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Assessing the ecological connectivity between man-made structures in the North Sea (EcoConnect)

For: INSITE

Kieran Hyder, Johan van der Molen, Luz Garcia, Alex Callaway, Paulette Posen, Serena Wright, Nick Taylor, Hannah Tidbury, Susana Lincoln and Mark Kirby

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Assessing the ecological connectivity between man-made structures in the North Sea (EcoConnect)

Submitted to: Richard Heard, INSITE Programme Director

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Executive summary

Man-made structures including rigs, pipelines, cables, renewable energy devices, and ship wrecks, offer hard substrate in the largely soft-sediment environment of the North Sea. These structures become colonised by sedentary organisms and non-migratory reef fish, and form local ecosystems that attract larger predators including seals, birds, and fish. From an environmental perspective, it is possible that man-made structures form a system of interconnected hard substrate in the North Sea. Two main mechanisms drive connectivity: (1) the 'planktonic dispersal' of the pelagic stages of organisms between the structures by ocean currents; and (2) 'movement' of mobile organisms. A third mechanism is also possible due to physical linkages (e.g. pipelines), but is thought to be of minor importance. Changes to the arrangement of hard substrate areas through decommissioning may affect the interconnectivity and could impact on the ecosystem of the North Sea. However, the scientific evidence 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 is lacking. This gap was recognised by Oil and Gas UK and the INSITE programme was set up to fund this research.

INSITE funded the EcoConnect project to assess the ecological connectivity between man-made structures in the North Sea. This was led by Cefas (https://www.cefas.co.uk/) with the aim to better understand connectivity between hard substrates, the role of man-made structures in the network of hard substrate, and effects of changing the network on structure and function. This was delivered through the collation of existing data, modelling the importance of pelagic dispersal, assessing interactions between mobile organisms and man-made structures, and evaluating the impact of removal of oil and gas infrastructure.

Compilation of data was a significant challenge due to the number, location, and differences between data sets and was done in collaboration with the INSITE project COSM (Figure E1). Data on man-made structures and natural habitats were compiled and the proportion of different types estimated in quarter degree squares across the North Sea. Generally, the area of oil and gas infrastructure was very small in comparison with other hard substrates. Seven species were selected to model based on likely occurrence on structures, ecological importance, and timing and duration of larval stage. These were: dead man's fingers, common sea urchin, cold water coral, plumose anemone, sponges, blue mussel, and slipper limpet. Five decommissioning scenarios representing realistic options were compared with the current baseline: current regulations, derogations removed, increased derogation, full removal, and maximum substrate. Assessment of the interactions between mobile predators and man-made structures showed negative effects during construction and positive effects during operation. No evidence exists on impacts of decommissioning in the North Sea, but the pressures are similar to the construction phase and habitat will be removed.

Modelling the planktonic dispersal showed differences in connectivity between years and species, with patterns driven by the weather. It was possible to identify areas with different roles in the network and categorise them as receivers, conductors, or suppliers of organisms. Structures in the western edge of the central bank were important for connectivity so retention should be considered, whereas the Norfolk Banks and northwest coast of the Netherlands had many wrecks so were less sensitive to removal of oil and gas structures. A decision tree for decommissioning of oil and gas platforms was

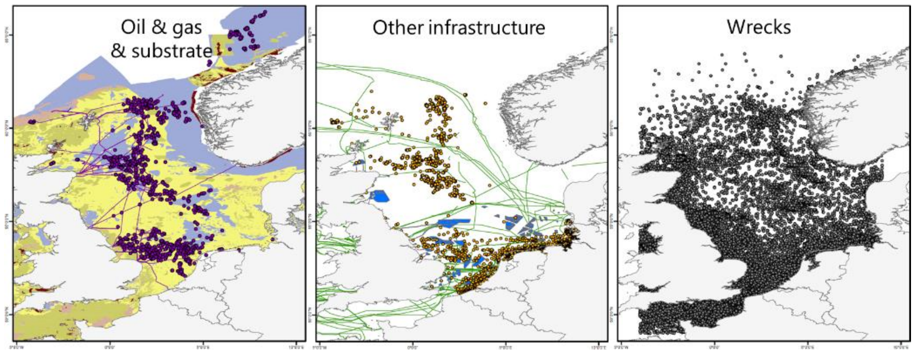

Figure E1. Offshore man-made structures types and natural substrate data layers.

developed based on the function of the sector and proximity to other man-made structures. This decision tree could be used on a case-by-case-basis to assess impact of removal of specific infrastructure where the aim is to preserve existing levels of connectivity.

Network analysis showed that decommissioning scenarios that removed more oil and gas infrastructure had a larger impact on the structure and function of network. Of the five scenarios, the largest contrasts in impact on network structure and function were between baseline (current situation), maximum structure (removal of platforms in southern North Sea), and the other decommissioning approaches (i.e. current regulations, increased derogation, derogation removed, and full removals) (Figure E2). These results indicated that there was little impact on the network of generic derogations, probably due to the small changes in area relative to the total amount of hard substrate. As a result, location approaches based on the areas identified as important for pelagic connectivity could be more effective in maintaining network structure and function.

Care should be taken interpreting these results as many assumptions were needed to generate the outcomes and a limited number of mechanisms accounted for. With additional data, it would be possible to use more comprehensive modelling approaches and reduce the uncertainty in the modelling results. With these conclusions in mind, the key recommendations from EcoConnect with respect to decommissioning are as follows:

1. Platforms can perform different functions with respect to ecological connectivity that vary between species and years. Structures on the western edge of the central bank of the North Sea appear to be important for connectivity, so retention should be considered.
2. Removal of oil and gas infrastructure reduced interconnectivity between hard substrates, but their relatively small area meant that generic derogations made little difference to the impact of decommissioning on the overall network. As a result, bespoke derogations should be considered to maximise the ecological benefits based on the location and function of specific platforms.
3. The data needed to underpin scientific studies of the impact of decommissioning were disparate and inconsistent. New studies should be developed to fill data and knowledge gaps through a mixture of sharing of industry data, reanalysis of existing routine monitoring, ecological experiments, and genetic analyses.
4. Further modelling is required to understand connectivity and impacts of thinning of the network, alongside broader network analysis and cumulative risk assessment to combine additional mechanisms (e.g. supply ships) and account for both positive benefits and negative impacts of connectivity (e.g. ecological connectivity versus spread of non-native species).
5. Cost-benefit analysis of decommissioning that considers the impacts of the different strategies on natural capital and ecosystem services, and includes the costs of post-decommissioning monitoring programmes is needed.

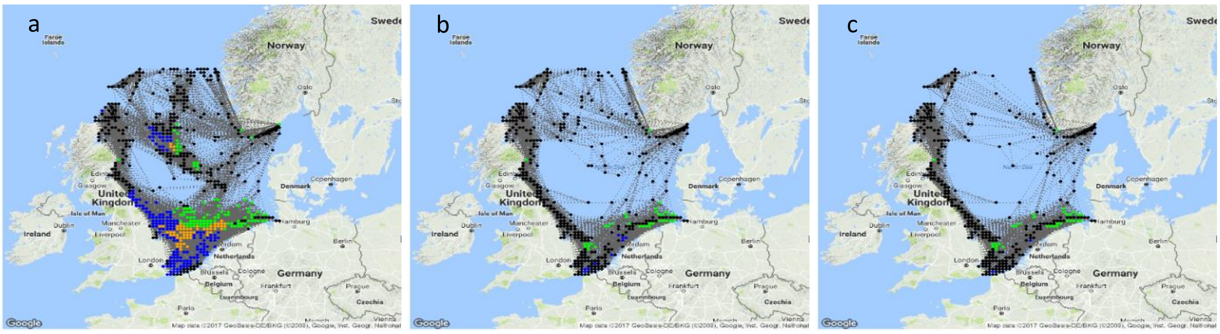

Figure E2. The spatial structure of networks representing baseline (a), and decommissioning under current regulations (b) and full removal (c). Network nodes are represented by dots and edges are presented by lines. Blue, green and orange nodes represent super spreaders, super sinks, and hotspots respectively.

1. Introduction

There are many potential influences of man-made structures on marine ecosystem structure and function. These include impact on habitat connectivity (e.g. stepping stones, pelagic dispersal, linkage – Macreadie *et al.* 2011) and movement of mobile marine species (e.g. crabs – Page *et al.*, 1999; fish – Løkkeborg *et al.*, 2002; birds – Tasker *et al.*, 1986; seals – Russell *et al.*, 2014). Man-made structures may also support communities that are different to those found on natural substrate, so affecting the function of the ecosystem (e.g. Mineur *et al.*, 2012). In fact, addition to the marine environment of man-made structures like oil platforms, wind turbines, and shipwrecks can be positive (e.g. strengthening natural connections between habitats and MPAs), or detrimental by introducing conduits for non-native species (Glasby *et al.*, 2007).

The connectivity of many marine systems has been assessed including coral reefs (e.g. Munday *et al.*, 2009), intertidal rocky shores (e.g. Caley *et al.*, 1996; Gaines and Roughgarden, 1985) and fish (e.g. Righton *et al.*, 2010). Many marine systems have been described as 'open' (Roughgarden *et al.*, 1985; Hyder *et al.*, 2001) and have been shown to have the potential for dispersal over large areas and protracted time frames during the pelagic phases of many marine organisms (Gaines *et al.*, 2007). More recently, the impact of pelagic dispersal on connectivity has been studied using particle tracking approaches that model both hydrodynamics and larval behaviour. These models have been used to assess recruitment of commercial fish (Bartsch and Knust, 1994a,b; Fox *et al.*, 2006; van der Molen et al, 2007; Lacroix *et al.*, 2013; Tiessen *et al.*, 2014) and jellyfish (van der Molen *et al.*, 2015). Corridors between structures such as pipelines provide a mechanism for colonisation of reef species that do not have pelagic dispersal (Mineur *et al.*, 2012). The behaviour of mobile organisms is also important and has been extensively studied (e.g. Righton *et al.*, 2010; Russell *et al.*, 2014).

Decommissioning of man-made structures at the end of their use is generally a condition of the licence to operate (e.g. UNICLOS 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 the estimated cost of decommissioning oil and gas infrastructure between 2016 and 2025 is £17.6 billion (Oil & Gas UK, 2016), with the best estimate of cost for the UK continental shelf to 2050 of £47 billion (Oil & Gas Authority, 2016). There are many different options for decommissioning structures, ranging from complete removal to leaving in place or dumping at sea. There are legal frameworks specifying the level of removal required (e.g. UNICLOS 1982), but derogations may be granted on health and safety, economic, social or environmental grounds (e.g. OSPAR Decision 98/3). For example, in the Northeast Atlantic, the decommissioning of offshore installations is regulated under OSPAR 98/3. This states that dumping or the leaving of disused offshore installations in place is prohibited, but derogations may be granted where an alternative disposal method is preferable to reuse, recycling, or final disposal (OSPAR 25 98/3). Derogations can include footings of a steel installation, concrete installations or anchors, or circumstances resulting from structural damage or deterioration (OSPAR 98/3). In practice, this is likely to mean that all topsides and substructures of less than 10,000 tonnes will be removed and brought to shore for recycling, with derogations for structures of greater than 10,000 tonnes for footing, heavy concrete gravity-based structures, floating concrete installations, and any concrete anchor- base, which can then be left in place.

Derogations may be granted if there are thought to be benefits for the marine environment (e.g. Rigs-to-Reefs), but there is debate about whether the effect is beneficial for the marine environment (e.g. Jørgensen, 2012; Macreadie *et al.*,2001; Picken and McIntyre, 1989). In the North Sea, the majority of the seabed is mud and sand, with rocky shores in many places and some reefs. Offshore installations and other man-made structures (e.g. wrecks) may provide hard substrate that impacts on the ecosystem in terms of productivity of the system and the connectedness of the network of hard substrate. Thus, it is important to understand the potential effects of man-made structures on the ecosystem and take these into account when deciding upon appropriate decommissioning scenarios. In the North Sea, this involves connectivity (pelagic dispersal, linkage by pipelines) and the movement of mobile predators, and how these structures contribute to the network of natural hard substrate that exists, but studies of the interconnectedness of the network of man-made structures are lacking.

The behaviour of mobile organisms has been extensively studied (e.g. Righton *et al.* 2010, Russell *et al.* 2014). Man-made structures are likely to have direct and indirect impacts on the behaviour and space use of mobile foragers. Understanding of spatio-temporal movements in relation to environmental and anthropogenic change is required to quantify these impacts. The association of these species with hard-substrates is difficult to quantify due to the nature of their habitat, but significant amounts of data on the movement of mobile organisms exist (e.g. Block *et al.* 2011, de Pontual *et al.* 2012).

Network analysis is used to understand the properties of a network and is derived from the level of connectedness between individual components. While traditionally associated with physics, computer science and social science, it is now applied in biology and ecology. The application of network analysis has provided valuable insight into ecosystem food webs (Dunne *et al.* 2002), protein interactions (Promislow 2004), and epidemiology (Christley *et al.* 2005, Dent *et al.* 2008). The importance of locations (nodes), and the connections and movement (edges) between them in terms of their contribution to dispersal across the entire network can be assessed. Network analysis can provide accurate information and novel insight into complex systems in comparison to analysis of individual system components (Proulx *et al.* 2005). It has also been used to quantify the consequences of changes in connectedness and the complexity of network structures (Taylor *et al.* 2010, 2011). Their potential for application to marine systems has been recognised, but few examples exist (Ferreira *et al.* 2012, 2013).

EcoConnect was funded by the INSITE programme to develop novel science to better understand connectivity between hard substrates, the role that man-made structures play in the network of hard structures, and the effects of changing the network of hard substrate on structure and function of the North Sea ecosystem. To achieve this, EcoConnect had the following objectives:

1. To collate existing data and knowledge on linkages between hard substrate.
2. To assess the importance of pelagic dispersal to the connectivity between communities on hard structures in the North Sea.
3. To develop understanding of how mobile marine organisms including fish, birds and mammals use the network of man-made structures.
4. To evaluate the impact of oil and gas infrastructure and compare with existing man-made structures and natural substrate.

This report contains a summary of the scientific outputs of EcoConnect, highlights how EcoConnect helped to deliver INSITE objectives, demonstrates how science from EcoConnect can impact on decommissioning, and identifies science requirements to support of decommissioning.

2. Research summary

Man-made structures including rigs, pipelines, cables, renewable energy devices, and ship wrecks, offer hard substrate in the largely soft-sediment environment of the North Sea. These structures become colonised by sedentary organisms and non-migratory reef fish, and form local ecosystems that attract larger predators including seals, birds, and fish. It is possible that these structures form a system of interconnected hard substrate through two main mechanisms: (1) the ‘planktonic dispersal’ of the pelagic stages of organisms between the structures by ocean currents; (2) ‘movement’ of mobile organisms. A third mechanism is also possible due to physical linkages (e.g. pipelines), but was thought to be of minor importance, so was not considered further. Changes to the overall arrangement of hard substrate areas through removal or addition of individual man-made structures will affect the interconnectivity and could impact on the ecosystem. EcoConnect assessed if a network of hard substrate exists and the extent to which man-made structures in the North Sea contribute to an interconnected system of hard substrate. To achieve this, existing data on physical features and communities were compiled to parameterise, calibrate, and test models that predict the impact of decommissioning. Connectivity was assessed using models that simulate the drift of planktonic stages and existing knowledge of mobile organisms. The impact of removal of oil and gas infrastructure was investigated using network analysis and compared to existing man-made structures and natural substrate. The key scientific research done within EcoConnect for each of these objectives is outlined in detail below.

2.1. Collation of existing data and knowledge

One of the most significant challenges in developing modelling approaches for understanding the impact of oil and gas platforms on connectivity in the North Sea was accessing the data required. Data were split across many different databases, often with little consistency between each source. This made development of comprehensive North Sea data sets and the subsequent processing into useable consistent products a real challenge. As a result, EcoConnect partnered with COSM to compile comprehensive data sets and process into useable products focussed in three areas: physical characteristics and structures; species and community data; and impact of decommissioning scenarios. All data were stored in a central repository and metadata submitted for inclusion in the INSITE metadata repository.

2.1.1. Physical characteristics and structures

Existing data on natural features in the North Sea were compiled for bathymetry (Stephens and Diesing, 2015) and natural substrates (EMODnet Phase II Seabed Habitats - http://www.emodnet.eu/seabed-habitats). Data representing man-made structures were collated (Table 1) including oil and gas platforms, subsurface structures, wind turbines and wind farm boundaries, wrecks, pipelines and submarine cables, and their spatial distributions mapped (Figure 1). Datasets were processed to derive gridded layers at 0.25 decimal degree resolution covering the entire spatial extent of the North Sea, representing the proportion of grid cell occupied by each feature. Man-made structures may occupy little space compared to natural features and most datasets did not include the size of the structure. As a result, it was necessary to estimate the proportion of grid cell occupied by each type of structure. The structures were defined as point features (platforms, subsurface structures, wind turbines, wrecks), linear features (pipelines, cables) or polygons (wind farms, wind power export cables). Generally, each structure was overlaid on the spatial grid and buffers were assigned depending on the structure type, before the proportion of each structure within each grid square was calculated. The number of subsurface structures were recorded due to the small area occupied. Wrecks were processed based on tonnage and construction material, and an approximation was assumed for decay and burial (van der Molen *et al.*, submitted; MacLeod and Harvey, 2014). There were gaps in the data related to low resolution substrates especially in coastal areas, physical attributes of man-made structures (e.g. size, shape), and accessing information for the eastern North Sea. Despite these issues, the data compiled within EcoConnect and COSM represent the most comprehensive data on structures and natural features in the North Sea, and are a significant resource for future oil and gas decommissioning projects. A paper relating the compilation of data for INSITE and modelling approaches to generate consistent products is being developed for submission to Applied Geography (see Section 4).

Man-made structures are very small compared with natural features (Table 2), model grid size, and model requirements. In addition, there is a lack of physical characteristics, so assumptions were made to define spatial footprints. This led to uncertainty in both the pelagic phase modelling and network analysis. In addition, this had implications for model outputs, including the scenario modelling, that was likely to have different effects across spatial scales. It is likely that future survey work on, for example sea bed substrates and bathymetry, will produce more accurate boundaries and depth measurements in some areas, improving modelling of connectivity. However, further data are needed to strengthen the evidence-base that underpins oil and gas decommissioning (Section 3).

Table 1. Summary of data compiled on man-made structures in the North Sea.

Type of structure	Data format	Source
Oil and gas platforms	Point locations and attributes compiled from Database of North Sea fixed platforms (Oil & Gas UK) October 2012, and OSPAR Offshore Installations Inventory 2015.	Oil & Gas UK http://oilandgasuk.co.uk/ OSPAR http://odims.ospar.org/)
Subsurface structures	Point locations of subsurface infrastructure, excluding features within 500m of oil and gas platforms, but including buoys and moorings marking the locations of sub-surface features from non-UK datasets (Belgium, Netherlands, and Germany).	Crown Estate https://www.thecrownestate.co.uk/ IMARES Wageningen UR http://www.imares.wur.nl by request from Joop Coolen.
Wind turbines	Point locations of individual wind turbines, substations and associated meteorological masts.	KIS-ORCA (Offshore Renewable & Cables Awareness) http://www.kis-orca.eu/
Wrecks	Point locations and attributes (including wreck type, size, material, depth and date sunk) of 33,255 wrecks in the North Sea and surrounding areas.	The Wreck Site http://wrecksite.eu/ by request from Jan Lettens.
Pipelines	Polyline data – UK waters only.	UK Hydrographic Office http://www.ukho.gov.uk/
Submarine cables	Polyline subsea cable data – North Sea and surrounding areas (Kingfisher Information Service), supplemented by additional data from UKHO.	KIS-ORCA (Offshore Renewable & Cables Awareness) http://www.kis-orca.eu/ UK Hydrographic Office http://www.ukho.gov.uk/
Offshore wind power export cables	Polygon boundaries of offshore wind power export cable facilities – UK waters only.	Crown Estate https://www.thecrownestate.co.uk/
Wind farms	Polygon boundaries of operational and proposed wind farms, supplemented by additional information, including number and capacity of turbines.	OSPAR offshore renewables database http://odims.ospar.org/ RenewableUK http://www.renewableuk.com/

Table 2. Summary of 'baseline' values of natural substrates and man-made structures in North Sea.

Feature	Area (km^2)	% of total	% of natural substrate
Natural:	**2,483,080**	**100**	
Mud	796,654	32.1	
Sand	1,152,375	46.4	
Coarse substrate	410,273	16.5	
Mixed sediment	86,518	3.5	
Rock & boulders	37,261	1.5	
Man-made:	**5,227**	**0.2**	**14.1**
Oil & gas	81	0.0033	0.217
Wind turbines	7	0.0003	0.020
Pipelines	2,578	0.1038	6.919
Cables	2,774	0.1117	7.445
Wrecks	23	0.0009	0.061

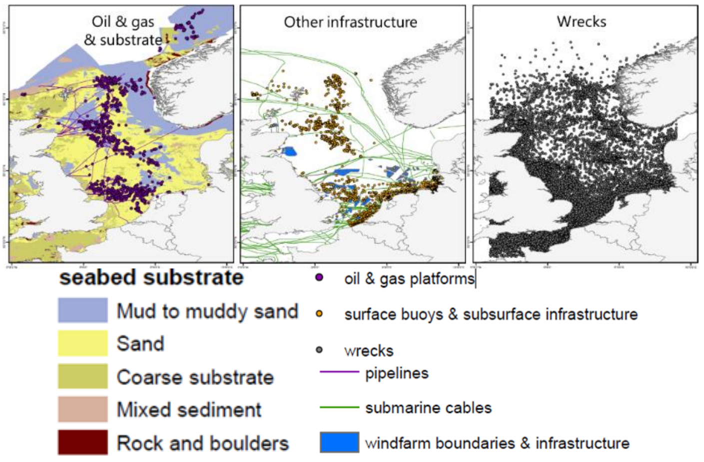

Figure 1. Offshore man-made structures types and natural substrate data layers.

2.1.2. Species and community data

Information on individual species was needed for parameterising and testing dispersal modelling and network analysis. This involved: selection of a limited number of species to model; egg and larval development and behaviour for pelagic dispersal models; probability of settlement at platforms for network analysis; and general information about the community structure on platforms for model testing. Various studies have investigated the colonisation, establishment and succession of benthic epifaunal communities on artificial substrates (Whomersley and Picken, 2003; Zintzen *et al.*, 2008; Coates *et al.*, 2014; van der Stap *et al.*, 2016). Whilst varying species richness has been observed on different substrates ranging from 23 taxa (Langhamer, 2016) to 94 taxa (Coates *et al.*, 2014) there was a level of consistency within the dominant taxa between studies and their sites of interest. *Mytilus edulis*, *Metridium senile* (var. dianthus), *Alcyonium digitatum*, *Tubularia* spp. and Porifera spp. were observed on the majority of investigated offshore artificial substrates in north-east Europe. The taxa selected for simulation in the particle tracking model comprised of a selection of those occurring on offshore structures (Whomersley and Picken, 2003; Zintzen *et al.*, 2008; Coates *et al.*, 2014; van der Stap *et al.*, 2016), augmented with taxa of ecological importance, such as *Lophelia pertusa* (rare and bioengineering) and *Crepidula fornicata* (non-native and highly fecund). *Echinus esculentus* was included as a representative taxon of natural hard substratum communities. Detailed information on egg and larval lifecycle stages of the selected species was in some cases difficult to source (Table 3). Where this was the case, expert opinion based on information from similar species and species from similar genera was used. Key factors thought to influence the distribution of the egg and larval phases of the selected species included spawning time, egg and larval duration, vertical migration, size, growth rates and larval stages (Kingsford *et al.*, 2002; Jackson, 1986) (Table 3).

Table 3. Species selected and life-history parameters in the model.

Species	**Total duration**	**Spawning**[1]	**Egg stage**[2]		**Larval stage 1**[3]				**Larval stage 2**[4]		
	[days]	Peak date and standard deviation	stage duration (days)	vertical migration	initial size (mm)	growth rate (mm/day)	vertical migration	final size (mm)	growth rate (mm/day)	vertical migration	final size (mm)
Dead man's Fingers (*Alcyonium digitatum*)	200	1 Jan 22 days	7	neutral	0.6	0.0015	neutral	0.615	0.0015	sinking 5 mm/s	0.9
Common Sea Urchin (*Echinus esculentus*)	50	15 Apr 35 days	1.5	neutral	0.6	0.0071	neutral	0.72	0.0071	sinking 5 mm/s	0.88
Cold Water Coral (*Lophelia pertusa*)	57	1 Apr 25 days	7	floating 5 mm/s	0.5	0.0714	floating 5 mm/s	1.5	0.0714	sinking 5 mm/s	4.07
Plumose Anemone (*Metridium senile var. dianthus*)	180	15 June 15 days	0.1	neutral	0.5	0.0139	neutral	0.722	0.0139	sinking 5 mm/s	1.5
Sponges (Porifera)	20	15 May 15 days	5	neutral	0.2	0.015	floating 5 mm/s	0.275	0.015	sinking 5 mm/s	0.5
Mussels (*Mytilus edulis*)	60	1 Aug 30 days	5	neutral	0.6	0.0053	floating 5 mm/s	0.75	0.0053	tidal, up flood, down ebb, 5 mm/s	0.9
Slipper Limpet (*Crepidula fornicate*)	21	1 Jun 90 days	5	neutral	0.5	0.0714	sinking 5 mm/s	-	-	-	2.0

1. Jackson, 1986; Kingsford *et al.*, 2002; Bocharova and Kozevich, 2011.
2. Wilson and Seed, 1974; Blanchard, 1979; Nicholl, 1979; Larsson, 2014.
3. Bayne, 1965; Seed, 1969; Sprung, 1984; Blanchard, 1997; Bierne *et al.*, 2002; Ruppert., et al 2004.
4. Bayne, 1965; Seed, 1969; Shick and Allen, 1977; Sebens, 1983; Sprung, 1984; Larsson *et al.*, 2014; Hand and Uhlinger, 1992; Bierne *et al.*, 2001; Larsson *et al.*, 2014.

To enable comparison between assemblages of natural reef and offshore infrastructure, ROV footage supplied by an Operator of a platform operating in the UKCS was compared against underwater video data acquired from a UK marine protected area (MPA). The three platforms for which observational data were available demonstrated similar characteristics of faunal assemblage. *Metridium senile* is the predominant taxon with high coverage between 20 – 100 m (Figure 2). There were differences between the communities found on the structures, with *Lophelia pertusa* only observed below 60 m, so was not present on structures in less than 100 m of water. Shallow areas were dominated by *Mytilus edulis* and Rhodophyta (Figure 2). Although there were broad similarities between assemblages observed on structures, subtle differences in less prevalent taxa suggest that each structure supports different taxa.

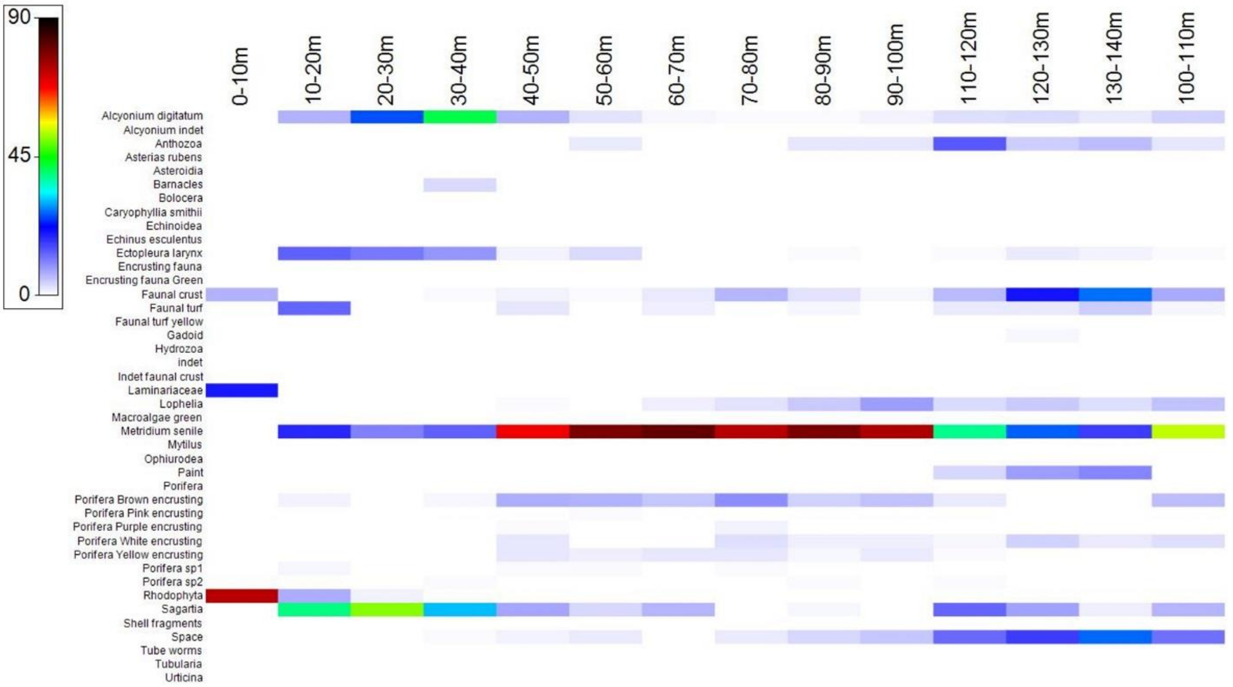

Figure 2. Shade plot illustrating percentage cover of organisms across 10 m depth bins at one of three offshore structures analysed.

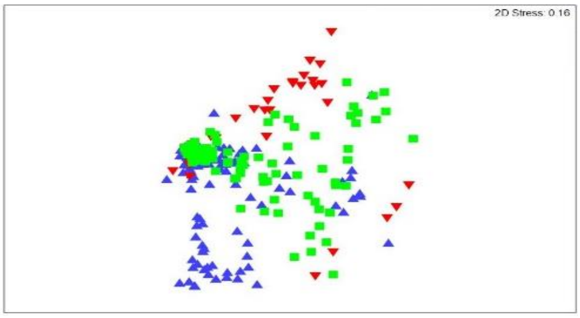

Figure 3. Non-metric multidimensional scaling of assemblages associated with each structure collected from routine monitoring ROV footage. Colours reflect different platforms (a = red, b = blue, and c = green).

The multidimensional scaling (MDS) illustrated the similarity between observations, but there was differentiation between structures due to varying levels of less abundant species (Figure 3). The shade plot from the MPA illustrated that *Alcyonium digitatum*, *Pomatoceros triqueter* and *Echinus esculentus* were the most prevalent taxa on the natural reef (Figure 4). A greater variety of large echinoderms was observed compared to the structures. There was also less predominance of a single taxon on the natural reef than the offshore structure (Figure 4).

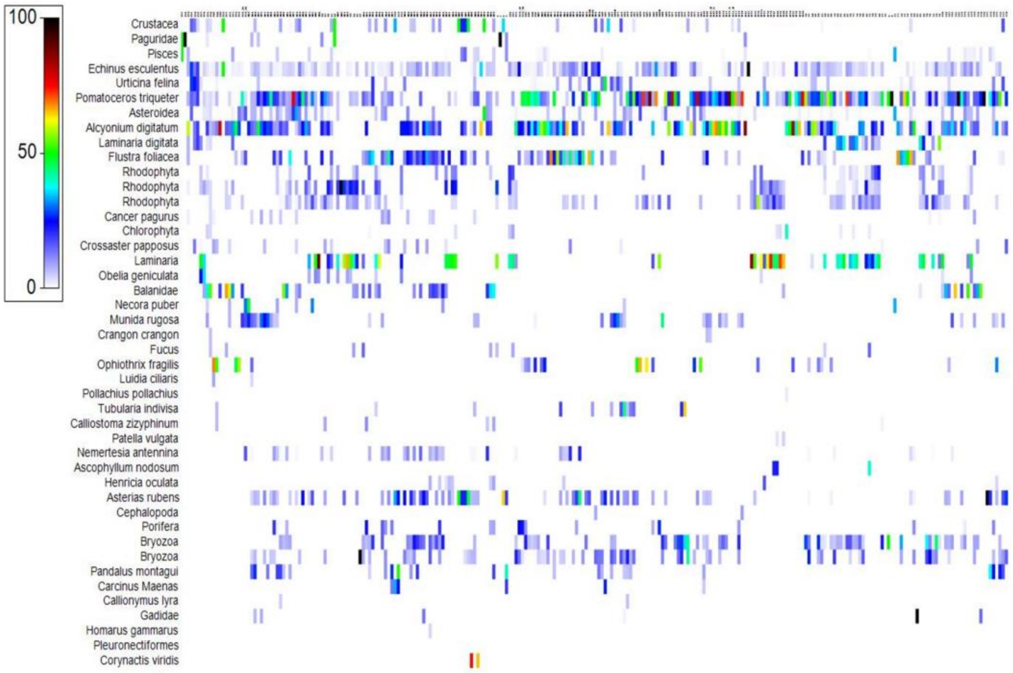

Figure 4. Shade plot of photographic observations of organisms from samples across the Berwickshire and North Northumberland European Marine Site. Data provided by Natural England.

2.1.3. Decommissioning scenarios

The INSITE Independent Scientific Advisory Board (ISAB) provided five different potential decommissioning scenarios that captured the range of options that could be applied by the regulator (Table 4).

Table 4. Description of potential decommissioning scenarios with the total area (man-made and natural – km^2) and percentage of existing natural hard substrate area for each scenario.

Scenario	Topsides and substructures	Pipelines	Area	%
1. Current regulations	<10,000 tonnes removed and brought ashore for recycling >10,000 tonnes footings left in place Heavy concrete gravity bases, floating concrete installations and concrete anchor-base left in place	>16” diameter left in place <16” diameter removed unless buried	42,661	99.85
2. Derogations removed	All structures except for concrete gravity structures and anchors removed and brought ashore for recycling	>16” diameter left in place <16” diameter removed unless buried	42,654	99.84
3. Increased derogation	<4,000 tonnes removed and brought ashore for recycling >4,000 tonnes footings left in place Heavy concrete gravity bases, floating concrete installations and concrete anchor-base left in place	>16” diameter left in place <16” diameter removed unless buried	42,666	99.86
4. Full removal	All structures removed apart from: • Any part of structure located below the surface of the sea bed. • Any concrete anchor-base associated with a floating installation which does not or is unlikely to result in interference with other legitimate users of the sea.	All pipelines removed regardless of size and whether buried or otherwise	42,643	99.81
5. Maximum substrate	Platforms in Central and Northern North Sea left in situ Structures associated with platforms in Southern North Sea removed down to mudline	All pipelines left in place regardless of size and whether buried or otherwise	42,702	99.95

The final gridded data for existing conditions represented the current 'baseline' values of hard substrate (both natural and man-made) (Table 2). These were processed to represent the extent to which hard substrate would change in spatial distribution under the different oil and gas platform decommissioning scenarios and was dependent on the location and number of structure removed (Table 4). Spatial data layers were created for each of these scenarios that were used to test the impact of these decommissioning scenarios.

2.2. Importance of pelagic dispersal for connectivity

2.2.1. Pelagic dispersal modelling approach

Pelagic dispersal modelling was done to assess connectivity between hard substrate in the North Sea and the potential impacts on connectivity of oil and gas decommissioning. Seven species representative of the hard substrate community were chosen to model (Section 2.1.2 and Table 3) and man-made structures were included based on processed gridded data sets sectors that included oil and gas platforms, wind farms and wrecks, and natural substrate (Section 2.1.1).

Table 5. Classification of each sector, where S_{sup} and S_{rec} were the number of sectors each sector supplied and received particles, respectively. The settling / supply factor (*R*) was measured on a scale from -1 to 1 and represented the difference in numbers of particles supplied and received as a proportion of the total number of particles.

Role	**Settling/supply factor**	**Supply type**	S_{sup}	**Reception type**	S_{rec}	**Category**
Suppliers	$R > 0.5$	multi	>5	-	-	8
		mono	≤5	-	-	7
Conductors	$-0.5 \le R \le 0.5$	multi	>5	Multi	>5	6
				Mono	≤5	5
		mono	≤5	Multi	>5	4
				Mono	≤5	3
Receivers	$R <- 0.5$	-	-	Multi	>5	2
		-	-	Mono	≤5	1

Pelagic dispersal was modelled for the years 2001-10 using the General Individuals Transport Model (GITM) for particle tracking that includes physical particle advection and diffusion, and biological development and behaviour (van der Molen *et al.*, 2017). Dispersal was modelled using hydrodynamics derived from the General Estuarine Transport Model GETM (www.getm.eu; Burchard & Bolding, 2002) that uses the General Ocean Turbulence Model (GOTM) to solve the vertical dimension. GETM was run for the North-west European shelf a resolution of approximately 5.5 km with 25 non-equidistant vertical layers (Van der Molen *et al.* 2016; 2017). Biological development and behaviour of the released particles was done using an individual-based modelling approach in GITM. Here, different egg and larval development stages of the selected species were identified, with constant growth rates and specific, stage-dependent vertical migration behaviour (neutrally buoyant, floating, sinking, diel migration, tidally cued migration). Particles represent super-individuals, which are packets of many individuals. For each of the seven species modelled, development and behavioural parameters were taken from the literature and covered the variety of species in the community (Section 2.1.2 and Table 3). Each of the offshore structures and natural substrates act both as the spawning and settling sites for the different sedentary species that were studied. Structures were grouped in sectors of a fixed size, with only sectors containing hard substrate used as release and settling sites. For each model experiment, particles were released at the centre of all 15 x 15 km grid cells identified as containing structures or hard substrate. Release times were assumed to be normally distributed with the mean at the known peak spawning time of the species under consideration. A connectivity matrix was derived between sectors, with connectivity defined as all sectors that a particle passes through when it is ready to settle. Each sector was then classified based on connectivity as a supplier, conductor, or receiver based on the difference between rates of settling and supply of particles (Table 5).

2.2.2. Impact of oil and gas infrastructure on connectivity

Results showed a relatively stable overall spatial distribution of function, but with distinct variations between species (Figure 5) and years (Figure 6). For anemone (*Metridium senile*) and cold water coral (*Lophelia* *pertusa*), multi-suppliers and multi-receiver sectors were found on the UK east coast, southern Bight, continental coast into the German Bight, and central North Sea (Figure 5a,b). Multi-suppliers were found on the Norwegian coast, west of the Orkney Islands, on the western side of the central region with oil and gas structures, in the vicinity of the Silver Pit, and in the northern approaches to the Strait of Dover (Figure 5a,b). The coastal region of Norway also contained sectors of mono-suppliers, and two bands of multi-receivers were found: in the frontal area in the southern North Sea, and to the east of the central region with oil and gas structures (Figure 5a,b). Slipper limpet (*Crepidula fornicata*) and sponges (Porifera species) showed dominance of multi-suppliers and multi-receivers sectors, except for a region of suppliers on the Norwegian coast, and suppliers and mono-receivers in the central region that contain oil and gas structures (Figure 5c,d).

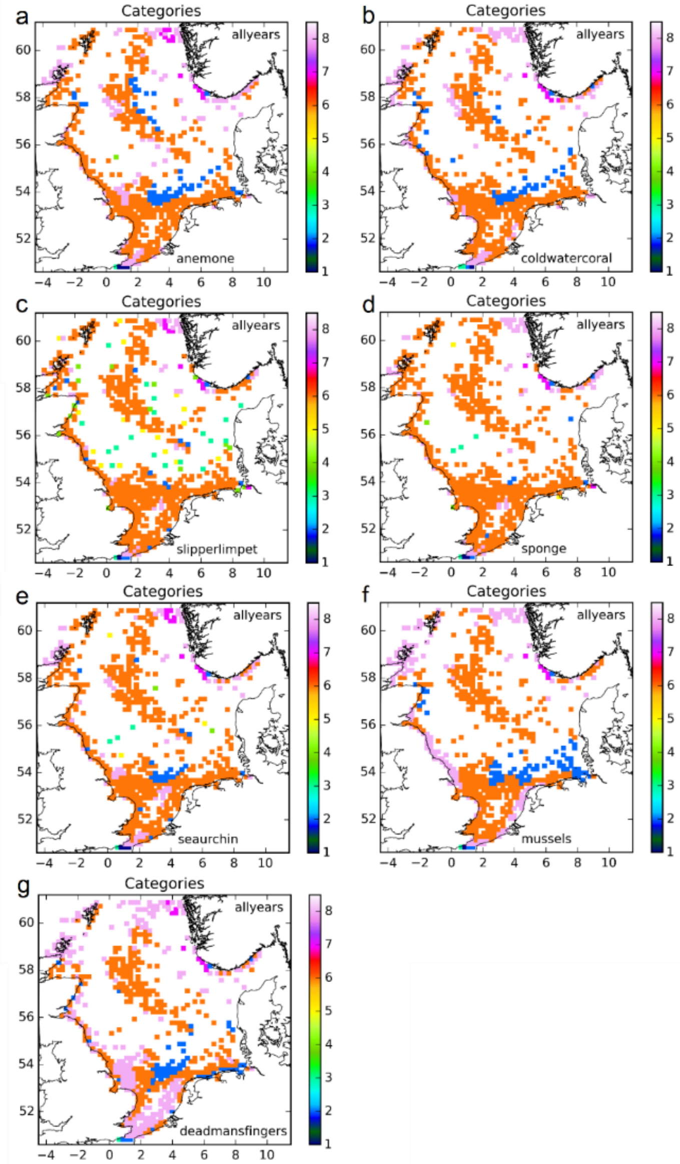

Figure 5. Functional categories aggregated over 2001-2010 for anemone (a), cold water coral (b), slipper limpet (c), sponges (d), sea urchin (e), mussels (f), and dead man's fingers (g). Categories are defined in Table 5.

Sea urchin (*Echinus esculentus*) was between these two patterns (Figure 5e). Mussels (*Mytilus edulis*) and dead-man's fingers (*Alcyonium digitatum*) had multi-suppliers around the Orkney and Shetland Islands, the east coast of the UK, the west coasts of Belgium, the Netherlands, and Norway, with a band of multi-receivers between the frontal area and the coast. The basic pattern of connectivity was the same for all years, with the most substantial interannual variations evident in the spatial extent of the region of sectors of multi-receivers along the frontal area in the southern North Sea, which was extended further east in some years than in others, and in the location of the group of sectors of multi-suppliers in the vicinity of the Silver Pit, along a northwest to southeast axis (Figure 6).

The differences in connectivity category distributions between the species was caused by their varying characteristics (spawning time, pelagic duration, and vertical migration behaviour) and differences in currents experienced. For instance, dead man's fingers (*Alcyonium digitatum*) showed a predominance of multi-suppliers in the southern North Sea due to the long pelagic duration and winter spawning, when westerly winds are strong and drive counter-clockwise circulation, causing transport out of the area.

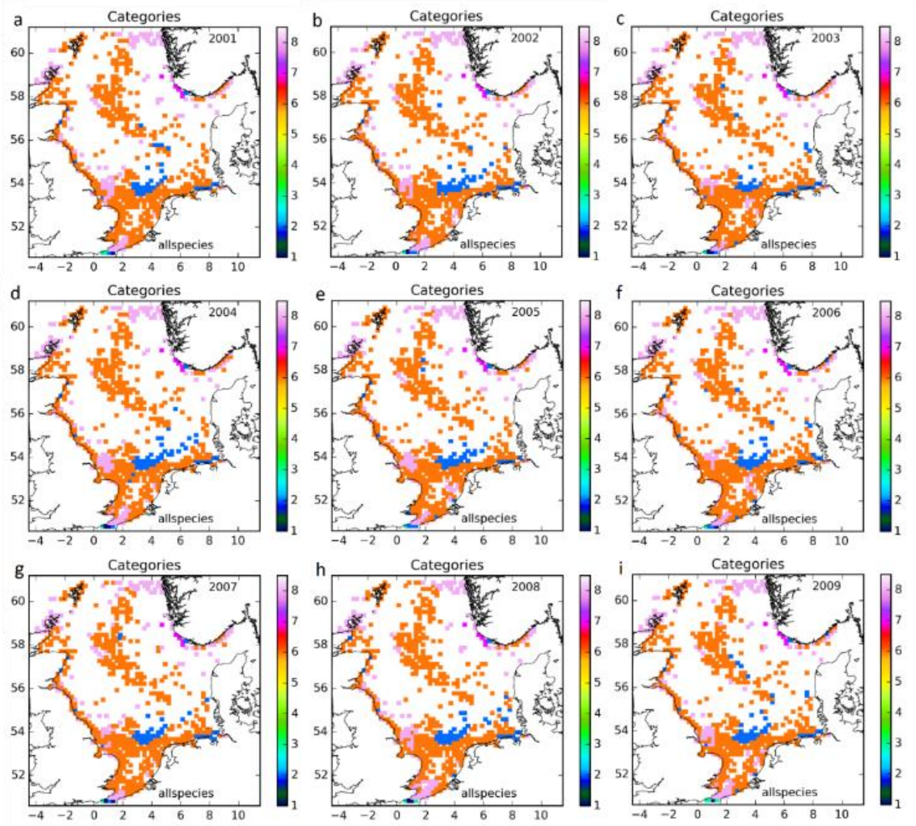

Figure 6. Functional categories, aggregated over all species for 2001 to 2009 (a - i). Categories are defined in Table 5.

The absence of multi-receivers along the frontal area in the southern North Sea for slipper limpet (*Crepidula fornicata*) and sponges (Porifera spp.) was due to short pelagic duration and summer spawning when meteorological conditions are relatively quiet, resulting in local supply and settlement. The short pelagic duration was also responsible for the mono-suppliers and mono-receivers sectors in the band around the central region for slipper limpet (and to a lesser extent for sponges) as these isolated sectors derive particles from a few nearby upstream sectors. Mussels were the only species with many multi-receivers in the inner German Bight driven by tidal stream migration behaviour and a dominant tidal current into the Bight (e.g. Holt *et al.*, 2001).

This dominant axis of flood and ebb flow in combination with the tidally cued vertical migration behaviour of the mussel larvae (up during flood flow and down during ebb flow) resulted in larger numbers of particles settling in inner German Bight than for the other species. Interannual variation in connectivity was caused by differences in meteorological forcing, that affected both water temperatures and currents.

2.2.3. Implications for oil and gas decommissioning

It is important to note that the categories of sectors result in different impacts on the network, so understanding the properties of each sector helps to assess decommissioning scenarios. It is clear that receivers are less important than suppliers and conductors, suppliers are more vulnerable than receivers and conductors, and the number of connections (multi- or mono-) affects both importance and resilience. To maintain a coherent network, structures in sectors that act as suppliers should not be decommissioned if the goal is to maintain the existing function of the network. Specific regions where different decommission strategies could be implemented included: the western edge of the central region (57-59N, 1-0W), on the Norfolk Banks (53-54.5N, 1-2E), and the north-west coast of The Netherlands (52-53.5N, 4-5E). The western edge of the central region may act as an anchor point so should be maintained, whereas Norfolk Banks and coast of The Netherlands contained many wrecks so may be less sensitive to removal of oil and gas structures. Removal of oil and gas structures in sectors of categories other than suppliers has least potential to affect network function, but this may change if substantial numbers of oil and gas structures are removed. Assuming that current ecosystem function of the network of structures needs to be preserved and no other ecosystem considerations exist for preserving structures other than pelagic connectivity, it is possible to propose a decommissioning scenario based the function of each sector (Figure 7). Structures in sectors that act as suppliers should be left in place, as these are likely to serve as anchor points for the network, and removal might trigger local extinction. Structures in sectors that function as conductors can be removed if sufficient number of other structures remain within a certain distance. It was not possible to determine what level is sufficient at present, as it depends on the specific decommissioning programme. Oil and gas structures in receiver sectors can be decommissioned. As structures are decommissioned, the connectivity will need to be reassessed as the role of individual sectors in connectivity may change.

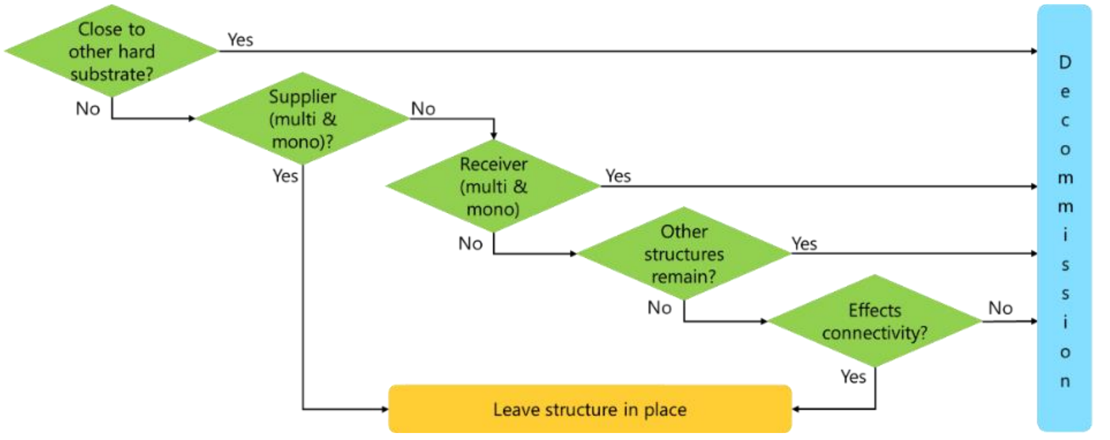

Figure 7. Proposed decision tree for decommissioning of oil and gas structures based on the assumption that it is important to preserve the existing level of network connectivity resulting from pelagic dispersal.

2.3. Use of man-made structures by mobile marine organisms.

Man-made structures are likely to have a direct and indirect impact on the behaviour and space use of mobile foragers. Understanding spatiotemporal movements in relation to environmental and anthropogenic change is required to quantify these impacts. Here, two approaches were developed to assess these interactions: a review of existing literature; and reanalysis of fish behaviour to assess interactions with man-made structures.

2.3.1. Review of the interactions between mobile predators and man-made structures

In the marine environment, man-made structures may originate from many sources, both unintentionally, for example as the wreck of a vessel or aircraft, and through deliberate placements (Figure 8). The numbers of man-made structures in the environment is increasing mainly due to the introduction of renewable energy platforms. To make evidence-based management decisions, it is important to consider the positive and negative impacts that construction, operation, and decommissioning could have on mobile predators like marine mammals, fish, and seabirds. However, a consistent comprehensive review that brings together all studies did not exist. Here, the interactions between man-made structures and fish, seabirds, and marine mammals were explored. The interactions between man-made structures and mobile predators were split into the different stages of the life-cycle of the structure, so were considered separately for construction, operation, and decommissioning.

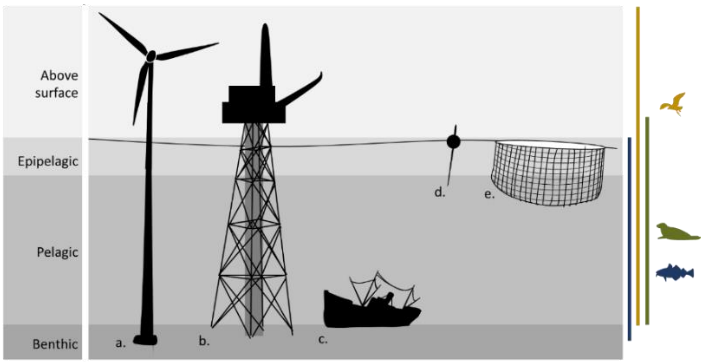

Figure 8. Offshore man-made structures types include: windfarms (a), oil and gas platforms (b), wrecks (c), floating aggregation devices (d), and mariculture (e).

Searches were made of literature databases and google scholar to identify scientific literature about the interactions between man-made structures and mobile predators in the North Sea. The relevant studies were reviewed and the direction of the interactions categorised as positive, no effect, or negative for each stage of the life-cycle of the structure. The outcome was an impact matrix and pressures for fish, seabirds and mammal based on a synthesis of existing studies for the North Sea (Figure 9). In addition, the existing environmental impact assessments (EIAs) for decommissioning currently being considered by the UK Government were assessed and impacts on the physical and chemical environment, marine habitats, and other users extracted.

The pressures identified for the construction phase were noise, disturbance, physical and chemical environment, and collision; for operation they were noise, habitat creation, fishing, collision, non-native species, nutrient enrichment, and pollution; and for decommissioning were removal of habitat, release of pollutants, noise, and collision. Generally, the impacts during construction were negative and positive during operation, apart from for birds and mammals (Figure 9). There has been limited decommissioning of man-made structures in the North Sea, so these impacts are difficult to assess. However, given that many of the pressures are similar to be the construction phase alongside removal of habitat, it is likely that many of the interactions will be negative.

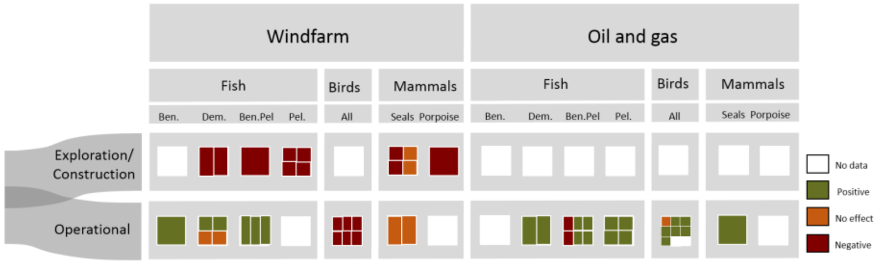

Figure 9. Effects of oil and gas platforms and windfarms on the abundance of fish, birds and mammals corresponding to positive, negative and no effects on abundance. Ben is benthic, dem is demersal, and pel is pelagic.

The EIAs currently being considered concluded that potential significant impacts on ecology are limited. Two of the eleven projects under consideration predicted significant impacts on: benthic ecology and conservation sites from seabed impacts (Viking Satellites); and birds from hydrocarbon releases and oil spill response (Ann and Alison installation). No significant impacts were predicted for fish, marine mammals, water quality, or other sea users. The approved decommissioning programme for the Brent field concluded that significant impacts on the marine environment were limited to: habitat changes due to retention of the gravity base and dumping of rock; increased turbidity and smothering from trenching pipelines and removal of structures and debris; and noise from cutting activities. Potential decommissioning impacts considered not to be significant from the Brent field were: non-native species; seabed disturbance; corkscrew injuries to seals; planned discharges; and effects on physical environment. Impacts on other users of the sea from the Brent field decommissioning were expected to be insignificant, as the Safety Exclusion Zone will remain in place to protect the remaining gravity structures.

From the review, it was clear that that data is lacking on many interactions, so new studies are required to develop the evidence-base for decommissioning. Analysis of existing environmental impact assessments to assess the potential effects of decommissioning varied between effects on receptors (e.g. pile cutting, pipeline removal) and impacts (e.g. underwater noise and seabed disturbance), so a standard receptor-based approach should be developed by regulators. This could use the guidance on operations tables produced by the Statutory Nature Conservation Bodies (SCNBs) and assess potential effects against each receptor present. Specific details of the EIA methodology applied in terms of how levels of sensitivity, magnitude, and significance have been defined and could be used in future. It was clear that there are ecological impacts associated with the removal of structures, although few were considered significant, so individual bespoke cases could be made for leaving specific structure in place.

2.3.2. Investigating interactions between fish and man-made structures using telemetry

Man-made structures are likely to have direct and indirect impacts on the behaviour and use of space by mobile foragers. The present study used data storage tagged Atlantic cod (*Gadus morhua*), European plaice (*Pleuronectes platessa*), and thornback ray (*Raja clavata*) to assess whether seasonal changes in behaviour were linked to environmental and physical changes in their available habitat (Figure 10).

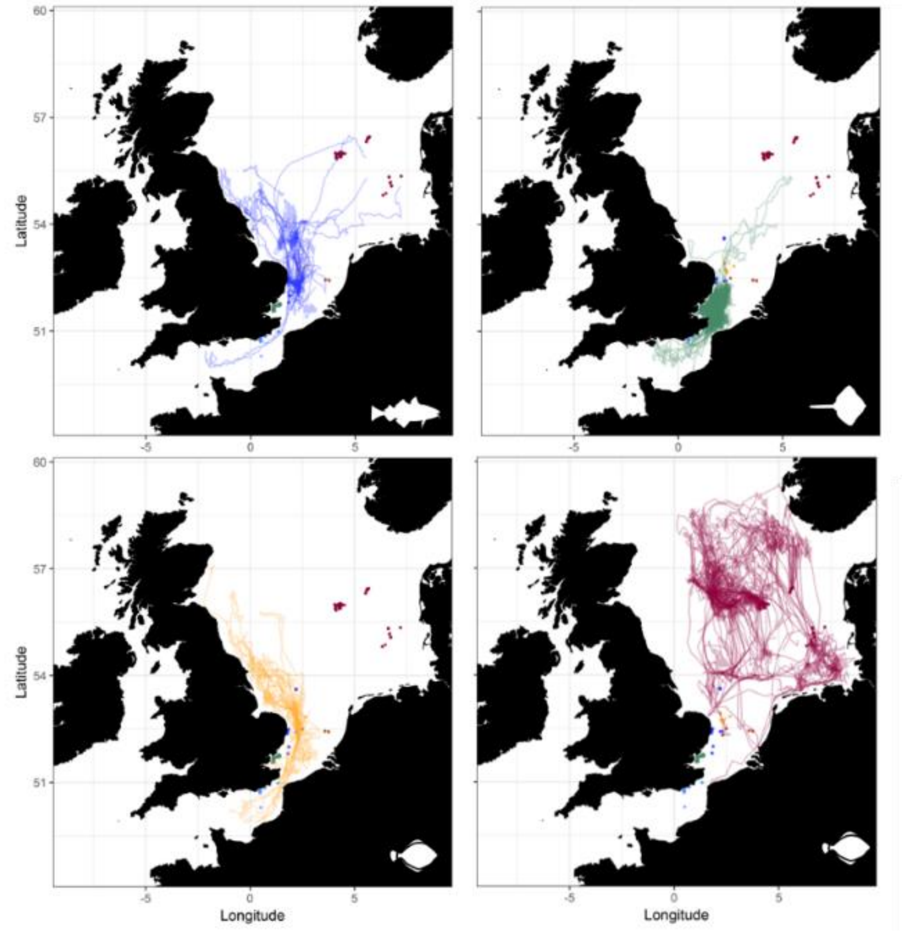

Figure 10. Fish tracks representing the most probable locations constructed using the Hidden Markov Model for individual fish (blue is cod, green is thornback ray, and purple and orange are plaice from two studies with differing release locations).

Individual fish locations were reconstructed using the Hidden Markov Model (HMM) (Pedersen *et al.*, 2011). The HMM uses the maximum depth and tidal signal to estimate the most probable daily location of the fish from release to recapture (Pedersen *et al.*, 2008) based on bathymetry, tidal amplitude, tidal phase and temperature. General Additive Models (GAMs) were used to compare distributions between data collected by fisheries surveys (IBTS) and data collected using data storage tags (DST). The variables included in the analysis included physical spatial data layers of bathymetry, temperature, and sediment (Section 2.1.1), biological parameters including abundance of fish and primary production, and man-made structures. The relationships between the response and predictor variables were assessed using nonlinear smoothing terms. The abundance was modelled using a negative binomial distribution with a log-link function and residuals were investigated for independence, constant variance and any remaining pattern. All DST and IBTS GAMs exceeded the evaluation criteria for predictive power (Spearman's $r_s > 0.1$, $P < 0.05$; and AUC > 0.5, $P < 0.05$), except for two DST models that were excluded from further analysis and interpretation. Overall, GAMs described between 12% and 50% of the variation for DST GAMS and between 3% and 36% of the variation for IBTS GAMs. Initial model fits for DST GAMs were evaluated by analysing the total deviance explained with and without each man-made structure type.

In general, depth and temperature were the most important predictor variables for the DST GAMs, with seasonal changes in the importance of each variable. Wrecks, oil and gas platforms, and cables were all shown to explain variation in the abundance of cod, plaice, and ray (Table 6), with regional differences in abundance linked to spatio-temporal changes in habitat characteristics. Cables were identified as important for all species. The spatial coverage of cables suggests that further work should identify the condition and level of colonisation of cables, for example, whether cables are buried or exposed.

Table 6. Relative importance of different parameters explaining the variation in fish distribution calculated as the proportion of the deviance explained when the predictor variable is removed from the full model. Variables which explained the greatest variation are highlighted in bold and man-made structures which explained the most are denoted as starred entries (*). Positive (POS) and negative (NEG) effects are highlighted in brackets.

			Predictor variable removed					
Species	Group	GAM type	Wrecks	Oil & Gas	Cables	Wind farm	Temperature	Depth
COD	1	Q1	0.00	0.00	0.00	0.00	5.66	**7.04** (NEG)
		Q2	1.73 (NEG)	0.21	5.12* (POS)	0.00	1.67 (POS)	**9.22**
		Q3	0.74	0.10	0.89*	0.00	0.34	**1.77** (POS)
		Q4	0.00	0.00	8.53* (POS)	0.00	**12.37** (NEG)	1.45
PLE	2	Full	0.00	19.64 (POS)	**30.24***(POS)	0.00	19.22	19.40 (POS)
		Q2	3.21 (POS)	10.51 (POS)	**17.68***(POS)	0.00	0.00	2.12 (POS)
		Q3	2.28 (NEG)	0.00	**41.55***(POS)	0.00	-9.70	0.00
		Q4	-1.77	**26.06***(POS)	18.08 (POS)	0.00	-1.77	1.93 (POS)
PLE	3	Full	0.00	0.41 (POS)	2.06*	0.00	0.36	**10.97** (NEG)
		Q1	0.00	0.17 (POS)	2.99*	0.00	0.15	**6.42** (NEG)
		Q2	0.00	0.00	-0.03	0.00	0.73 (NEG)	**17.47** (NEG)
		Q3	0.00	0.00	-6.66	0.00	0.00	**1.34** (NEG)
		Q4	0.00	0.00	4.91*	0.00	0.60 (POS)	**6.61**
THR	4	Full	4.68*	2.76 (POS)	3.48 (POS)	0.00	1.26 (POS)	**7.55**
		Q1	**4.80***(POS)	2.60 (POS)	2.24 (POS)	0.00	2.64 (POS)	4.33
		Q2	**22.22***(POS)	2.90 (NEG)	18.84 (NEG)	0.00	8.00	9.90
		Q3	34.65*(POS)	0.90	13.96	0.00	**39.49** (POS)	13.96
		Q4	7.79*	0.77 (NEG)	2.62 (POS)	0.00	3.95	**9.16** (POS)

This study was one of the first to link fish behaviour to cables, though previous studies have highlighted the importance of cables and pipelines to marine mammals (Russell *et al.* 2014). The significance of predictor terms identified in these models may be indicative of other physical or environmental changes. Therefore, future studies could benefit from additional predictors, such as substratum information (distance to coast and biomass and composition of the benthic community) and environmental layers (including lunar phase, current speeds, wind patterns, depth of mixed layer).

2.4. Quantifying ecological connectivity and the implications of decommissioning

2.4.1. Network analysis

Network analysis is used to understand the properties of a network and is derived from the level of connectedness between individual components. Here, network analysis was used to assess the impact of decommissioning of oil and gas infrastructure on network structure and function in the North Sea. To achieve this, comparisons were made between existing conditions (baseline) and five possible decommissioning scenarios (Table 4), and the impact of different strategies was assessed.

Discrete networks were created to represent connectivity between sectors under the baseline scenario and each decommissioning scenario. The proportion of each sector comprised of hard substrate was taken from processed gridded products (Section 2.1.1) and used as a proxy for community establishment scores. Community connectivity scores were derived from the mean larval dispersal scores across all years and species simulated in the pelagic dispersal modelling (Section 2.2). Network nodes represented 15 x 15 km sectors, with edges representing links between sectors based on larval dispersal weighted to account for the level of connectivity and the likelihood of establishment. Edge weights were calculated by multiplying the community connectivity score from particle tracking modelling (Section 2.2) and the community establishment score.

For the baseline and each decommissioning scenario, network attributes were calculated (Table 7), stylised network plots created, and the location of high functioning nodes shown using spatial network plots. A stochastic network simulator was developed to further investigate and compare connectivity between hard substrate in the North Sea. The simulator tracked movement of an organism from one node (sector) to another based on the weighted networks created for each scenario.

Table 7. Definitions of network attributes calculated.

Property	Definition
Nodes	Entities (e.g. people, groups, organisations, and in this case, North Sea hard substrate sectors) between which connections are being examined
Edges	Connections between nodes
Density	Proportion of total potential connections that are realised
Clustering	Local connectivity in terms of the proportion of nodes connected to a single node that are also connected to each other
Assortativity	Preference for nodes to attach to other similar nodes
In-degree	Number of inward connections to the node
Out-degree	Number of outward connections from the node
Super spreaders	Nodes with many outward connections (out-degree ≥ 50)
Super sinks	Nodes with many outward connections (in-degree ≥ 50)
Hotspots	Nodes with high connectivity (in-degree and out-degree ≥ 50)

An organism was randomly placed on a node (sector) at the start of each simulation and the number of further nodes (sectors) populated over time tracked. Reduction in hard substrate resulting from decommissioning was dependent on the specific scenario (Table 4). Given the location of oil and gas platforms, hard substrate coverage reduced most, and in many cases, was lost, in the central sectors under the decommissioning scenarios 1 to 4, though under decommissioning scenario 5, hard substrate coverage was reduced, or lost, in southern central sectors only.

2.4.2. Impacts of decommissioning on network of hard substrate

There were a total 26,269 edges linking the 625 nodes, indicating that a total of 26,269 links were possible between areas of hard substrate by larval dispersal. The relative reduction in links compared to the baseline scenario was dependent on the specific decommissioning scenario. Edges were reduced to under 10,000 (<38%) under scenarios 1, 2 and 4, to just over 11,000 (42%) under scenario 3.

The least reduction in edges was seen under scenario 5, with 15,084 (57%) remaining (Table 8; Figure 11). A reduced network density and increased clustering coefficient was seen for networks based on all decommissioning scenarios, reflecting a reduction in total connections and distance over which connections are made (Figure 11 to Figure 13). Assortativity was reduced for decommissioning scenarios compared to the baseline scenario, with the greatest reduction for scenario 5, due to the dilution of high functioning nodes (Table 8).

Table 8. Attributes associated with networks based on baseline and decommissioning scenarios 1-5. Note that super spreaders have an out degree ≥50, super sinks have an in degree ≥50 and hotspots are both super spreaders and super sinks. "High funct" represent high functioning nodes and DS decommissioning scenario.

	Property	Baseline	DS 1	DS 2	DS 3	DS 4	DS 5
Network attributes	Nodes	645	645	645	645	645	645
	Edges	26,269	9,919	9,427	11,114	9,203	15,084
	Density	0.06	0.02	0.02	0.03	0.02	0.04
	Clustering coefficient	0.62	0.67	0.67	0.65	0.68	0.65
	Assortativity	0.28	0.17	0.14	0.17	0.14	0.03
Node attributes	degree mean	40.7	15.4	14.6	17.2	14.3	23.4
	In degree median	35	8	4	12	4	24
	In degree min	0	0	0	0	0	0
	In degree max	205	101	91	130	90	186
	Out degree median	37	9	6	14	5	24
	Out degree min	0	0	0	0	0	0
	Out degree max	112	53	53	53	52	72
High funct	Super spreaders	224	9	4	9	2	28
	Super sinks	162	34	32	37	32	53
	hotspots	62	0	0	0	0	4

Node attributes were impacted by removal of oil and gas platforms, with a reduction in both in-degree and out-degree and reduction in high functioning nodes (Table 8). While decommissioning resulted in loss of connectivity, overall it did not result in loss of strength of the remaining connectivity (i.e. edge weights).

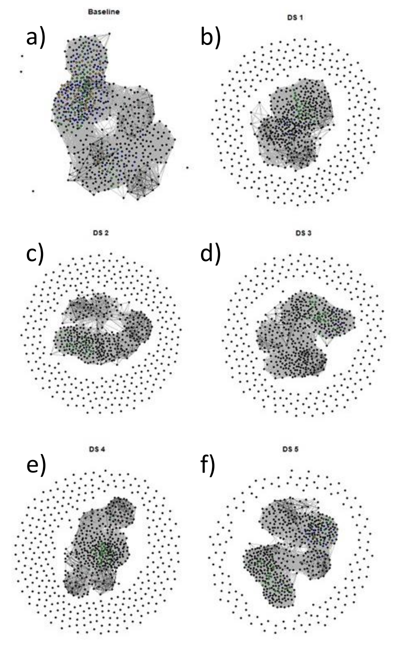

Figure 11. Stylised network plots for the baseline and 5 decommissioning scenarios (a) Baseline; b) DS1; c) DS2; d) DS3; e) DS4; f) DS5).

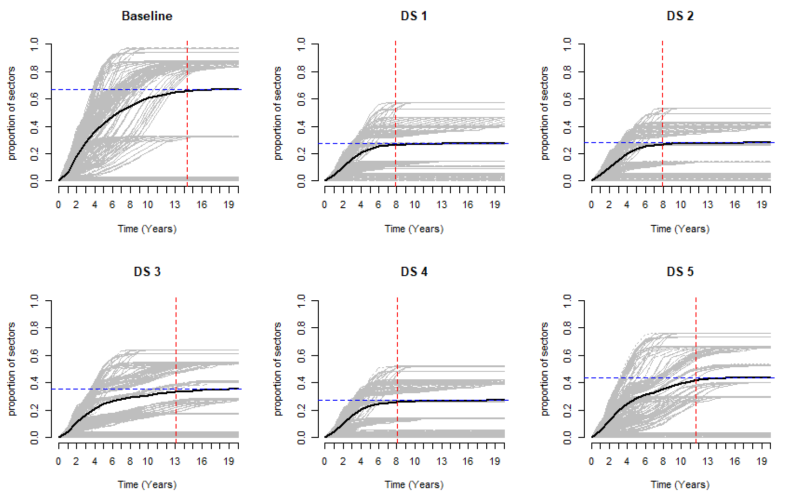

Figure 12. The proportion of nodes featured in the baseline network which a species may travel to over 20 years following establishment at a randomly selected node, based on baseline and 5 decommissioning scenarios. 1,000 simulations were run (grey lines) and means calculated (bold black line). The mean maximum proportion of total nodes and mean time taken to reach a dead-end node (no onward connections) are highlighted by the blue and red lines respectively.

The mean strength of connectivity increased under decommissioning due to removal of low strength nodes and small proportion of hard substrate comprised by individual oil and gas platforms (Table 4). The impact of decommissioning on network structure and function was demonstrated by outputs from the simulator, with fewer sites reached due to loss of connections through removal of oil and gas platforms (Figure 12). The impact of decommissioning on the spatial structure and extent of the network was illustrated, with regions most affected by removal of oil and gas platforms under decommissioning scenarios offshore, where oil and gas platform were often located (Figure 13).

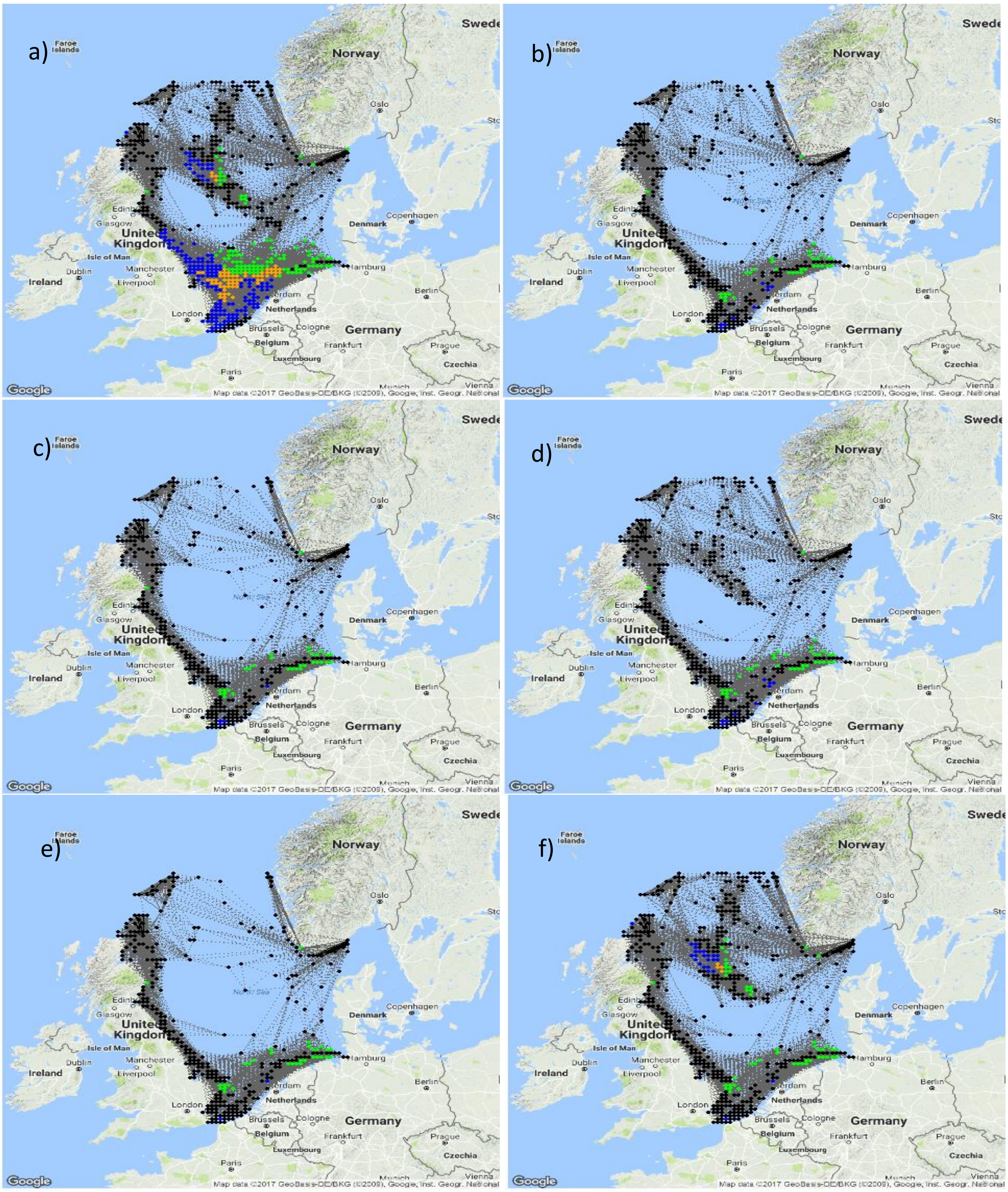

Figure 13. The spatial structure of networks representing baseline (a), and decommissioning scenarios 1 (b), 2, (c), 3 (d), 4 (e), and 5 (f). Network nodes are represented by dots and edges are presented by lines. Blue, green and orange nodes represent super spreaders, super sinks and hotspots respectively.

3. Discussion

EcoConnect aimed to assess the impact of oil and gas decommissioning on the network of hard substrate in the North Sea. To achieve this, connectivity due to pelagic dispersal and mobile predators were investigated and network analysis to assess different decommissioning scenarios conducted. The challenges and potential issues with the data compiled, reviews and reanalysis, and modelling will be addressed in this section. Results are discussed in terms of the impacts of oil and gas decommissioning scenarios on ecological connectivity, delivery against INSITE aims, and suggestions made for the further work needed to underpin oil and gas decommissioning.

3.1. Impact of oil and gas decommissioning on the network of hard substrate

One of the biggest challenges was accessing the data required to underpin the modelling performed within EcoConnect. Compiling and processing data was a significant undertaking as data sets were split across many different sources, collated by different countries, and were not consistent. Hence, many assumptions were necessary to develop consistent gridded products that were used to underpin analyses. Specifically, there were significant data gaps around the characteristics of the individual structures (e.g. size, shape, footprint etc.) that are vital for accurate processing of the size of the oil and gas footprint. This was dealt with by making assumptions about the size of the buffer around different man-made structures which, despite being based on best existing knowledge, will have introduced uncertainty in the outcomes from the modelling. Better information on the characteristics of the structures and the local effects of individual structures, would be beneficial for future studies. In addition, better understanding of the ecological characteristics of the pelagic phase of organisms, the potential for establishment on reaching a structure, the existing communities on structures, and the genetic connectivity between structures, would lead to more robust modelling of decommissioning scenarios. Some information on key species was identified from the literature and limited analysis of existing ROV footage within EcoConnect. However, it is important that future research delivers in-situ studies of the ecological factors and communities on existing oil and gas platforms. This could be done through existing footage captured during regular maintenance or experiments done in collaboration with operators.

Modelling the pelagic phase dispersal of species using particle tracking approaches and individual based models has been used successfully to predict the distribution of many species (e.g. Bartsch and Knust, 1994a,b; Fox *et al.*, 2006; van der Molen et al, 2007; Lacroix *et al.*, 2013; Tiessen *et al.*, 2014; van der Molen *et al.*, 2015). In this case, only a small number of species and years could be simulated using a single hydrodynamic model due to issues with identification of biological parameters and computational burden. Despite this, it was possible to show that sectors had different roles in ecological connectivity, with receivers, conductors, and suppliers identified. The roles differed among species and year, but some patterns were reasonably consistent. The differences were explained by the meteorological forcing of the hydrodynamic model used to estimate current velocity and direction, and the biological behaviour of the larval phases of the species. Structures in the western edge of the central bank were important for connectivity and should be retained, whereas structures on the Norfolk Banks and northwest coast of The Netherlands contained wrecks so were less sensitive to removal of oil and gas structures. It was possible to develop a decision tree for decommissioning of oil and gas platforms based on the function of the sector and proximity to other platforms that could be used on a case-by-case-basis to assess impact of removal of specific infrastructure. There was uncertainty in the predictions from GETM, and comparisons have been made between real data and several physical parameters (see Ford *et al.*, 2017). Several alternate hydrodynamic models were run in other INSITE projects including UNDINE and ANCHoR, so it would be sensible to develop a multi-model ensemble approach for particle tracking to assess the impact of model uncertainty (see Kwiatkowski *et al.*, 2014; Hyder *et al.*, 2015). The effect of thinning of the network also needs further investigation as it was not possible to assess the proportion of structures removed at which the network would cease to function. As man-made structures were small in comparison with natural features and model grid size, it was necessary to make assumptions about spatial footprint of structure types. This increased uncertainty and had implications for model outputs that will vary across spatial scales. In addition to the generation of complex models, simple approaches are needed to communicate the outcomes to a non-specialised audience in order to maximise the uptake of the model outputs (Hyder *et al.*, 2015; Cartwright *et al.*, 2016; Lynam *et al.*, 2016).

Network analysis showed that the combined effect of decommissioning on the overall network structure and the node and edge function, resulted in less community connectivity and reduced network resilience. Generally, decommissioning scenarios that removed more oil and gas structures had a larger impact on the network. Of the five scenarios, the largest contrasts in impact on network structure and function were between baseline (current situation), maximum structure (removal of platforms in southern North Sea), and the other decommissioning approaches (i.e. current regulations, increased derogation, derogation removed, and full removals). This was due to the oil and gas structures comprising of a very small proportion of the total area of hard substrate in the North Sea. The decommissioning scenario which maximised the substrate available had the least impact on the network. Importantly, under this scenario, community establishment and connectivity were maintained in northern central North Sea, an area within which hard substrate was only provided by oil and gas platforms. These results indicated that there was little impact of generic derogations, meaning that location based approaches that focus on the areas identified as important for pelagic connectivity might be more effective in preserving network structure and function.

From the review of interactions with mobile predators, analysis of existing environmental impact assessments to assess the potential effects of decommissioning varied between effects on receptors (e.g. pile cutting, pipeline removal) and impacts (e.g. underwater noise and seabed disturbance), so a standard receptor based approach should be developed by regulators. It was clear that there are ecological impacts associated with the removal of structures, although few were considered significant, so individual bespoke cases could be made for leaving a specific structure in place. Statistical modelling of the interactions between fish and man-made structures highlighted that both physical (e.g. depth) and man-made infrastructure (e.g. cables) influenced distribution, but more data were needed to exclude the influence of other factors that may be important or co-vary with existing variables.

EcoConnect only considered connectivity between areas of hard substrate by larval dispersal and mobile predators. It was possible that other mechanisms of connectivity could occur, for example, connectivity though movement of supply ships. While quantification of additional means of connectivity and additional pathways is not straight forward, extension of the network to include these factors is an important next step. Further work is needed to investigate the results of this study in the context of marine protected areas. The implications of reduced community connectivity between marine protected areas and areas of conservation concern may be important even in less vulnerable areas. The implication of removing oil and gas platforms is likely to depend on the ecosystem associated with the specific platforms that are removed, so further modelling of community structure is also needed. Here, reduced community connectivity was primarily considered to be a negative impact, but a broader consideration of these factors in relation to colonisation by harmful invasive non-native species is needed as reduced connectivity between hard substrate will limit dispersal and reduce impact. In this context therefore, removal of oil and gas platforms through decommissioning, and the reduction in connectivity which will occur, may be considered positive. A cumulative risk-based assessment would be an appropriate way to take both positive and negative impacts into account. While generic assessment of the impact of decommissioning is valuable, consideration of the impact at an individual platform level, with respect to location associated ecosystem, is required to inform a more accurate impact assessment.

3.2. Suggestions for further work

Future work to support oil and gas decommissioning should focus on several key areas. EcoConnect has highlighted the issues with collection and collation of data needed to underpin modelling approaches. This should include working with operators to secure existing data held by industry, reanalysis of existing footage from routine maintenance, experimental studies on establishment, and genetic analysis to provide independent assessments of connectivity between platforms. In addition, it is important to build on the existing data initiative and data compiled by all INSITE projects. This should focus on ensuring storage and access to comprehensive data needed to underpin both further research and EIAs for future decommissioning. Further modelling is needed to improve understanding of fine-scale pelagic connectivity and thinning of the network, and should bring together existing approaches in a multi-model ensemble to account for the uncertainty in pelagic dispersal models. Another potential point of focus could be to start investigating the potential effects of spatially differential mortality of larvae by linking a Dynamic Energy Budget (DEB) model to the particle tracking model, and using results from a biogeochemical model as food fields. Broader network analysis and cumulative risk-based approaches are important to look at the importance of connectivity between oil and gas platforms alongside additional mechanisms for connectivity (e.g. supply ships) and identify approaches that account for both positive benefits and negative impacts of maintaining connectivity. Finally, only the biological importance of oil and gas infrastructure has been addressed, but it is important to assess the social and economic impacts at the same time. To address this, cost-benefit analysis should be done for decommissioning that account for impact on natural capital and ecosystem services, and the costs of monitoring.

3.3. Delivery against INSITE objectives

INSITE was established to generate new research on how the presence of the various man-made structures has influenced the ecosystem of the North Sea. The primary objectives of INSITE were to: assess the effects of man-made structures compared to natural variability; and establish if man-made structures represent a large inter-connected hard substrate system. EcoConnect has delivered novel science focussed primarily on the second INSITE objective around ecological connectivity. EcoConnect has showed the importance of oil and gas infrastructure in pelagic connectivity and provided a decision tree for decommissioning that takes into account impacts on pelagic dispersal. The interactions between man-made structures and mobile predators has been reviewed and the critical interactions during different stages of the life-cycle of platform identified. This also identified infrastructure that appeared to influence distribution of fish in comparison to natural variation, where more research can be targeted. Network analysis demonstrated that decommissioning will impact on the ecological network, but targeted location-based strategies may be more effective in protecting the network than generic derogations.

4. Outreach and products

Several outreach activities and products have been produced by EcoConnect. Outreach has focussed on talks at conferences and the preparation of papers for publication, along with attendance at decommissioning events to drive additional funding. The main product that has been produced is the processed data layers derived from existing data sets (Table 1; Figure 1). Compilation and processing of these data was a significant undertaking and will provide an important base data set for future decommissioning projects. Metadata has been provided to the INSITE data project, so that it can be used to support future studies and assessments.

Several presentations have been made at events and international conferences about EcoConnect including:

- SUT/MASTS Decommissioning & Wreck Removal workshop. Glasgow, UK. 5-6 October 2017.
- ICES Annual Science Conference 2017. Fort Florida, USA. 18-21 September 2017.
- iMarco 3rd Marine Connectivity Conference. Louvain-La-Neuve, Belgium. 11-13 September 2017.
- AMEMR 2017 Advances in Marine Ecosystem Modelling Research. Plymouth, UK. 3-6 July 2017.
- NERC Oil and Gas Decommissioning Brokerage Event. Aberdeen, UK. 5 July 2016.

Five papers will be submitted for publication in peer-reviewed scientific journals based on the research done in EcoConnect. 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.

- van der Molen J, Garcia L, Whomersley P, Callaway A, Posen P, Hyder K (submitted). Modelling connectivity of larval stages of sedentary marine communities between offshore structures in the North Sea. Scientific Reports (a copy of this manuscript has been submitted with this report).
- Randall K, Wright SR, Russell D, Marsden E, Hyder K (in prep.) A review of the influence of man-made structures on fish, seabirds and marine mammals. Marine Pollution Bulletin.
- 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.
- Tidbury H, Taylor N, van der Molen J, Garcia L, Callaway A, Posen P, Hyder K (in prep.). The impact of oil and gas decommissioning on ecological connectivity between hard substrate in the North Sea. Marine Environmental Research.

Applications have been made for additional funding in collaboration with Cranfield through NERC, IFCA studies on spiny lobster, and MPA connectivity. Support from Cefas has been secured for the INSITE II NERC Programme. In addition, links have been built with an Operator of a platform operating in the UKCS to share ROV footage leading to a non-disclosure agreement, and significant efforts have been made to engage with other INSITE projects including MAPS, ANCHOR, UNDINE, RECON, and COSM.

5. Conclusions and recommendations for decommissioning

EcoConnect has delivered novel science that helped to understand the role that man-made structures play in the network of hard structures and the effects of changing the network of hard substrate on structure and function of the North Sea ecosystem. It has helped to deliver the primary INSITE objective to better understand the network of hard substrate. This was done through the use of pelagic dispersal modelling, assessment of use of structures by mobile predators, and network analysis to assess the impact of decommissioning of oil and gas infrastructure on ecological connectivity. A decision tree for the removal of man-made structures has been developed based on the role of structures in pelagic dispersal, and generic decommissioning scenarios have been shown to have little impact on networks of hard substrate meaning that bespoke location based solutions should be investigated. The research has delivered a large data base to underpin future studies and knowledge gaps been highlighted. With these conclusions in mind the key recommendations from EcoConnect with respect to decommissioning are as follows:

1. Platforms can perform different functions with respect to ecological connectivity that vary between species and years. Structures on the western edge of the central bank of the North Sea appear to be important for connectivity, so retention should be considered.
2. Removal of oil and gas infrastructure reduced interconnectivity between hard substrates, but their relatively small area meant that generic derogations made little difference to the impact of decommissioning on the overall network. As a result, bespoke derogations should be considered to maximise the ecological benefits based on the location and function of specific platforms.
3. The data needed to underpin scientific studies of the impact of decommissioning were disparate and inconsistent. New studies should be developed to fill data and knowledge gaps through a mixture of sharing of industry data, reanalysis of existing routine monitoring, ecological experiments, and genetic analyses.
4. Further modelling is required to understand connectivity and impacts of thinning of the network, alongside broader network analysis and cumulative risk assessment to combine additional mechanisms (e.g. supply ships) and account for both positive benefits and negative impacts of connectivity (e.g. ecological connectivity versus spread of non-native species).
5. Cost-benefit analysis of decommissioning that considers the impacts of the different strategies on natural capital and ecosystem services, and includes the costs of post-decommissioning monitoring programmes is needed.

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