, using turbot as an example



Species affinities for natural habitats (based on proportion of the habitat sampled by surveys where the species is present) e.g. for turbot at mud/muddy sand value = 0.12 and mixed 0.32

Species affinities for man-made structures (statistical model of probability of occurrence of species given natural habitat using gridded data 0.25 x 0.25 degrees) e.g. for turbot near pipelines value = 0

i. Base capacity

For the majority of groups (67 of 69 groups) base capacity was set at 1 across the map. For two highly exploited species, cod and herring, generating acceptable spatial distributions for the adult stage proved problematic despite implementing both habitat affinities (ii) and functional response functions (iii). Base capacities were given spatial pattern (Figure 8) following a review of their known spatial distribution and detailed examination of the survey data. Cod have been found in commercial catch data to have shifted distribution in recent decades due to the combined effects of climate change and fishing pressure with the stock now residing largely in the north of their range with previous hotspots in the 1970s/1980s noticeable off the English coast (Engelhard *et al.* 2014). Herring have a known migration such that adults (age 3+) typically feed in the northern North Sea, while juveniles (age 1) are restricted to their nursery area in the south-eastern North Sea (Ellis *et al.* 2012).

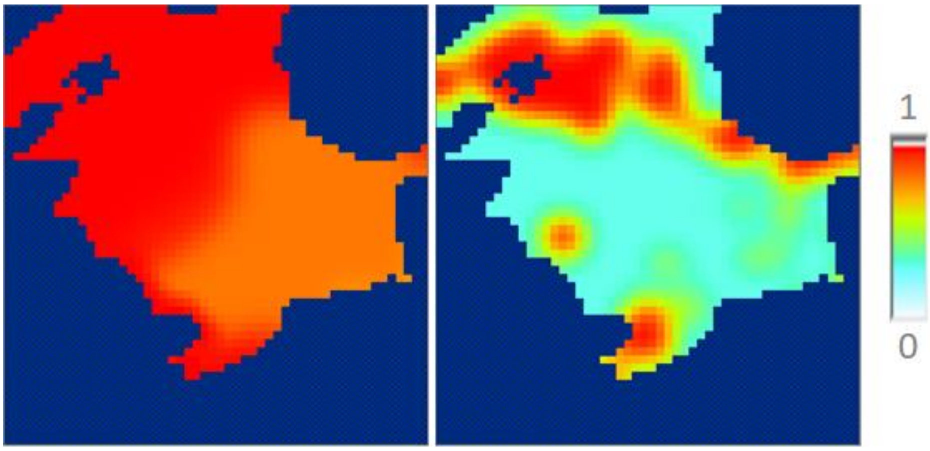


Figure 8. Base capacity (from low, 0, to high capacity, 1) for herring adult (left) and cod adult (right).

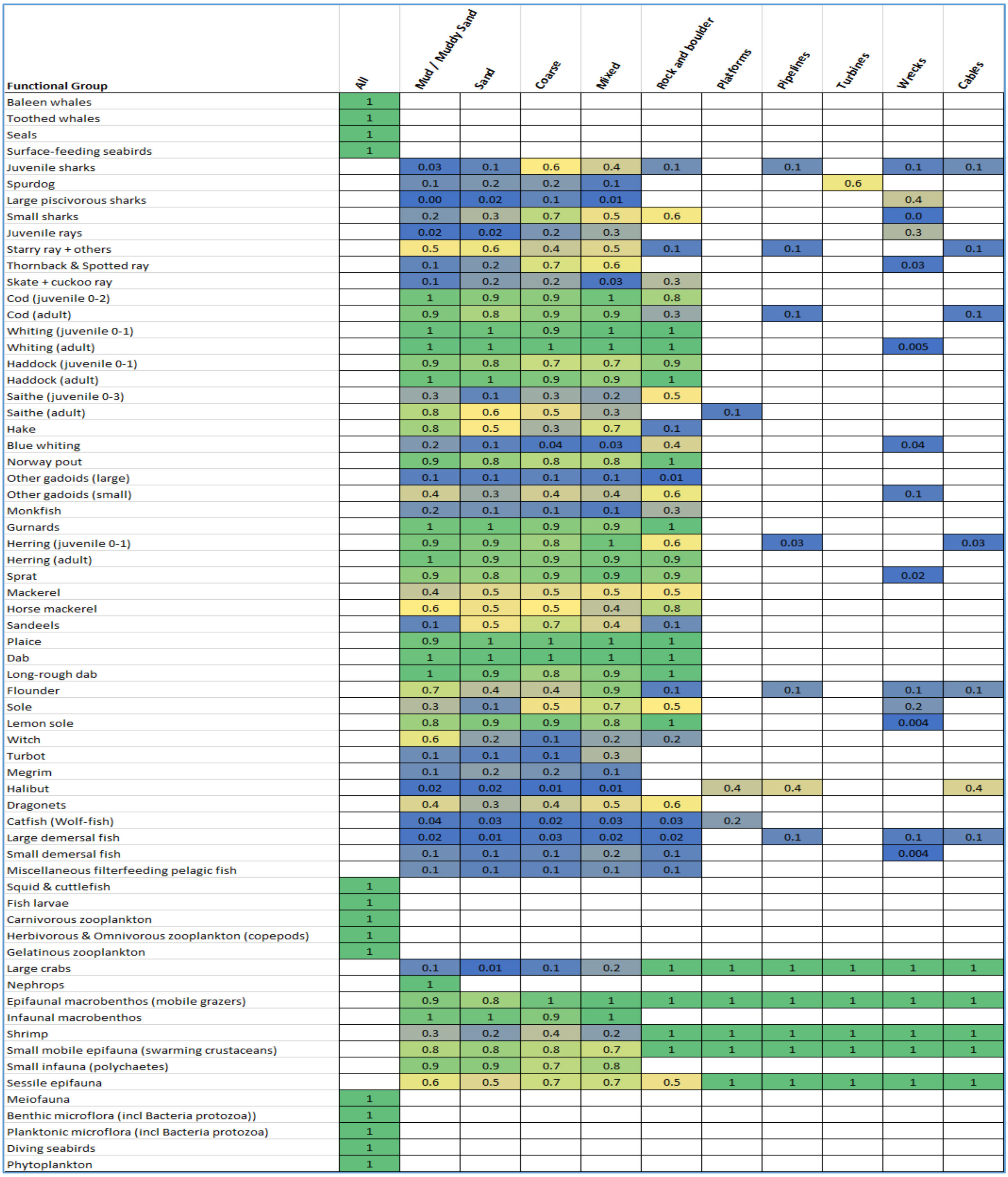
ii. Species affinities for natural and artificial habitats

For each functional group present in the survey data, habitat affinity values for natural substrates were identified by estimating the proportion of the sampled substrate in which each functional group was found to occur (Table 1). For *Nephrops*, affinity was set at 1 for 'mud/muddy sand' habitat given that burrowing activity is limited to these substrates.

Areas with man-made structures were poorly sampled by the available surveys, so affinities for these habitats by functional groups of fish were identified by predictive modelling of gridded data (using the 0.25 x 0.25 decimal degree grid) with both natural and artificial habitat as predictors and presence-absence data as response (M1 above). Where models were considered informative, the probability of occurrence of the group over the North Sea was contrasted between predictions where man-made structures were included in the predictors or when 'removed' (i.e. values of predictors set to zero, but model structure unchanged). The loss in occurrence between the predictions was thus attributable to the degree of affinity for the structures. To estimate the affinity value, for a structure when present, a correction was made to determine a value that is not dependent on the number of structures present (i.e. the absolute change in predictive occurrence was divided by the proportion of cells in the grid with the specific type of structure present).

Data were insufficient to follow the predictive approach for benthic groups. To explore the possible food web effects of structures due to the addition of artificial benthic habitat, the affinity for man-made structures was set to 1 for the following epibenthic groups: large crabs, epifaunal macrobenthos (mobile grazers), shrimp, small mobile epifauna (swarming crustaceans), and sessile epifauna. The remaining infaunal groups were not attributed any affinity for man-made structure due to a lack of information on the likely impact on these groups.

Table 1. Affinities for natural substrate and man-made structures coded in Ecospace (green = high, blue = low).



Functional Group	All	Mud / Muddy Sand	Sand	Coarse	Mixed	Rock and boulder	Platforms	Pipelines	Turbines	Wrecks	Cables
Baleen whales	1										
Toothed whales	1										
Seals	1										
Surface-feeding seabirds	1										
Juvenile sharks		0.03	0.1	0.6	0.4	0.1		0.1		0.1	0.1
Spurdog		0.1	0.2	0.2	0.1				0.6		
Large piscivorous sharks		0.00	0.02	0.1	0.01					0.4	
Small sharks		0.2	0.3	0.7	0.5	0.6				0.0	
Juvenile rays		0.02	0.02	0.2	0.3					0.3	
Starry ray + others		0.5	0.6	0.4	0.5	0.1		0.1			0.1
Thornback & Spotted ray		0.1	0.2	0.7	0.6					0.03	
Skate + cuckoo ray		0.1	0.2	0.2	0.03	0.3					
Cod (juvenile 0-2)		1	0.9	0.9	1	0.8					
Cod (adult)		0.9	0.8	0.9	0.9	0.3		0.1			0.1
Whiting (juvenile 0-1)		1	1	0.9	1	1					
Whiting (adult)		1	1	1	1	1				0.005	
Haddock (juvenile 0-1)		0.9	0.8	0.7	0.7	0.9					
Haddock (adult)		1	1	0.9	0.9	1					
Saithe (juvenile 0-3)		0.3	0.1	0.3	0.2	0.5					
Saithe (adult)		0.8	0.6	0.5	0.3		0.1				
Hake		0.8	0.5	0.3	0.7	0.1					
Blue whiting		0.2	0.1	0.04	0.03	0.4				0.04	
Norway pout		0.9	0.8	0.8	0.8	1					
Other gadoids (large)		0.1	0.1	0.1	0.1	0.01					
Other gadoids (small)		0.4	0.3	0.4	0.4	0.6				0.1	
Monkfish		0.2	0.1	0.1	0.1	0.3					
Gurnards		1	1	0.9	0.9	1					
Herring (juvenile 0-1)		0.9	0.9	0.8	1	0.6		0.03			0.03
Herring (adult)		1	0.9	0.9	0.9	0.9					
Sprat		0.9	0.8	0.9	0.9	0.9				0.02	
Mackerel		0.4	0.5	0.5	0.5	0.5					
Horse mackerel		0.6	0.5	0.5	0.4	0.8					
Sandeels		0.1	0.5	0.7	0.4	0.1					
Plaice		0.9	1	1	1	1					
Dab		1	1	1	1	1					
Long-rough dab		1	0.9	0.8	0.9	1					
Flounder		0.7	0.4	0.4	0.9	0.1		0.1		0.1	0.1
Sole		0.3	0.1	0.5	0.7	0.5				0.2	
Lemon sole		0.8	0.9	0.9	0.8	1				0.004	
Witch		0.6	0.2	0.1	0.2	0.2					
Turbot		0.1	0.1	0.1	0.3						
Megrim		0.1	0.2	0.2	0.1						
Halibut		0.02	0.02	0.01	0.01		0.4	0.4			0.4
Dragonets		0.4	0.3	0.4	0.5	0.6					
Catfish (Wolf-fish)		0.04	0.03	0.02	0.03	0.03	0.2				
Large demersal fish		0.02	0.01	0.03	0.02	0.02		0.1		0.1	0.1
Small demersal fish		0.1	0.1	0.1	0.2	0.1				0.004	
Miscellaneous filterfeeding pelagic fish		0.1	0.1	0.1	0.1	0.1					
Squid & cuttlefish	1										
Fish larvae	1										
Carnivorous zooplankton	1										
Herbivorous & Omnivorous zooplankton (copepods)	1										
Gelatinous zooplankton	1										
Large crabs		0.1	0.01	0.1	0.2	1	1	1	1	1	1
Nephrops		1									
Epifaunal macrobenthos (mobile grazers)		0.9	0.8	1	1	1	1	1	1	1	1
Infaunal macrobenthos		1	1	0.9	1						
Shrimp		0.3	0.2	0.4	0.2	1	1	1	1	1	1
Small mobile epifauna (swarming crustaceans)		0.8	0.8	0.8	0.7	1	1	1	1	1	1
Small infauna (polychaetes)		0.9	0.9	0.7	0.8						
Sessile epifauna		0.6	0.5	0.7	0.7	0.5	1	1	1	1	1
Meiofauna	1										
Benthic microflora (incl Bacteria protozoa))	1										
Planktonic microflora (incl Bacteria protozoa)	1										
Diving seabirds	1										
Phytoplankton	1										

iii. Functional responses

Habitat capacity functions for each species group (fish and benthos) were identified by GAM analyses (type M1 above), where the relationship between the probability of occurrence of the species and both presence of man-made structures and environmental predictors (depth, water column salinity and temperature) was modelled by smooth splines. Where significant, these splines were then considered for direct coding in Ecospace. For the man-made structures, relationships that demonstrate potential negative effects of structures were selected for inclusion in Ecospace in order to represent behavioural effects to noise and disturbance. Overwhelmingly positive relationships with structures were not included since these relationships were already coded using the habitat affinity linkage (see ii above) and this simpler approach was considered suitable to represent the additional habitat offered by structures. Iterative runs were made to investigate the impact of simplifying the model by including/excluding splines. Simulations were made to evaluate the capability of the runs to capture the expected distributions and where issues were identified responses were removed or modified accordingly. A limitation of the current implementation of the functional responses in Ecospace is that each is given the same relative weighting (i.e. a response with relation to depth is equal to a response function with relation to another variable such as temperature). Functions that had minimal impact or overly strong impact on the resulting spatial distribution were ultimately removed. Adult cod-, herring- and haddock-depth functions, plus adult cod-temperature and adult whiting-salinity responses were manually edited to trim the uncertain ends of splines away and in the case of cod and herring altered to emphasise the desired difference in juvenile/adult distributions. The final set of functions used are indicated in Table 2. Habitat capacity functions (included where filled) for environmental variables (positive and negative responses) and presence of man-made structures (negative responses).Table 2 and an example in Figure 9.

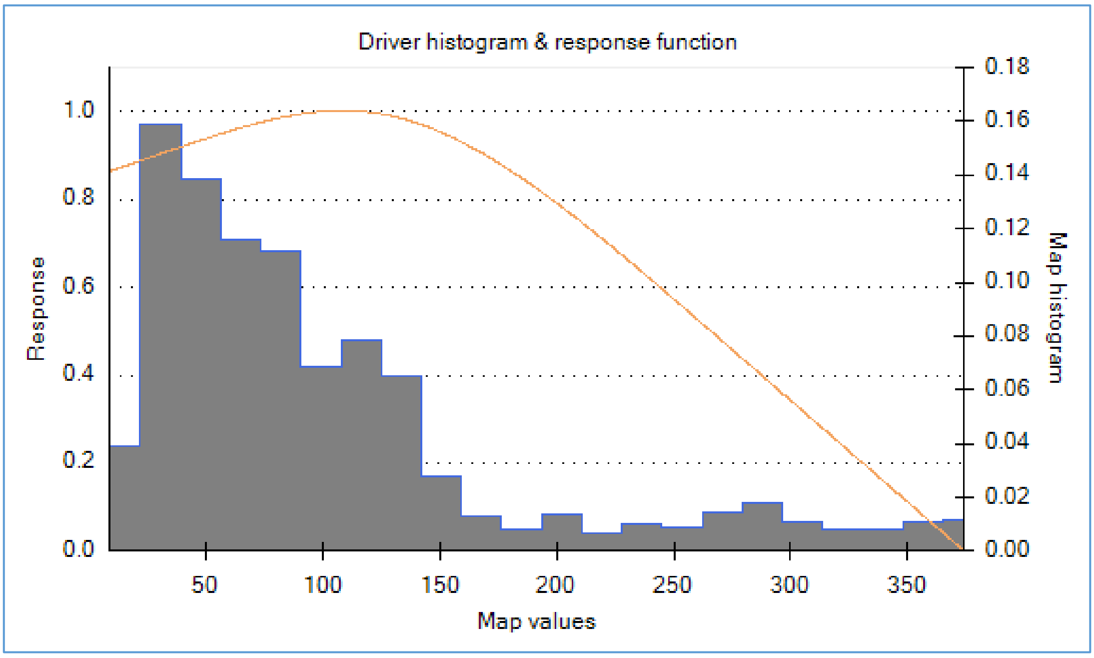


Figure 9. An example of a habitat capacity function, here for adult whiting depth preference (line) versus a histogram of depth values (bars) within the Ecospace base map. Whiting are given a preference (response > 0.8) for depths <200 m, but with a maximum preference above the mode of depths in the grid.

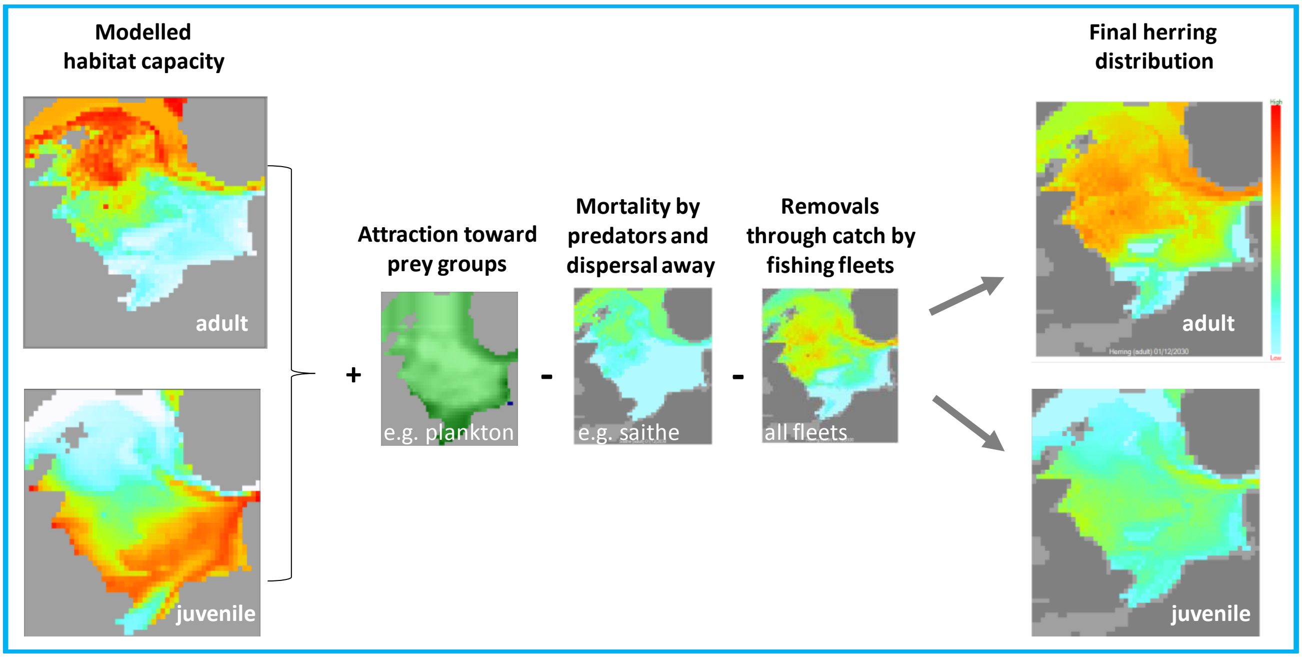
Table 2. Habitat capacity functions (included where filled) for environmental variables (positive and negative responses) and presence of man-made structures (negative responses).

Functional Group	Depth	Salinity	Temperature	Platform	Pipeline	Cable	Turbine	Wreck
Baleen whales								
Toothed whales								
Seals								
Surface-feeding seabirds								
Juvenile sharks	■	■	■		■	■		■
Spurdog	■	■	■				■	
Large piscivorous sharks	■							■
Small sharks		■	■					
Juvenile rays	■							■
Starry ray + others	■		■		■	■		■
Thornback & Spotted ray	■	■	■					
Skate + cuckoo ray	■							
Cod (juvenile 0-2)	■		■					
Cod (adult)	■		■					
Whiting (juvenile 0-1)								
Whiting (adult)	■	■	■					
Haddock (juvenile 0-1)	■							
Haddock (adult)	■		■	■				
Saithe (juvenile 0-3)								
Saithe (adult)	■	■	■					
Hake	■		■					
Blue whiting	■		■					
Norway pout	■	■	■					
Other gadoids (large)	■	■	■					
Other gadoids (small)		■	■					
Monkfish	■	■	■					
Gurnards		■	■					
Herring (juvenile 0-1)	■	■	■					
Herring (adult)	■							
Sprat	■	■	■					
Mackerel	■	■	■					
Horse mackerel	■	■	■					
Sandeels	■							
Plaice	■	■	■					
Dab	■	■	■					
Long-rough dab	■							
Flounder	■	■	■					■
Sole	■	■	■					■
Lemon sole	■	■	■					
Witch	■		■					
Turbot	■	■	■	■				■
Megrim	■	■	■					
Halibut	■		■		■	■		
Dragonets		■	■					
Catfish (Wolf-fish)	■							
Large demersal fish	■	■						
Small demersal fish		■	■					
Miscellaneous filterfeeding pelagic fish		■	■					
Squid & cuttlefish								
Fish larvae								
Carnivorous zooplankton								
Herbivorous & Omnivorous zooplankton (copepods)								
Gelatinous zooplankton								
Large crabs								
Nephrops	■							
Epifaunal macrobenthos (mobile grazers)								
Infaunal macrobenthos								
Shrimp	■							
Small mobile epifauna (swarming crustaceans)	■							
Small infauna (polychaetes)	■							
Sessile epifauna	■							
Meiofauna	■							
Benthic microflora (incl Bacteria protozoa))								
Planktonic microflora (incl Bacteria protozoa)								
Diving seabirds								
Phytoplankton								

Dispersal parameters

The dispersal of functional groups from cell to adjacent cell allow to model groups to move in monthly time-steps towards their favourable habitats and areas of abundant prey and to avoid risk of predation (Box 2). Ecospace dispersal parameters for functional groups were adopted following Mackinson and Daskolov (2007) with the exception of one multi-stage group: herring. Herring actively migrate and the adult and juvenile stages thus have centres in differing areas of the North Sea. To mimic this migration, their base dispersal rates were increased to very high values (10000 and 100000 km/year for adults and juveniles respectively) to enable the model to attain the differing spatial distribution of adults and juveniles.

Box 2. An overview (using the two-stage group herring as an example) of the food-web modelling steps that allow fish to distribute throughout the North Sea, groups initially prefer areas of high modelled habitat capacity (see box 1) but disperse to areas of high prey and low predator abundance



2.4. Ecospace Model Assessment

The model was initialised through a 10-year spin-up and then run from the base year for 40 years to reach equilibrium conditions. At this point, the spatial distribution of each functional group is output from the model (Figure 10) and compared to survey data (average spatial pattern in years 2009-2016) to screen for poor predictive performance of the Ecospace model using a Mantel spatial correlation with 999 permutations to test the significance level. In the final model fit, 35 of 42 functional groups (83%) with data showed positive correlation with $p < 0.05$. The remaining 7 functional groups were investigated visually and considered acceptable since each modelled pattern was consistent with the distribution of the group either at a historical period, prior to the current exploited state, or for the distribution in a particular season.

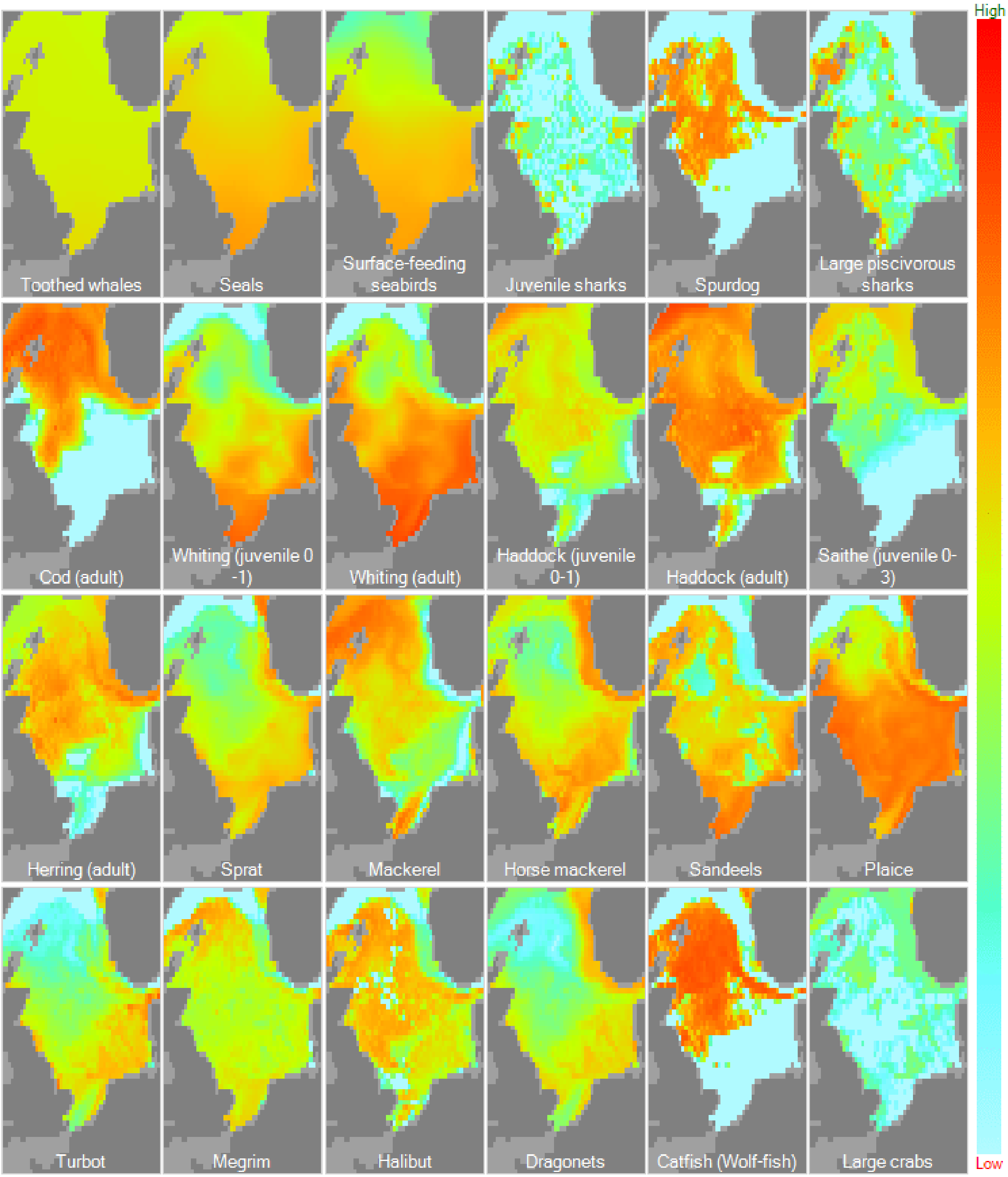


Figure 10. Modelled distributions of functional groups at equilibrium.

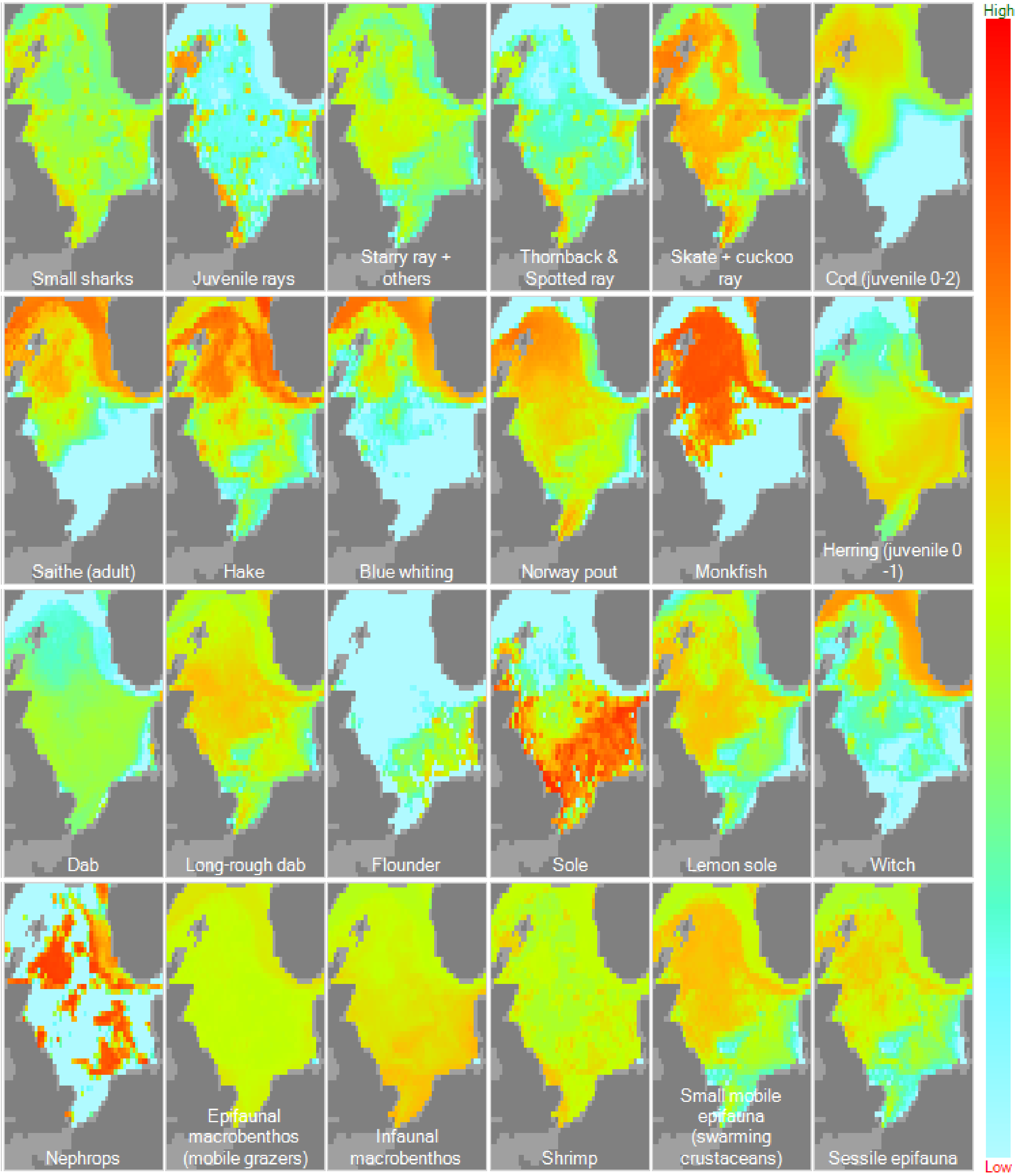


Figure 11. (*Cont.*) Modelled distributions of functional groups at equilibrium.

2.5. Ecospace Model Scenarios

To explore the impact of man-made structures on the functioning of the North Sea food web, the model was simulated forward under five simple management scenarios:

S1: No removal of structures with fishing effort at 2014 levels;
S2: Complete removal of platforms and pipelines with fishing effort at 2014 levels;
S3: Complete removal of platforms, pipelines and cables with fishing effort at 2014 levels;

S4:	Complete removal of platforms, pipelines, cables, turbines and wrecks with fishing effort at 2014 levels;
High F:	No removal of structures with increase in fishing effort to 1990 levels.

To contrast any effect of man-made structures with the natural variability in the system, the management scenarios above were then re-run including interannual variation in historical and projected trends in sea temperature using the spatial-temporal framework (Steenbeek *et al.* 2013). Monthly maps of water column average temperatures from January 1985 to June 2014 were obtained from the online data portal http://marine.copernicus.eu/ (see the Annex). The last year of water column averaged temperature data was replicated from 2014 onward to December 2030 with steadily increasing temperatures to represent potential long-term climate change. One degree Celsius of temperature increase was allowed in the shallow southern North Sea falling to a 0.4 degree increase in the deepest northern areas. This scenario was developed following the findings of Hughes *et al.* (2017) where a gradient in rates of warming between the southern and northern North Sea was demonstrated. The exact figures for the rate of warming are dependent on the data source and analysis, but for the southern North Sea the rate was reported to be between 0.2 – 0.4°C/decade, while for the northern North Sea the rate was up to 0.2°C/decade. Monthly data were converted to annual averages and included through the spatial temporal data framework into the Ecospace temperature data layer. In addition to the primary production at the base of the food web, those functional groups with temperature sensitivities identified through GAM analyses (Table 3) were thus driven by the series of temperature maps through the Ecospace habitat foraging capacity model (Christensen *et al.* 2014).

Table 3. Aggregated groups were made to demonstrate overall shifts in structure within the food web using the following categories.

		Aggregated functional groups			
DEMERSAL ROUNDFISH	**FLATFISH**	**BENTHOS**	**PELAGIC**	**RAYS**	**SHARKS**
Cod (juvenile 0-2)	Plaice	Large crabs	Blue whiting	Juvenile rays	Juvenile sharks
Cod (adult)	Dab	*Nephrops*	Herring (juvenile 0-1)	Starry ray + others	Spurdog
Whiting (juvenile 0-1)	Long-rough dab	Epifaunal macrobenthos (mobile grazers)	Herring (adult)	Thornback & Spotted ray	Large piscivorous sharks
Whiting (adult)	Flounder	Infaunal macrobenthos	Sprat	Skate + cuckoo ray	Small sharks
Haddock (juvenile 0-1)	Sole	Shrimp	Mackerel		
Haddock (adult)	Lemon sole	Small mobile epifauna (swarming crustaceans)	Horse mackerel		
Saithe (juvenile 0-3)	Witch	Small infauna (polychaetes)	Miscellaneous filter feeding pelagic fish		
Saithe (adult)	Turbot	Sessile epifauna			
Hake	Megrim	Meiofauna			
Norway pout	Halibut				
Other gadoids (large)					
Other gadoids (small)					
Monkfish					
Gurnards					
Dragonets					
Catfish (Wolf-fish)					
Large demersal fish					
Small demersal fish					

2.6. Ecospace Transect Extraction tool

Within COSM, Ecospace has been extended with a transect extraction tool. Transects, like regions in Ecospace, are a mechanism to extract model estimates of biomass and catches for user-defined map areas for every time step executed by the model. Regions and transects differ in purpose: regions provide area averages for a cluster of cells, while transects capture how model estimates fluctuate across a cross-section of the area to allow exploration of local patterns. Transect start and end points are entered by the user, and transects can be assigned unique names. With transects in place Ecospace is executed. At the end of the Ecospace run, results along a transect can be explored in the EwE user interface and can be saved to CSV files (in X, Y, T, {variables}), one file per transect, for further analysis. The user guide to the transect extraction tool is included in the Annex.

In COSM, transects were used to investigate whether or not local changes in biomass of functional groups were evident across cells with man-made structures.

3. Key Findings

3.1. Statistical results

The detection/non-detection models (M1) for functional groups used in the Ecospace model were not found to violate the assumptions underpinning their use.

Inspection of semi-variograms for models of type M2 and M3 indicated numerous occurrences in which patterns were evident in the residuals suggesting that not all processes determining spatial patterns in abundance were captured by the models and residuals could not be considered spatially independent. M2 and M3 models have not been considered further here. Simpler M1-models were not found to suffer from this issue. Similarly, partial residual plots for M1 models did not identify any remaining patterns that were not captured by the model and its error structure. Variance-inflation factors for the predictor variables of M1 models, were all < 3 for datasets where either quarter 1 and 3 data were combined or quarter 1 data investigated independently. For models based on quarter 3, VIF >3 for several groups and VIF > 4 for gurnards, miscellaneous filter feeding pelagic fish, large demersal fish, horse mackerel, small sharks (adult) indicating multi-collinearity between predictors for these 5 models.

The percentage of deviance explained by M1 models range from 9% for the poorest performing model (adult cod) to 63% for the best model (adult haddock). The predictive performance of each model was assessed by way of the ROC with the poorest models (adult cod and adult herring) achieving an area under the curve (AUC) score of 0.62, which was still significantly greater than 0.5 with $p < 0.001$. Predictive performance > 0.90 was achieved for juvenile and adult haddock (combined data or Q1 respectively), large piscivorous sharks (Q3), adult saithe (combined), blue whiting (Q1), Norway pout (combined), dab (combined), long-rough dab (combined), and flounder (combined). Where data for Q1 and Q3 could be combined (following the examination of spatial correlation), models that were based on combined data were considered preferable to data based on one quarter only. Where data could not be combined Q1 data were considered superior to Q3 given the greater number of data points available.

The majority of models based on fish survey data retained depth and environmental variables (temperature and/or salinity) after stepwise deletion of model terms. Benthic data was not considered of sufficient quality to include multiple predictors, so only depth was chosen to model the epibenthic and infaunal groups. Numerous models for fish functional groups did show significant relationships with the presence of man-made structures (Figure 12). The spurdog model only showed an association with the presence of turbines. A strong positive association between halibut and platforms, pipelines and cables was found. The strongest positive association with wrecks was found for large piscivorous sharks, sole, and thornback and spotted ray. Negative associations with platforms for sand eels, haddock and turbot were also apparent.

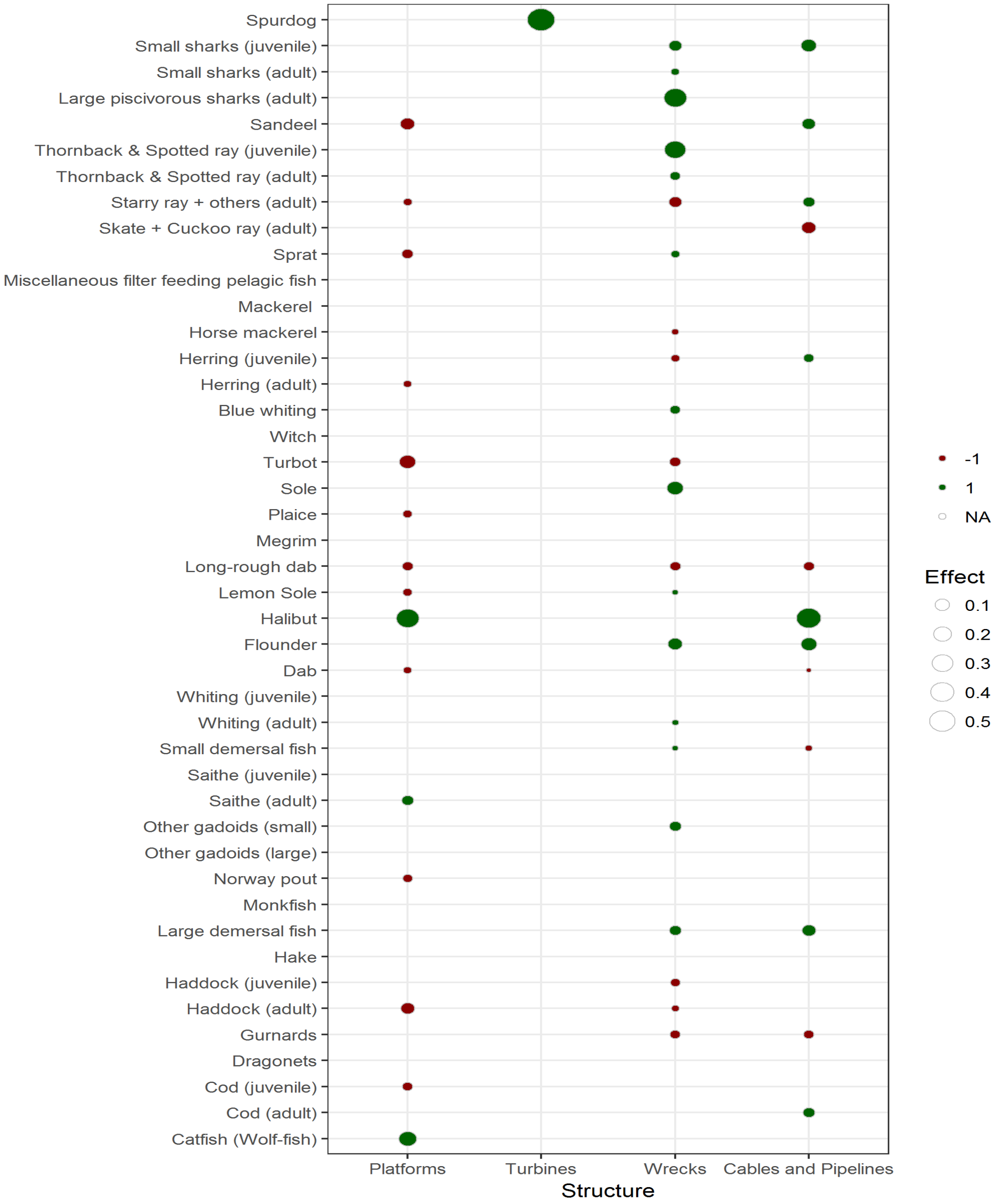


Figure 12. Effect on structure types on functional groups identified through statistical analyses (significant relationships shown only). A positive (green bubble) effect indicates that the occurrence of the group is increased through the presence of structures, while negative effects (red bubbles) indicate the opposite. Bubble size is proportional to the change in probability of occurrence of the group in the region where the relevant structure type is present (so independent of spatial coverage of the structures).

When functional groups were aggregated, based on their relative abundance in the survey, clearer patterns are evident in the degree of association with structures (Figure 13). Sharks showed positive association with all structures other than platforms. All groups other than flatfish were positively associated with cables and pipelines. All groups, other than sharks, were dominated by negative association with the presence of platforms. Although wrecks were positively associated with sharks, all other groups other than sand eels were found to be negatively associated with wrecks. Anecdotally, fish have been reported to be in high abundance at structures (e.g. cod, haddock, whiting at wrecks) yet here we see null or negative results for many species and even aggregated groups in terms of probability of occurrence in the cell. The disparity in the results here could be due to a redistribution of fish at local scales and an attraction toward the structures; as a result, they might be in high abundance at the structure but occur less frequently in surveys of the wider area (grid cell that contains the structures). However, if the increase in biomass at structures were great a “spill over effect” should be evident in the area resulting in higher biomass within grid cells that include the structure in a similar way as is often seen with protected areas. As COSM is attempting to uncover the effects of structures in the wider ecosystem large effects are particularly important. The evidence here is not conclusive due to the paucity of data, but the results provide hypotheses that can be challenged further with additional data.

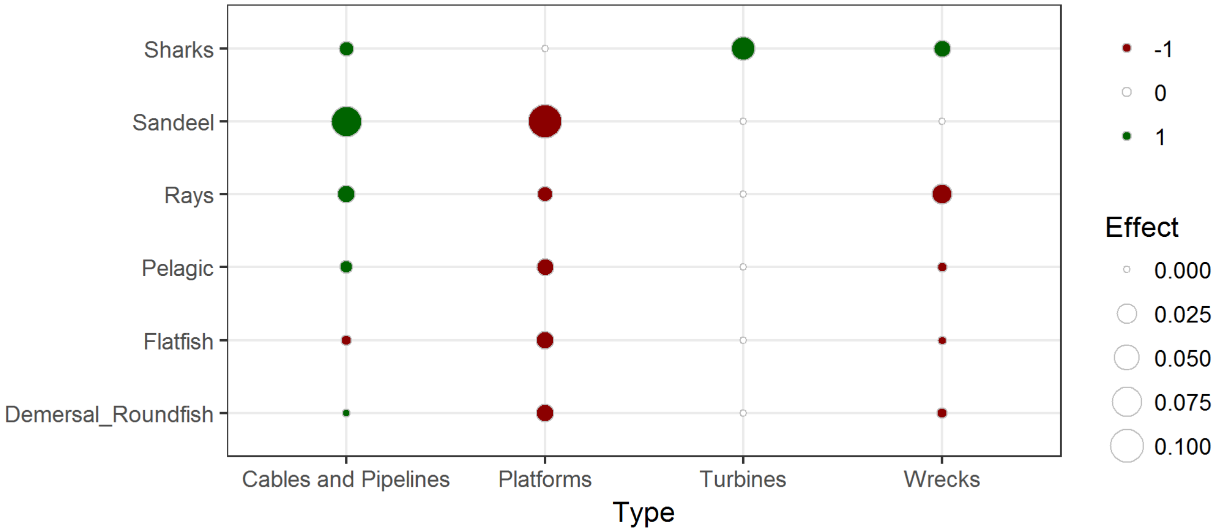


Figure 13. Effect of structure types on aggregated functional groups identified through statistical analyses of gridded survey data (significant relationships shown only). A positive (green bubble) effect indicates that the occurrence of the group is increased through the presence of structures, while negative effects (red bubbles) indicate the opposite. Bubble size is proportional to the change in probability of occurrence of the group in the region where the relevant structure type is present (so independent of spatial coverage of the structures).

3.2. Ecospace model simulations

The simple forward simulation using constant environmental conditions and no change in the presence of man-made structures was taken as a baseline against which other scenarios were evaluated. Results were interpreted in terms of the change in biomass between scenarios for each functional group. Aggregations of the model groups were made to demonstrate overall shifts in structure within the food web. Results were extracted for the region in which structures were present and additionally for all grid cells that comprise the North Sea. The newly developed transect tool allowed for effects to be visualised and demonstrated that removal of structures allowed for the dispersal of biomass of some groups (e.g. whiting) while others with lower dispersal rate such as halibut show localised effects only (Figure 14). Also, the impact of removing structures differed in differing areas of the North Sea, due to the competing affinities of species to natural habitats and due to predator-prey interactions.

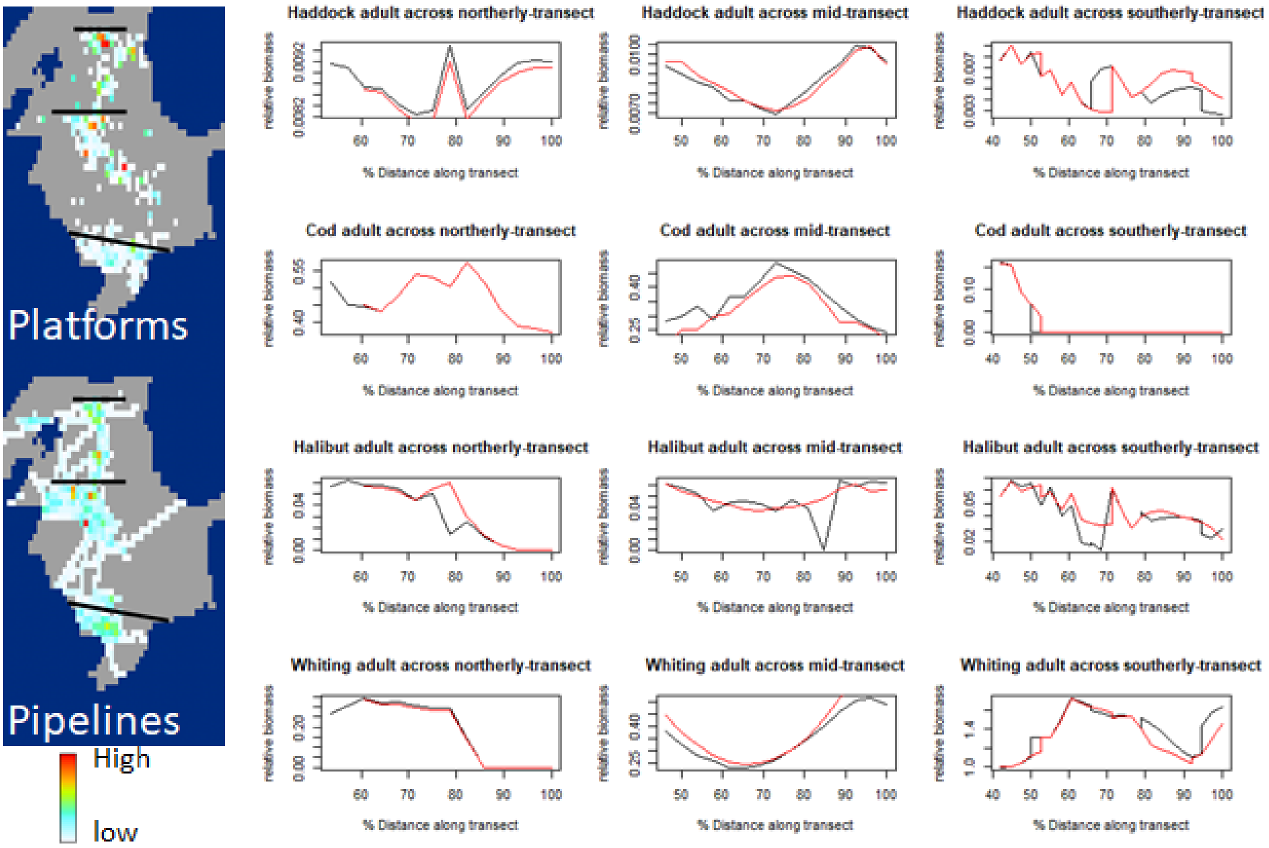


Figure 14. Exploration of effects of removal of structures on the relative biomass of groups across three transects (one in the north, mid and southern North Sea, see map) using the transect tool. The relative biomass along the transect (moving from left to right) of haddock, cod, halibut and whiting is shown when all man-made structures are present (baseline scenario, black lines) and when platforms and pipelines are removed (Scenario 1) from the model (red lines).

A range of 'winners' and 'losers' were evident from the simulations, for example when the complete removal of platforms and pipelines was contrasted to the baseline, decreases in sessile epifauna and epifaunal macrobenthos were modelled within the cells where structures were present, while increases were found in both small mobile epifauna and infaunal macrobenthos (Figure 15). When change in functional groups were assessed for the entire North Sea a similar pattern in winners and losers was evident, with the important exception that the decline in biomass of sessile epifauna was less pronounced since these decreases were offset by increases elsewhere due partly to change in the community composition of predators (Figure 16). The increase in small mobile epifauna was more pronounced relative to other groups since this group benefited from a great affinity to natural habitats (Table 1). In fact, when summed over the entire North Sea, the total biomass of benthic groups increased once structures were removed (Table 4) in contrast to the overall decrease near the structures themselves. Further removal of cables and other structures serve only to decrease the overall biomass in the benthos.

Changes in the benthic system contribute to the cascade of changes found in fish groups, with increases in biomass most notable in plaice, dab, haddock and halibut. The biomass of the latter two groups (haddock and halibut) were directly positively impacted by loss in man-made structures since the survey data had indicated higher abundance in natural habitats than in grid cells with man-made structures present (Table 2). A knock-on effect of increases in these species emerged through a decline in the biomass of sand eel, a keystone species (Smith *et al.* 2014). Subsequently a great decrease was manifest in whiting juvenile biomass, for which sand eel prey are key, followed by an increase in Norway pout, sprat and herring that are prey sources of the now diminished biomass of adult whiting (Figure 17). In addition, decreases in the biomass of rays are also modelled as platforms, pipelines and cables are removed. Interestingly the presences of wrecks and turbines appears far more important to ray than the oil and gas infrastructure and removal of these in addition leads to a reversal of their fortunes (Table 4). The opposite is true for demersal roundfish (including cod, haddock, saithe and whiting among others) that generally benefit as a group when oil and gas structures are removed, but suddenly decline when wrecks and turbines are removed from the model. Flatfish and sharks increase beyond baseline abundances in each management scenario (S1-4) tested other than the high fishing effort scenario.

At the level of the North Sea, the effect of an increase in fishing effort (Figure 18) or inclusion of natural variability in the system was greater than the effects of removal of platforms, pipelines and cables combined for each group, with the exception of a minor effect of natural variability on sharks (Table 4). Although the biomass of benthos is generally lowered under natural variability, little change is evident in large crabs and small increases in *Nephrops* within the vicinity of the structures (Figure 19). For sand eels, demersal and pelagic roundfish the signal of natural variability clearly outweighs the impact of structures on group biomass (Figure 20). Despite effects of natural variability being large at the North Sea scale, for flatfish, rays and sharks there may be a response near structures to their removal that is comparable to the effect of natural variability (Figure 20). Increasing fishing effort resulted in a decrease in all aggregated functional groups.

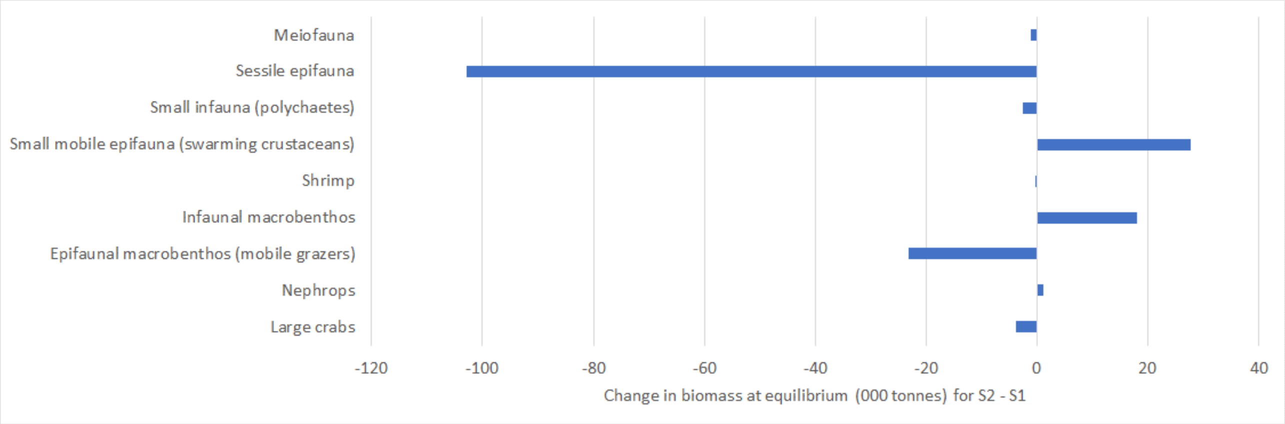


Figure 15. Changes in benthic functional group biomass at equilibrium within the grid cells occupied by platforms and pipelines, when these structures are removed.

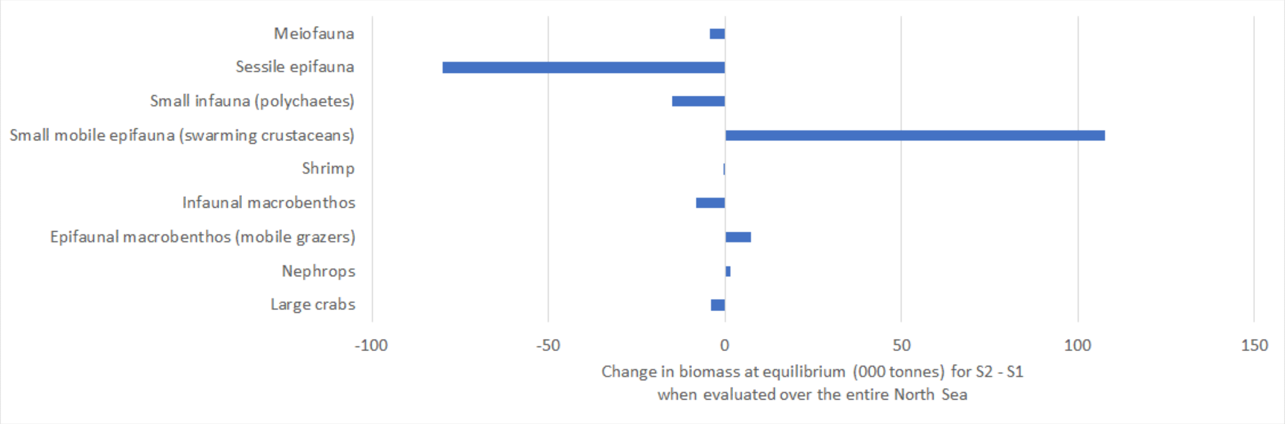


Figure 16. Changes in benthic functional group biomass at equilibrium integrated over the whole North Sea when platforms and pipelines are removed.

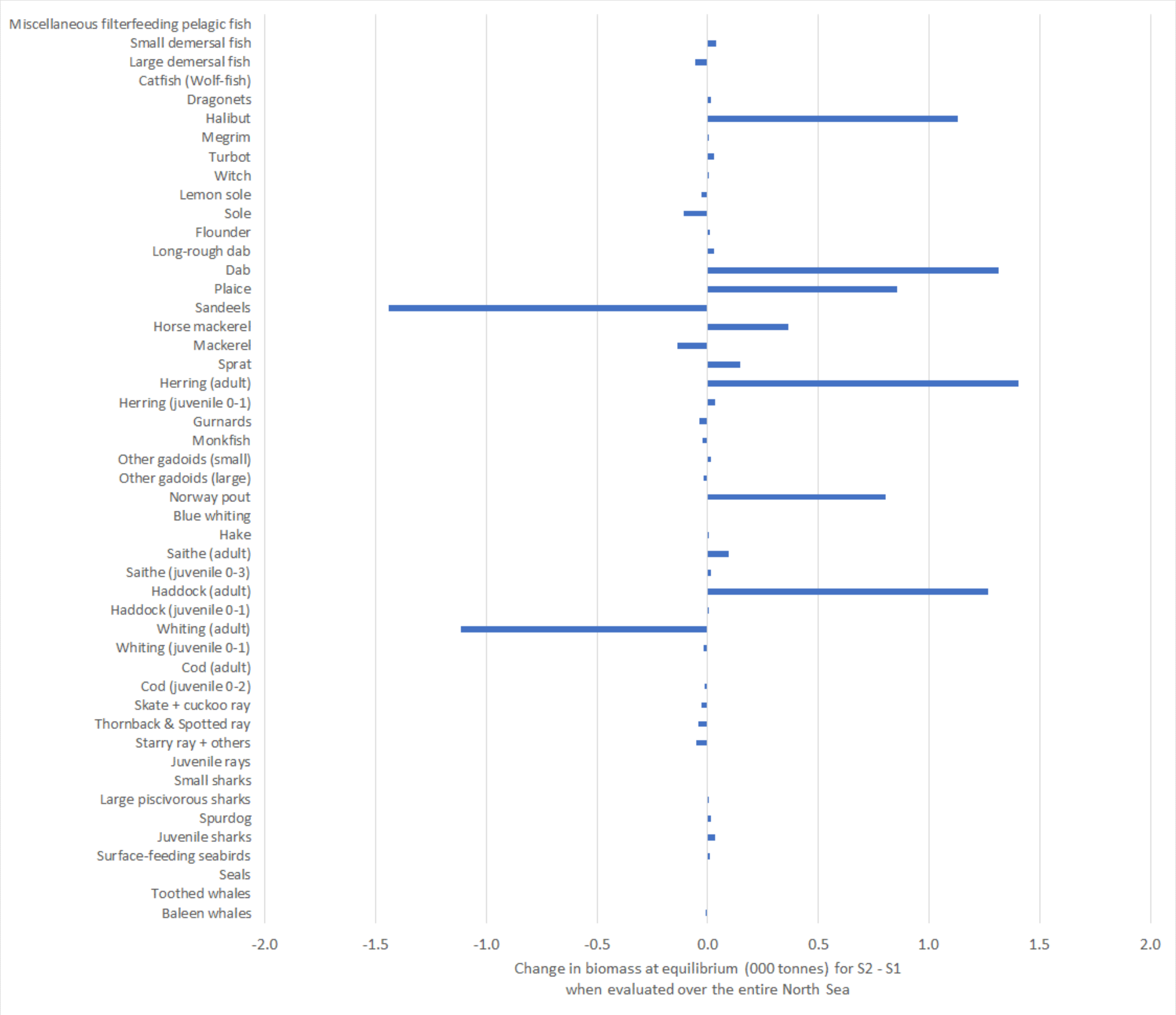


Figure 17. Changes in predator functional groups biomass at equilibrium at the scale of the North Sea when removal of platforms and pipelines was modelled.

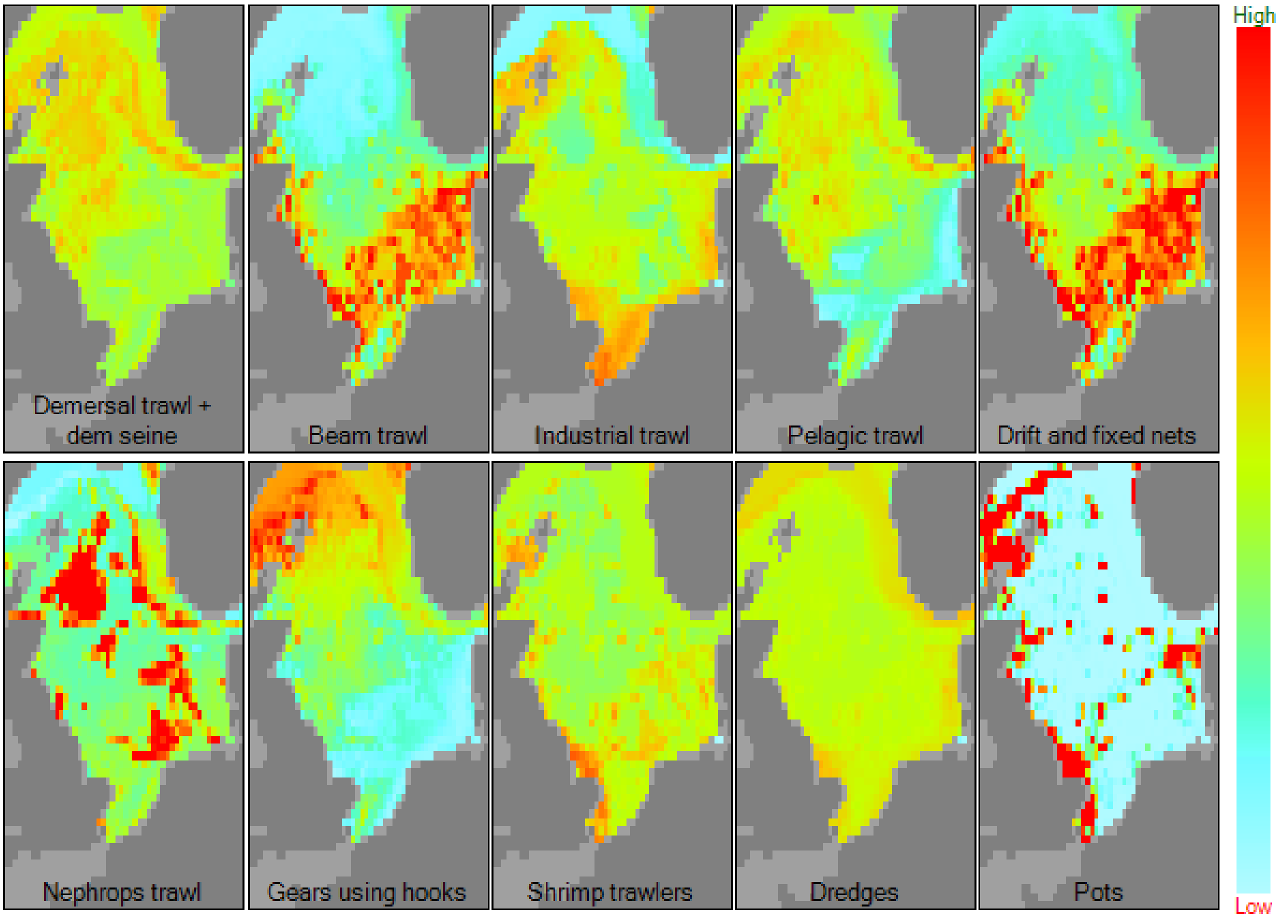


Figure 18. Spatial distribution of fishing effort at equilibrium for model fleets (‘Other’ fleet not shown) under a high effort scenario.

Table 4. Effects of man-made structures, natural variability and fishing pressure on aggregated functional groups within the North Sea ecosystem. Change is given in terms of the difference in total biomass (tonnes) between scenarios modelled for the whole North Sea and rounded to the nearest hundred tonnes, with the exception of the Sharks group that is rounded to the nearest ten tonnes. Scenarios are simulated with constant environmental conditions unless the scenario label is followed by a V which indicate variability in temperature included. Fishing effort is constant at 2014 levels in each scenario other than the High F scenario in which fishing effort is increased to 1990 levels.

Scenario compared	Benthos	Sand eel	Rays	Demersal Roundfish	Pelagic Roundfish	Flatfish	Sharks
S2 – S1	5600	**-1400**	**-100**	1000	2600	3200	50
S3 – S1	**-14400**	**-2000**	**-300**	500	2400	3700	100
S4 – S1	**-40200**	**-6400**	4800	**-1300**	2300	11800	170
S1V – S1	**-272000**	22600	1200	**-21800**	**-8200**	10300	**-20**
High F – S1	**-3635700**	**-140500**	**-21700**	**-310200**	**-375100**	**-493400**	**-15100**

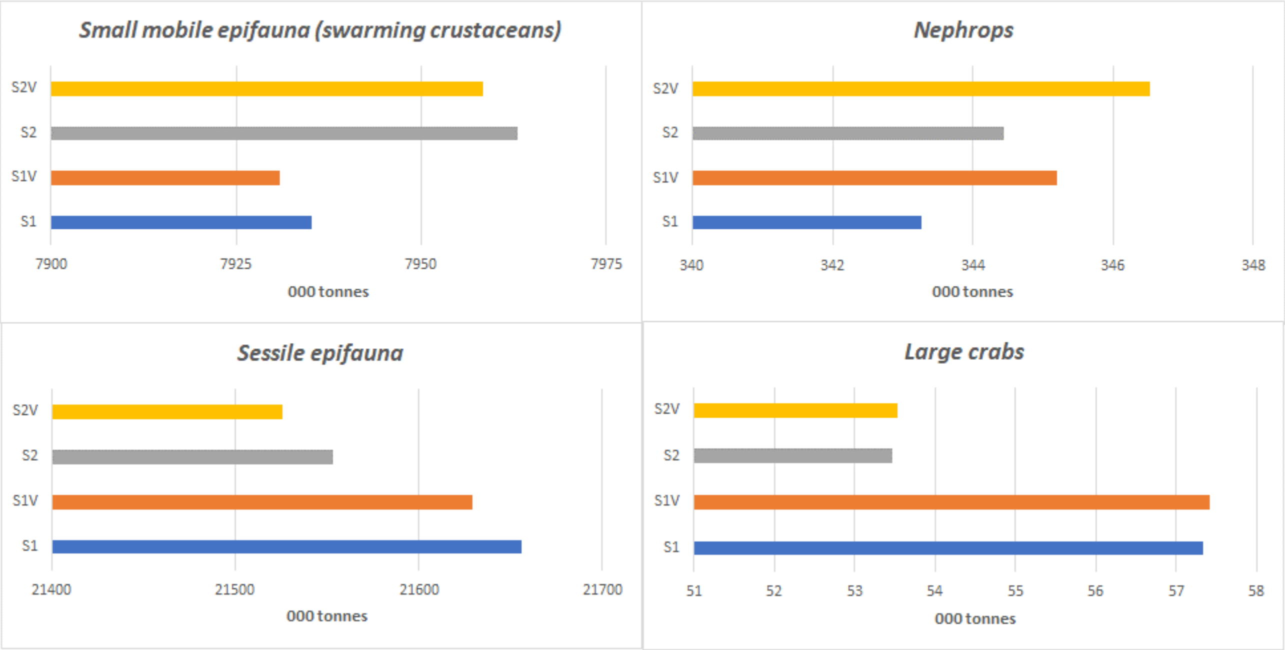


Figure 19. Regional estimates of selected benthic functional groups biomass at equilibrium within the region occupied by platforms and pipelines for management scenarios (no change, S1, and with platforms and pipelines removed, S2) with and without natural variability (V).

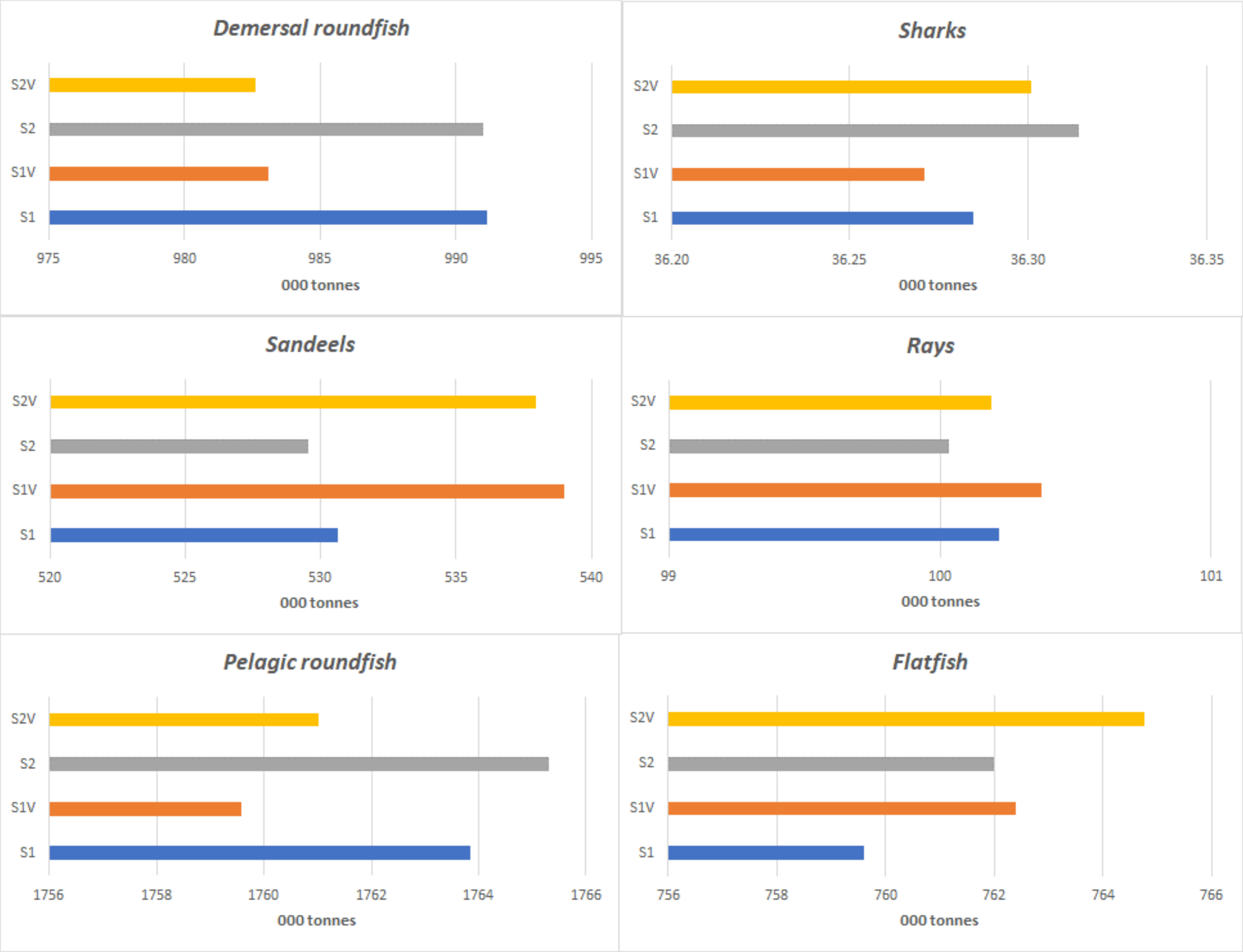


Figure 20. Regional estimates of the biomass of aggregated functional groups of fish at equilibrium within the region occupied by platforms and pipelines for management scenarios (no change, S1, and with platforms and pipelines removed, S2) with and without natural variability (V).

4. Discussion

This project aimed to provide stakeholders with a food-web model that can be used to better understand the magnitude of the effects of man-made structures compared to the spatial and temporal variability of the North Sea ecosystem. COSM has delivered a tool (the North Sea Ecospace model) from which early analyses have been made to explore ecological effects of man-made structures at the whole ecosystem level. The current model is performing well spatially and is capable of making spatio-temporal assessments that are particularly useful to screen the integrative effects of differing management actions on the ecosystem. However, the model is only as good as the data available to create it and this is weak in some aspects relating to the effects of man-made structures locally. Further work can be pursued to address these limitations.

4.1. Suggestions for future work

4.1.1. Further data collection

Further biological data on production and biomass of functional groups at structures would strengthen the underpinning of the model. Finer scale observational studies would be beneficial in this regard, particularly to focus on those groups suggested by the modelling to be either winners or losers within the vicinity of structures (Figure 14, Figure 19 and Figure 20). The results of which can be incorporated in the broad scale model by updating the current functional group affinities for man-made structures (i.e. Table 1) or their habitat capacity functions (Table 2). If additional fine scale dynamics are present that result in functioning that the model cannot replicate (such as a change in predator-prey interactions, highly elevated production rates or local scale behaviours of fishing fleets) improvements to the model may be necessary.

4.1.2. Considering fine scale dynamics in the basin-wide model

The current cell resolution of the North Sea Ecospace model is 0.25 decimal degrees, which captures well the basin-scale processes at play, but remains relatively coarse in comparison to the local effects of structures. We explored additional strategies within the EwE environment to model the impact of fine-scale dynamics and link these to the North Sea-wide Ecospace model developed in COSM. Our initial proposal considered reworking the Ecospace model to enable the use of nested areas with different cell sizes. A review by the EwE core developers showed that this would require most of the Ecospace source code to be rewritten to account for the consideration of, and movement between, cells with different resolutions. As this would be an expensive, multi-person and multi-year effort, alternative options were developed. A preferable option would involve the use of sub-models to inform the basin-wide model. Here, sub-models that capture local features of the North Sea at fine resolution would be built to quantify the food web effects of man-made structures of different type on functional group biomass and, potentially, fisheries catch, following the findings from the various projects in INSITE (including EcoConnect and UNDINE). Then, these local biomass-and-catch effects of local structures would be scaled up across the North Sea map to positively or negatively affect biomass and catches where structures are present, in a direct relationship with the amount and type of structure present in each map cell. This hybrid solution allows the inclusion of positive or negative local effects of structures into the basin-wide model, even when the coarse model is too coarse to compute these local effects. This hybrid solution is far more cost and time effective than recoding Ecospace, and can be implemented with minor additions to existing model capabilities. However, for this approach to be successful additional data on local effects of structures will be crucial.

4.1.3. Dynamic simulations using migration and advection modules

Within the current Ecopath model formulation, migratory groups such as herring do not distribute dynamically through time between spawning and feeding areas as they should. With further work, the North Sea EwE model can be improved to properly capture these distribution cycles. First, the adult group must be linked to migration area maps that reflect their spawning and non-spawning areas within the year. Secondly, an Ecosim egg-production function will be required to coincide the timing of spawning with the coastal migration. Thirdly, an extra life stage ‘eggs and larvae’ will need to be introduced as an advected species. Finally, the Ecospace advection system must be parameterized with monthly maps of currents (x and y velocity) across the North Sea.

4.1.4. Other pressures

Further study on the impacts of fishing fleets on species would benefit the model; currently the model includes 11 fleets and 69 functional groups and may capture dynamics more accurately if further subdivision of fishing fleets were considered. Model simulations that account for recently agreed management plan for demersal fish (EC, 2016) and the upcoming plan for pelagic fish would provide more realistic projections.

5. Outreach and products

Several outreach activities and products have been produced by COSM. The major product produced is a tool (the Ecospace model) that can be used in future to integrate results from other INSITE projects and further explore the objectives as set out by INSITE. More generally the tool can be used to provide Environmental Impact Assessments for developments and activities that potentially impact the functioning of the North Sea food web. Also, important, are the processed data layers created by the project (in conjunction with EcoConnect) and metadata that has been provided to the INSITE data project, so that it can be used to support future studies and assessments.

Scientific papers are in preparation for submission to peer-reviewed journals based on the research done in COSM. Indicative titles and target journals are as follows:

- Posen P, Lynam C, Hyder K (in prep.). Modelling the influence of North Sea structures: working with data to support the INSITE initiative. Applied Geography.
- Wright SR, Lynam C, Righton DR, Hunter E, Hyder K (in prep.) Structure in a sea of sand: The importance of man-made structures to fish assemblages in the North Sea. ICES Journal of Marine Science.
- Lynam C, Posen P, Wright SR, Garcia C, Mackinson S (in prep.). Spatial modelling of the North Sea food web and the response to the influence of North Sea structures. Ocean & Coastal Management.

6. Conclusions and recommendations

The model simulations indicate that man-made structures do influence the local community composition and these effects can disperse throughout the North Sea ecosystem mediated by interactions between species. The removal of oil and gas platforms and pipelines may ultimately contribute to declines in some aggregated groups (rays and sand eels), but increases in others (sharks, flatfish and roundfish) due partly to a change in benthic community composition, favouring small mobile epifauna over sessile epifauna and small infauna, and partly to direct predator-prey interactions between fish. Importantly, all modelled effects relating to removal of platforms, pipelines and cables are minor compared to the potential effect of environmental variability on the ecosystem or the change in fishing effort modelled. Additionally, the presence of wrecks and turbines appears to have a much greater impact than oil and gas infrastructure on rays, sharks, sand eels, flatfish and demersal roundfish.

The ultimate realised impact of removal of structures is thus dependent on the presence of other structures, natural variability and fisheries management. Although the additional habitat provided by platforms and pipelines may be relatively small this difference should not be disregarded at this stage for non-commercial species of conservation concern, such as rays, since natural variability is, by its very nature, unmanageable and the removal of other structures such as wrecks is unlikely to be a common occurrence.

Now that the tool is available, scenario testing of specific decommissioning options in tandem with recently agreed fisheries management plans (EC, 2016) and alongside UK climate projections (www.metoffice.gov.uk) should provide further evidence to inform the industry on the long-term effects on the ecosystem of proposed management.

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