PACES, N., DAVIES, A.J. and HASTINGS, A. 2024. Is OSPAR 98/3 science-based politics or politics-based science? *Frontiers in marine science* [online], 11, article number 1264892. Available from: https://doi.org/10.3389/fmars.2024.1264892

Is OSPAR 98/3 science-based politics or politics-based science?

PACES, N., DAVIES, A.J. and HASTINGS, A.

2024

frontiers | Frontiers in Marine Science

TYPE Review
PUBLISHED 19 July 2024
DOI 10.3389/fmars.2024.1264892

OPEN ACCESS

EDITED BY
Theo C. Prins,
Deltares, Netherlands

REVIEWED BY
Thadickal V. Joydas,
King Fahd University of Petroleum and Minerals, Saudi Arabia
David M. Paterson,
University of St Andrews, United Kingdom

*CORRESPONDENCE
Abigail J. Davies
a.davies.1@rgu.ac.uk

RECEIVED 03 November 2023
ACCEPTED 02 July 2024
PUBLISHED 19 July 2024

CITATION
Paces N, Davies AJ and Hastings A (2024) Is OSPAR 98/3 science-based politics or politics-based science?. *Front. Mar. Sci.* 11:1264892.
doi: 10.3389/fmars.2024.1264892

Is OSPAR 98/3 science-based politics or politics-based science?

Nicole Paces[1], Abigail J. Davies[2,3]* and Astley Hastings[4]

[1]MSc Decommissioning programme, University of Aberdeen, Aberdeen, United Kingdom,
[2]The National Decommissioning Centre, University of Aberdeen, Newburgh, United Kingdom,
[3]Aberdeen Business School, Robert Gordon University, Aberdeen, United Kingdom, [4]The School of Biological Sciences, University of Aberdeen, Aberdeen, United Kingdom

Man-made structures in the marine environment such as offshore Oil & Gas infrastructure are known to provide a hard substrate that enables ecosystems to develop on and around them. Current decommissioning practices on the UK Continental Shelf are mandated by the OSPAR Decision 98/3 with the premise of a clean seabed at its core, meaning that it is the expectation that all infrastructure is completely removed at the end of its operation life, leaving a clear seabed behind. This study critically reviewed 49 peer-reviewed articles relating to the ecosystem and the impact to these ecosystems by current removal practices. The results clearly demonstrate that current science-based evidence shows that existing O&G platform substructures act as multipurpose artificial reefs upon which rich ecosystems have developed and that their removal degrades the overall North Sea marine environment. Furthermore, this study shows that clear-sea bed policies, such as OSPAR 98/3, do not reflect, nor understand the complex relationship and interdependencies between biology and man-made structures and do not reflect current scientific knowledge. It is concluded that based on current knowledge, it is no longer scientifically justifiable to mandate the removal of all O&G infrastructure during decommissioning and that applying the principle of a clean seabed according to the OSPAR Commission should be re-considered.

KEYWORDS

OSPAR 98/3, manmade structures, ecosystem, ecology, Oil & Gas, marine, environmental impact

1 Introduction

Offshore decommissioning regulations in the UK are controversial, as evidenced by a recent focus of scientific research programs investigating the impact of man-made structures (MMS) on the marine environment (Birchenough and Degraer, 2020). MMS are emplaced in the marine environment for a number of different purposes by a range of different industries and can include fixed and mobile Oil & Gas (O&G) installations and infrastructure, offshore wind farms (OWF), pipelines and cables, shipwrecks, and fish farms.

Recent research identifying the potential ecological benefits of MMS on the marine environment (Fowler et al., 2020), highlight environmental and political challenges of both decommissioning *in situ* and full removal (Sommer et al., 2019) and list gaps in our understanding and knowledge of MMS ecology (Dannheim et al., 2020; Fortune and Paterson, 2020). It is not the intention of this study to repeat this work, instead, a synopsis of the findings of each of the reviewed articles is presented, and key ecological criteria are identified from within these articles and a qualitative analysis is presented in a 'traffic light system'.

This study focuses on decommissioning of offshore O&G infrastructure located on the UK Continental Shelf in the North Sea where according to OGUK, 2019 36 % of it is expected to be decommissioned and removed by 2028 (OGUK, 2019).

When the operator (owner of the infrastructure) decides to decommission they must seek permission from the UK government and as a requirement of that process an Environmental Impact Assessment (EIA) is required (Department for Business, Energy & Industrial Strategy, 2018). However, because of current policy, the EIAs do not consider the full impact of the removal of MMS on the marine environment (Fortune and Paterson, 2020) and that the clean seabed policy mandated by the OSPAR Decision 98/3 results in biased comparative assessments by not considering the full impact of decommissioning on the marine environment, nor a comprehensive range of decommissioning options, including decommissioning *in situ*.

1.1 Decommissioning in the UK

In 1998 the United Kingdom and Europe introduced the most stringent regional decommissioning framework worldwide (Fam et al., 2018). After the 1995 Brent Spar incident the *OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations* (OSPAR Commission, 1998) became legally binding under the Petroleum Act 1998 as amended by the Energy Acts 2008 and 2016. It generally prohibits *"dumping, and the leaving wholly or partly in place, of disused offshore installations within the maritime area"* of the North Sea. Derogations, such as leaving footings or the complete installation in place, may be permitted by the competent authority of a Contracting Party only for the following types of structures:

- large steel installations weighing more than 10,000 tonnes, installed before 1999.
- gravity-based/floating concrete installations.
- damaged/deteriorated structures.

To qualify for derogation one of these cases must apply and an in-depth comparative assessment must be carried out to demonstrate that the disused O&G installation cannot be re-used, recycled or disposed on land. Currently, only 12 % of the O&G platforms located on the UKCS may qualify for derogation (Oil & Gas Authority, 2020a). All other platforms must be removed to ensure a clean seabed. It has been argued that rigs-to-reefs is a valid method of re-using existing material and creating artificial reefs, however, the *OSPAR Guidelines on Artificial Reefs in relation to Living Marine Resources* (OSPAR Commission, 2012) demand artificial reefs to be built from inert, virgin materials. Hence, the guidelines exclude any type of rigs-to-reefs model in the North Sea. An in-depth analysis (Jørgensen, 2012) of the development process of these guidelines indicated that the Contracting Parties originally intended to find suitable ways of using O&G installations as artificial reefs. However, due to the Brent Spar controversy, many of the Contracting Parties argued that the rigs-to-reefs alternative would be mistakenly considered as dumping at sea by the general public and the environmental NGOs (Jørgensen, 2012). Without consulting the scientific community all Contracting Parties except for Norway decided to ban rigs-to-reefs in the North Sea in order to avoid any further public debates and protests.

Following the long history of decommissioning in the U.S. Gulf of Mexico (Kaiser and Pulsipher, 2005), UK was the second country to enter the decommissioning market at scale (Wood, 2018). The North Sea Transition Authority (NSTA) (previously the Oil & Gas Authority (2020b)) estimate the overall decommissioning expenditure for the UKCS will be £44.5 billion, the cost of which will be met by the operators (60%) and the UK tax payers (40%) through tax relief (National Audit Office, 2019). These figures include various decommissioning activities but are dominated by well plug and abandonment (P&A) and the complete removal of the O&G installations (subsea, floating, and fixed structures).

According to Oil & Gas UK (OGUK, 2019) £15.2 billion is forecast to be spent on decommissioning in the North Sea over the next decade. Furthermore, OGUK calculates that approximately 20 % of these decommissioning costs will be used for the removal and onshore disposal of more than 100 platforms, topsides and substructures. Depending on the region the topsides removal may be marginally more expensive than substructure removal. This equates to an estimate of £1.4 billion to be spent over the next ten years; just for substructures' decommissioning. In total, it will cost between £4 billion and £5 billion to fully remove the 306 substructures that are currently installed UKCS platforms (steel only) (OGUK, 2019).

1.2 Clean seabed or protection

The ecosystems of the North Sea have been significantly impacted by human activities such as fishing, environmental pollution, greenhouse gas (GHG) emissions, increase of sea temperature due to climate change, sand, oil and gas extraction as well as introduction of wind farms, shipwrecks and shipping (Halpern et al., 2008; Lindeboom et al., 2011). This altered ecosystem led some scientists (Schläppy and Hobbs, 2019; van Elden et al., 2019) to adopt the "novel" ecosystem approach, which acknowledges the functions and services of a new ecosystem that is formed by the presence of MMS. Some scientists argue that instead of hoping that the ecosystem will be restored to its 'original' environmental baseline without human intervention (Ounanian et al., 2019), we could start to accept the new state of the ecosystem and try to restore it pro-actively and appropriately (Macreadie et al., 2011; Fowler et al., 2018). Furthermore, the evidence for this 'original' environmental baseline is completely absent. Decommissioning *in situ* (leaving the platform substructure in place) can be seen as active marine restoration and an investment in the future to be evaluated on an unbiased case-by-case basis (Ekins et al., 2006; Fowler et al., 2014).

In the rigs-to-reefs model used in the U.S. Gulf of Mexico for example, 50 % of the savings made by reefing rather than full removal must be paid by the O&G operators to the artificial reef fund (Scarborough Bull and Love, 2019). Liability for the structure is transferred to the state, which is then responsible for maintenance and monitoring. This model could be adapted and incorporated into the Maximise Economic Recovery (MER) strategy as a life extension option of O&G installations in the North Sea (Falcone, 2020).

From a marine spatial planning perspective, one might argue that a clean seabed is the preferred choice to reopen the sea to other users such as fisheries. However, the 500 m safety zones around the 1350 O&G installations in the North Sea (OSPAR Commission, 2017) only represents a maximum of 0.1 % of the total North Sea area (Fowler et al., 2020), in comparison, the Marine Protected Areas (MPA) cover 18.6 % (OSPAR Commission, 2019b).

1.3 Marine protected areas

The main goals of both OSPAR and the EU are protection of key threatened and/or declining species and natural habitats, conservation and restoration of natural ecosystems and enhancement of biodiversity in the maritime area (OSPAR Commission, 2019a) and EU protected Reef Habitats (European Environment Agency, 2013). To secure these goals, Marine Protected Areas were established over the last two decades. O&G installations were historically awarded licenses in MPAs and therefore MMS exit in these areas. Supplementary Figure 1 illustrates all designated OSPAR MPAs (OSPAR Commission, 2019a) and EU protected Reef Habitats (European Environment Agency, 2013) in which UKCS platforms are located. Most of these MPAs were designated after the platforms' installation and that is why currently more than 50 % of all UKCS platforms (152 in total) are located either in designated OSPAR MPAs or 1170-Reefs Habitats. No specific guidance is provided on how to address the challenge of decommissioning platforms located in these areas. Hence, 16 out of 21 platforms located in a MPA with "not in use" status have not yet been removed.

Some researchers have developed comprehensive decision-making tools for decommissioning the infrastructure in MPAs, for example Burdon et al. (2018) but all are based on full removal and therefore do not compare the other options such as decommissioning *in situ*.

1.4 Protected marine species and MMS

The cold-water coral *Desmophyllum pertusum* (previously named *Lophelia pertusa* and named as such in the 49 articles reviewed for this study but will be referred to as *D. pertusum from* here), is a protected and endangered marine species. It is found in many locations throughout the North East Atlantic region and although it may be a protected species, there is no legal requirement for it to be protected if it is found on an O&G MMS.

On both the Murchison (CNR International, 2013) and Ninian North (CNR International, 2016) platforms. *D. pertusum* colonies were found on the steel jackets, which was highlighted in the EIA. The Joint Nature Conservation Committee (JNCC), the public body that advises the government and is required to assess the EIAs as part of the statutory decommissioning regulations, advised that because the *D. pertusum* colonies would not have occurred without the presence of the platforms, the mortality of the protected cold-water coral because of decommissioning operations would not be considered as an issue of significant concern.

In the case of the decommissioning of the Brent Delta (Shell U.K. Limited, 2017) and Dunlin Alpha (Fairfield Energy Limited, 2019) platforms *D. pertusum* colonies were found on both and *Arctica islandia* (ocean quahog) was observed near Dunlin. The EIAs, however, concluded that it was not deemed necessary to take any measures to protect these rare and threatened species during the decommissioning.

In all these examples derogations were allowed, but the basis for these decisions were not due to species and thereby environmental protection.

1.5 Ecological benefits of MMS

According to Fabi (2015) artificial reefs are human built structures that actively enhance and/or recover natural habitats, raise productivity and manage marine resources and can serve many other purposes. In the North Sea an offshore artificial reef should achieve at least one of the following objectives: 1) provide new hard substrate for sessile invertebrates; 2) provide shelter for juvenile and mature motile invertebrates; 3) restore depleted habitats and mitigate habitat loss; 4) enable growth and reproduction of rare, threatened and commercially important species and habitats; 5) enhance biodiversity; 6) protect sensitive habitats from fishing activities; 7) create potential networks of MPAs to manage connectivity and species' life cycle; 8) enable research and educational activities.

While demonstrating which of these objectives are generally met by an existing O&G reef, it is also important to identify any uncertainties and knowledge gaps. This will further help in concluding whether there is enough science-based evidence available to enable an unbiased comparative assessment of different options for decommissioning platform substructures. Based on Fowler et al. (2014), a distinction is made between the following *in situ* and full removal options for decommissioning:

- Full removal: transport complete substructure to shore and re-use or re-cycle.
- "Leaving intact": remove topsides and leave complete substructure in place (add navigational aid).
- "Topping": cut top section and either transport to shore or deploy next to structure (cutting depth requirement is the IMO free draught of minimum 25 m following the examination of Fowler, Jørgensen and Coolen et al.

(2020) or 55 m following the Department for Business, Energy & Industrial Strategy guidelines).
- "Toppling": topple whole structure in place.

Reefing of the structure in a designated area will not be discussed further in this study as no research data are available to evaluate this option in detail for the North Sea.

2 Evaluation methodology

In total, 49 peer-reviewed articles were examined in depth and the most important data were extracted, see Table 1. More than 50% of the research articles are from 2018 to 2020. A slight bias towards the Southern North Sea can be observed.The most comprehensive research review study conducted by Fowler et al. (2020) was further used as guidance for the qualitative critical-analysis. The study outlines five key ecological considerations when undertaking decommissioning assessments: *1) provision of reef habitat; 2) productivity of offshore ecosystems; 3) enhancement of biodiversity; 4) protection of the seabed from trawling; 5) enhancement of connectivity*. The main criteria related to each of the ecological considerations were then used to qualitatively evaluate the literature findings. In addition, a colour-coded traffic light system was introduced to highlight the current state of knowledge:

- Green: Mature, science-based evidence is available. The findings are statistically significant and are confirmed by other studies.
- Gray: Immature early research studies and simulation-based evidence available. The results suggest a trend, but extensive validation is lacking.
- Red: No science-based evidence available.

For the final presentation of the evaluation results the average of the knowledge status of the respective criteria related to the five key consideration was determined by reflecting this in the colour and its brightness. The stronger the green colour, the more mature, science-based evidence is available. The lighter the green colour, the less science-based evidence is available. If the criteria is marked as green, the current research knowledge status can be considered as mostly mature, science-based evidence. However, if the criteria are marked as gray, only immature research is available. If a criterion is red, then no science-based evidence is available. The red brightness scale is to be interpreted inverted to the green scale.

3 Results

More than 50 % of the research studies examined in depth were conducted between 2018 and 2020. This strong interest is due to the fact that environmental scientists identified a potential ecological value in leaving O&G structures partly or fully in place (Fowler et al., 2018; Fortune and Paterson, 2020). That is why it is important to understand the current knowledge status and highlight the remaining knowledge gaps before the O&G structures are finally removed (OGUK, 2019). Time is pressing and changing regulatory frameworks and legislation takes a while as seen in the past in California (Scarborough Bull and Love, 2019). It can take 10 years until the research work is completed (see *INSITE Programme – Phase 2*), all stakeholders involved are coordinated (Shaw et al., 2018; Tung, 2020) and finally the political consensus to update OSPAR Decision 98/3 was found. Past experience has shown that aligning the OSPAR Parties could be the especially difficult (Jørgensen, 2012). However, many research initiatives gained considerable momentum worldwide (McLean et al., 2020), therefore further research should be supported and access granted to the not yet freely accessible but available extensive environmental data (Macreadie et al., 2018; Murray et al., 2018) in order to close the remaining knowledge gaps.

In the next sections the traffic light rating results of the current knowledge status are presented, organised by the ecological considerations identified by Fowler et al. (2020): *3.1) provision of reef habitat; 3.2) productivity of offshore ecosystems; 3.3) enhancement of biodiversity; 3.4) protection of the seabed from trawling; 3.5) enhancement of connectivity*.

3.1 Provision of reef habitat

Refer to Tables 2 and 3.

3.2 Productivity of offshore ecosystems

Refer to Table 4.

3.3 Enhancement of biodiversity

Refer to Tables 5 and 6.

TABLE 1 Summary of parameters for data extraction of the peer-reviewed articles.

Receptor	No. articles	Meta data	Community ecology	Findings/effects
Seabed Benthos Fish Mammals Fisheries	9 12 12 6 3	Key species Location Max. depth Substrate type Sampling method Sampling period Data analysis Food web	Abundance Richness Biodiversity Detection (first records) Biomass Recover/reproduction Dispersal Disturbance	Species characteristics Water depth Substrate material Substrate type Location Interconnectivity Spatio-temporal

TABLE 2 Provision of reef habitat (part 1): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
O&G reef vs. natural reef	• O&G reefs provide the same kind of habitat as natural reefs (hard substrate). The same benthic communities are significantly abundant on both reefs except for *M. edulis* and *J. herdmani* which are not normally found far offshore on natural reefs.	Supplementary Table 7
	• The habitat provided by deeper sections of O&G reefs is more like the habitat of natural reefs than that of shallower O&G sections, where *M. edulis* and *J. herdmani* are abundant.	Supplementary Table 7
	• O&G reefs provide fish with the same good quality prey as natural reefs, as compositional analysis shows. However, the prey species may slightly differ from open water supply.	Supplementary Table 11
O&G reef vs. other artificial reefs	• O&G: reefs made of concrete and steel provide the same kind of habitat, as the same benthic species communities are significantly abundant on both structure materials. However, the reef habitat of mobile units differs from that of fixed structures, as different sessile invertebrate species are found there.	Supplementary Table 7
	• OWF: mature O&G and young OWF reefs, both located in Southern North Sea, provide the same kind of habitat, as the same benthic species and fish communities are significantly abundant on both structure types. Within the OWF reefs the edible crab prefers rocky scour protection of a monopile more than a tripod type of jacket structure. Due to the areal footprint grey and common seals prefer OWF structures and pipelines for foraging over O&G platforms.	Supplementary Tables 7, 14
	• Wrecks: research indicates that O&G reefs and wrecks provide different types of habitats, as not the same benthic species and fish communities are found on these reefs, e.g. *C. smithii* prefers pipelines and O&G structures, but has only been detected once at a wreck.	Supplementary Tables 4, 5, 14
Ecologically or commercially important species	O&G reefs provide habitat for many different species:	
	• Benthic fauna: *M. edulis*, other Mollusca, Cnidaria, Echinodermata, tube-building Amphipods and crabs showing most significant abundance on O&G/OWF.	Supplementary Table 4 and 5
	• Fish: Atlantic cod, Pouting, Saithe, European plaice showing most significant abundance at O&G/OWF. Flat fish species and Whiting are also regularly sighted near the structures, but their density increases with distance to the structures.	Supplementary Table 11
	• Mammals: Harbour porpoise showing the highest abundance of mammals at/near O&G, but also Minke, Killer, and Pilot whales are significantly abundant.	Supplementary Table 16
Non-native or invasive species	• O&G reefs provide habitat for a low percentage of non-native or invasive species.	Supplementary Table 4
	• Non-native or invasive benthic fauna are predominantly found in the intertidal zone on O&G/OWF, if abundant.	Supplementary Table 4
	• Non-native or invasive benthic fauna also use other reefs than O&G/OWF: *C. smithii* normally lives at O&G/pipelines using wrecks as steppingstones; *C. mutica* uses near-shore reefs as habitat while *C. linearis* prefers offshore structures (co-existing possible); *M. leidyi* only appears on O&G in summer months due to higher sea temperature.	Supplementary Table 4

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red).

TABLE 3 Provision of reef habitat (part 2): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
	O&G reefs not only provide habitat for rare and threatened species, but also support the self-restoration of biogenic reefs:	
Rare and/or threatened species	• Relict populations of *O. edulis* found on O&G/OWF showing potential to form self-sustaining reefs.	Supplementary Table 4
	• Massive populations of M. edulis abundant on shallower parts of O&G/OWF, although not naturally found offshore. "*Mytilusation*": through biomass export, shells form natural beds.	Supplementary Table 4
	• Colonies of *L. pertusa* found on O&G showing strong potential to form self-sustaining reefs.	Supplementary Table 5
	• Atlantic cod shows significant abundance at O&G/OWF using the reefs for foraging, e.g. *Jassa* spp. as prey.	Supplementary Table 11
	• Harbour porpoise showing high abundance at/near O&G especially during night. However, it remains unclear whether they use the reef for certain activities such as foraging.	Supplementary Table 16
Impact on soft-bottom ecosystems	• The installation of O&G/OWF increases the abundance of fish assemblages in the short term, but does not show any significant effects in the long term. However, the richness of benthic fauna increases with community age.	Supplementary Tables 9, 13
	• Klunder et al. (2020) indicate that O&G have an impact on the local carbon cycling, while Reeds et al. (2018) observes a local ecological halo effect around the O&G.	See research studies
Impact of decom-missioning options	• Full removal of O&G will clearly result in complete loss of reef habitat for benthic and fish species communities as discussed above.	Supplementary Table 1
	• "Leaving intact" of O&G substructure will provide full reef habitat functions as discussed above.	Supplementary Table 1
	Partial removal of O&G has different impacts depending on the selected option ("topping" vs. "toppling"), as the benthic and fish species are very sensitive to depth:	
	• Due to the buildup of vertical zonation on O&G, all partial removal options result in the loss of reef habitat in the intertidal and infralittoral zones meaning that not only the non-native and invasive species will lose their habitat, but also the Blue mussel *M. edulis* and the European Flat Oyster *O. edulis* (if abundant).	Supplementary Tables 6, 9
	• Depending on the platform and cutting depth the reef habitat of the circalittoral zone including the tube-building Amphipods *Jassa* spp. may be partly or fully removed. Shallower platforms in the SNS have tight depth bands with richness peaks at intermediate depths and are therefore sensitive to the cutting depth. Toppling may be technical unfeasible in shallower water.	Supplementary Table 6
	• Motile invertebrates and Cnidarians are predominantly abundant in the epi-benthic zone near the bottom. These species together with the cold-water coral *L pertusa*, which is found in deeper waters in the NNS, may not significantly affected by neither of the both partial removal options, only by disturbance.	Supplementary Tables 5, 6
	• Pelagic fish living mid-depth to surface will certainly lose their habitat including shelter and prey. Benthopelagic fish such as Atlantic cod and Saithe, which live in the bottom zone but also look for prey in the upper zones (according to their food web), may lose interest in the remaining cut-off habitat.	Supplementary Tables 11, 12

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red).

TABLE 4 Productivity of offshore ecosystems: Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Sessile invertebrates	• Significant biomass of *M. edulis, M. senile* and other types of Mollusca and Cnidaria is produced on O&G/OWF.	Supplementary Tables 4, 5
Motile invertebrates	• Echinodermata, tube-building Amphipods and crabs show significant abundance and high richness on O&G.	Supplementary Tables 4, 5
	• *J. herdmani* develops distinct genetic populations on O&G/OWF that hardly show any inter-connectivity of structures.	Supplementary Table 8
Behaviour of important fish species for fisheries	• Atlantic cod shows high residency and site fidelity towards O&G/OWF.	Supplementary Table 11
	• Atlantic cod and Saithe use the O&G reef for foraging. Atlantic cod *prefers Jassa* spp., while Saithe prefers Euphausiacea as prey that is different from the prey available at open water.	Supplementary Table 11
	• Atlantic cod shows larger body size at O&G/OWF than in the surrounding soft-bottom ecosystem.	Supplementary Table 14
Reproduction & nursery grounds	O&G reefs provide potential nursery and spawning grounds, and give coral reefs the possibility to reproduce. Observations so far include the following:	
	• The crab *C. pagurus* use OWF as nursery grounds. • Egg masses of the whelk *B. undatum* were found on O&G.	Supplementary Table 4
	• The Lumpsucker fish broods its eggs on O&G. • Juveniles of Atlantic cod were spotted at O&G.	Supplementary Table 11
	• Conflict of interest: Simulation models show a potential overlap between spawning grounds of flatfish species and future OWF sites. Flatfishes are not significantly attracted by OWF, hence an increase of these structures may result in a decrease in reproduction or displacement of flatfishes.	Supplementary Table 14
	• *L. pertusa* has strong potential to form cold-water coral reefs on O&G, particularly in the NNS. This is confirmed by various industry studies, e.g. Shell identified a total of 199 *L. pertusa* colonies on Brent D and is complemented by extensive simulation models that show the potential of highly interconnected coral ecosystem networks.	Supplementary Tables 5, 7, 8, (Shell U.K. Limited, 2017)
Local growth rate	• The growth rate of benthic fauna species on O&G/OWF and its biomass production and export rate are well studied and vary seasonally.	Supplementary Tables 4, 9
	• O&G provide fish with good quality prey and therefore larger than usual Atlantic cod fish are observed at O&G/OWF, but overall growth rates for different fish species are not available.	Supplementary Tables 11 14
	• There is no distinct science-based evidence of growth rates of mammals related to O&G reefs.	n.a.
	• Comparative data on local growth rates between O&G reefs and other artificial or natural reefs are not available.	n.a.
Regional total productivity	• Direct measures of ecosystem productivity are lacking for O&G/OWF, therefore no regional total productivity is available for fishery-important species.	n.a.

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red). n.a., Not available.

3.4 Enhancement of connectivity

Refer to Table 7.

3.5 Protection of the seabed from trawling

Refer to Table 8 and 9.

3.6 Traffic light rating of qualitative analysis

Table 10 presents the traffic light rating results of the qualitative analysis. As the evaluation results highlight, the traffic lights for the key ecological considerations are predominantly showing green. This means that in general the current research knowledge status can be considered as mostly mature, science-based evidence. In detail, it can be seen that more mature, science-based evidence is available for proving that O&G reefs provide reef habitat and enhance biodiversity. Less mature science-based evidence is available for showing that O&G reefs protect the seabed from trawling, enhance the inter-connectivity of hard substrate for larval dispersal, and are productive offshore ecosystems.

When examining the main criteria related to the key ecological considerations, it can be seen that not all of them are highlighted in green and the knowledge gaps have been identified and are discussed as follows.

Only immature research data was available to assess the effectiveness of protecting rare and/or threatened species from trawling. It is evident that benthic fauna species and habitats such as European Flat Oyster *O. edulis* beds (Kerckhof et al., 2018), cold-water coral *D. pertusum (L. pertusa)* reefs (Bergmark and Jørgensen, 2014; Henry et al., 2018) and deep-sea sponge *Porifera* spp. (Gates et al., 2019; Vad et al., 2020) aggregations are actively protected by the O&G reef from trawling, however, it is not evident if certain fish species or marine mammals are effectively protected from trawling. Furthermore, only immature research data are available to determine the fishing results near the O&G reefs at the boundaries of the exclusion zones (Reubens et al., 2013; Rouse et al., 2020).

It is evident that non-native or invasive species use hard substrate such as O&G reefs as stepping-stones (Coolen et al., 2016, 2018, 2020) to disperse. However, the exact larval dispersal mechanism and the extent to which O&G reefs contribute to their inter-connectivity has not yet been determined.

Due to the complexity, growth rates, especially of mobile species in connection with O&G reefs, are difficult to measure and are therefore lacking. For this reason, the overall productivity of O&G reefs and thus their impact cannot be determined on a regional basis.

The qualitative analysis shows that the knowledge status on the impact of MMS on the marine environment can be considered as mostly mature, science-based evidence, however, some knowledge gaps have been identified. In order to determine if the current knowledge status is sufficient to conduct an unbiased comparative assessment and decide whether to remove or not to remove the O&G structures, the main evaluation criteria need to be critically assessed (Martins et al., 2020). For example, are all criteria relevant generally or do they need to be adapted on a case by case basis? Do all identified knowledge gaps need to be closed before conducting a comparative assessment? These questions should be answered by stakeholder collaboration (Tung, 2020) and an integrated scientific team as suggested by Shaw et al. (2018) in order to avoid a Brent Spar 2.0 (Side, 1997). Meanwhile, Fowler et al. (2020) recommend temporarily suspension of the mandatory removal of the O&G structures. The decommissioning community is currently undergoing a paradigm shift and until now, the knowledge gaps mandated the precautionary principle (OSPAR Commission, 1992) of full removal. However, scientific evidence may soon be available that will allow assessments on a case by case basis, so that the application of the precautionary principle will become obsolete.

3.7 Main features of O&G reefs

Tables 2, 3 clearly demonstrate that O&G reefs provide the same excellent reef habitat for benthic fauna, fish and marine mammals as natural and other artificial reefs. However, it should be noted that they also provide habitat to species that are not normally found far offshore, such as *M. edulis* and *J. herdmani*. Furthermore, rare and/or threatened species such as the cold-water coral *D. pertusum* colonise O&G reefs and the overfished Atlantic cod resides there.

Table 4 shows that O&G reefs significantly produce biomass of sessile and motile invertebrates and larger body sizes of Atlantic cods have been observed. Furthermore, O&G reefs serve as reproduction and nursery grounds especially for the edible crab, but also for rarer species such as the whelk *B. undatum* and the lumpsucker fish. A total of 199 *D. pertusum* colonies have been identified on Brent D in 2008 (Shell U.K. Limited, 2017), 30 years after start-up. Only the total productivity of mobile species at a local and regional level has not yet been determined.

Tables 5–7 highlight that not only is the local biodiversity significantly increased by O&G reefs, but also that regional biodiversity can be enhanced. This is achieved by inter-connectivity of hard substrates through larval dispersion. The physical parameter that most affects biodiversity is water depth. The material and type of substrate seem to play a less important role when it comes to species abundance and richness.

Tables 8, 9 present that especially rare and/or threatened benthic fauna species colonising a O&G reef are actively and effectively protected from trawling. Since bottom trawling is the number one cause of physical disturbance to the seabed, it is expected that each exclusion zone, although very small compared to the entire North Sea, will help protect valuable ecosystems (Fowler et al., 2018).

In conclusion, the study clearly demonstrates that O&G reefs act as artificial reefs according to the definition of Fabi (2015).

3.8 O&G reefs to be protected?

Tables 3, 6 and 9 highlight that different decommissioning options will have different impacts on the O&G reef habitat and fisheries.

TABLE 5 Enhancement of biodiversity (part 1): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Physical and environmental impacts	• Water depth: The species richness of sessile invertebrates definitely shows a buildup of vertical zonation. The distribution is non-linear with the peak at intermediate depths or in the bottom zone. Motile invertebrates show highest species richness in the bottom zone.	Supplementary Table 6
	• Substrate material/type: Structures made of concrete could increase the species richness and biodiversity of benthic fauna locally. However, studies did not observe significant differentiation between rock and steel.	Supplementary Table 7
	• Design: Compared to laid pipelines, trenching significantly decreases the species richness of benthic fauna and Whiting and increases other fish species' richness.	Supplementary Tables 9, 13
	• Time: Species richness of benthic fauna increases with community age.	Supplementary Table 9
Regional impacts	• When comparing O&G reefs located in the CNS and SNS, significant clustering in benthic communities was observed. Species abundance is higher in CNS than in SNS.	Supplementary Table 8
	• More data sets are available for the SNS than for the CNS and NNS regions, therefore only indicative conclusions can be drawn.	Supplementary Tables 2, 3
O&G reef vs. natural reef	• In general, no great differentiation in species richness between artificial and natural hard substrates are reported.	Supplementary Table 7
Trade-offs: O&G reef vs. soft-bottom ecosystem	• O&G/OWF reefs significantly enhance the local biodiversity of benthic fauna and fish species compared to its surrounding soft-bottom ecosystem. Concrete O&G reefs can also host unique benthic communities (+ 23%) compared to natural reefs located in close proximity.	Supplementary Tables 7, 14
	• First records in the SNS of obligate hard substrate fish species such as Goldsinny wrasse and Grey triggerfish underline the attractiveness and biodiversity potential of O&G/OWF reefs.	Supplementary Table 11
O&G reef vs. other artificial reefs	• OWF: Neither significant differences in species richness between old O&G and young OWF nor between rock (scour protection of OWF) and O&G steel reefs are reported.	Supplementary Table 7 and 9
	• Wrecks: Much more different fish species are observed at OWF than at wrecks indicating that wrecks have less biodiversity than OWF and O&G structures.	Supplementary Table 11
Local vs. regional biodiversity	• Various studies clearly show that benthic fauna such as *M. edulis* use artificial structures as stepping-stones to spread out into areas that they otherwise could not reach.	Supplementary Table 8
	• Simulations indicate that all different types of hard substrates (artificial and natural) are highly interconnected through larval dispersal. Especially O&G reefs contribute to the distribution of *L. pertusa*, Echinodermata and *Porifera* spp.	Supplementary Table 8

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red).

TABLE 6 Enhancement of biodiversity (part 2): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Impact of decom-missioning options	• Full removal of O&G will clearly result in the loss of local biodiversity	Table 1
	• Full removal of O&G may also result in the decrease of regional biodiversity due to the loss of connectivity between hard substrates. Simulations predict 60% reduction in connectivity.	Supplementary Table 8
	• There is no clear evidence that the soft-bottom ecosystem in the North Sea could fully recover after full removal of O&G.	
	• If "leaving intact" the O&G substructure, neither the local nor the potential for improving regional biodiversity will change.	Tables 1, 10
	• Partial removal of O&G result in the reduction of local biodiversity. Due to the buildup of vertical zonation, both removal options "topping" vs. "toppling" result in the loss of the upper zones including M. edulis	Supplementary Table 6
	• Partial removal of O&G may also result in the reduction of regional biodiversity due to the loss of connectivity between hard substrates. However, simulations indicate that benthic species living in deeper sections or in the bottom zone such as *L. pertusa*, Echinodermata and *Porifera* spp. may stay connected through larval dispersal using the remaining parts of O&G as stepping-stones. Vertical extension of reef habitat by "toppling" in place or "topping and deploy top next to structure" may even enhance the epi-benthic biodiversity and connectivity.	Supplementary Table 8

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red).

TABLE 7 Enhancement of connectivity: Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Connectivity through larval dispersal	• Various studies clearly highlight that benthic fauna use different types of structures incl. O&G reefs as stepping-stones to spread out into areas that they otherwise could not reach.	Supplementary Table 8
	• Simulations show that all different types of anthropogenic (e.g. O&G, OWF, wrecks, buoys, pipelines, etc.) and natural hard substrates are interconnected.	Supplementary Table 8
	• Simulations underline that O&G reefs in the CNS and NNS contribute to the distribution of benthic fauna through larval dispersal. Note that not all of the simulations are yet validated against real data.	Supplementary Table 8
Larval dispersal mechanism	• *J. herdmani* develops distinct genetic populations on O&G/OWF that hardly show any inter-connectivity of structures. It is assumed that structures get populated by populations from the surrounding ecosystem that date back to the time of the glaciers and not from neighbouring structures.	Supplementary Table 4
	• Genetic taxa data show that M. edulis can spread over 181 km offshore, whereas the current models predict locations greater than 85 km offshore to be isolated from coastal communities.	Supplementary Table 8
Rare and/or threatened species	• Studies and simulations show that *L. pertusa* form highly interconnected coral ecosystem networks and that the deep-sea sponge *Porifera* spp. uses the O&G structure as stepping-stone to settle down in the surrounding seabed.	Supplementary Table 8
Non-native or invasive species	• Non-native or invasive benthic species use hard substrate as stepping-stones and are found in the intertidal zone.	Supplementary Table 4
	• No connectivity simulations of non-native or invasive benthic species are available. No studies of larval dispersal and mechanism available.	n.a.
Impact of decom-missioning options	• Full Removal: evaluation see Table 4	Supplementary Table 8
	• "Leaving intact": evaluation see Table 4	Supplementary Table 8
	• Partial Removal: evaluation see Table 4	Supplementary Table 8

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red). n.a., Not available.

TABLE 8 Protection from trawling (part 1): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Protected vs. non-protected seabed	• As a result of the compulsory exclusion zone of 500 m established around O&G, roughly 0.1% of the North Sea area is currently protected from fishing activities. Estimates of future OWF exclusion zones lead to a similar result as for O&G.	Supplementary Table 17
	• Further 18.6% of the North Sea area are covered by designated Marine Protected Areas reducing the fishing pressure.	
	• More than 50% of all UKCS platforms are located either in designated OSPAR MPAs or 1170-Reefs Habitats.	Supplementary Figure 1
	• Bottom trawling is the leading cause of physical disturbance to the seabed. Any type of disturbance has a significant impact on the benthic habitat and associated fish assemblages.	Supplementary Table 9
	• Due to the development of a local ecosystem around the O&G, which provides reef habitat and improves biodiversity and productivity, it is assumed that the soft-bottom ecosystem within the undisturbed exclusion zone is in equilibrium and is different from the disturbed, unprotected zone. This unprotected ecosystem has to be constantly re-established and calibrated in order to function properly	Supplementary Tables 2–6
	• Comparative data on the status of soft-bottom ecosystems in the exclusion zones, MPAs and other areas are not available.	n.a.
Ecologically or commercially important species	• Direct measures of the biomass of the benthic fauna within the protected exclusion are available.	Supplementary Tables 4, 5
	• Only indirect measures and estimates of the biomass of the fish assemblages within the exclusion are available.	Supplementary Table 11
Rare and/or threatened species	• Benthic fauna such as Oyster *O. edulis* beds, cold-water coral *L. pertusa* reefs and deep-sea sponge *Porifera* spp. Aggregations are highly sensitive to disturbance and bottom-trawling. Protected O&G reefs clearly support the reproduction and recovery of these species.	Supplementary Tables 4, 5, 8, 9
	• Atlantic cod is highly overshed and use O&G reefs as shelter, nursery, school and for foraging. However, overall protected fish biomass can only be estimated by observation.	Supplementary Tables 11, 13
	• Harbour porpoises are significantly abundant at O&G reefs and are very sensitive to any kind of disturbance. However, there is no clear evidence that these mammals use the protected O&G areas as shelter or for other relevant activities.	Supplementary Table 16

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red). n.a., Not available.

While full removal will result in the complete loss of reef habitat, the "leaving intact" option will provide the full reef habitat. Depending on the partial removal option, cutting and platform depth, certain species communities will lose their habitat and some others may gain new extended habitat (Sammarco et al., 2014). This should be assessed on a case-by-case basis.

However, it remains unclear whether scientists would agree that O&G reefs should be protected because they provide full artificial reef services. Ounanian et al. (2019) introduced the "human-made oasis" metaphor for O&G reefs. Hard substrate supports life, but it is also uncommon in most parts of the North Sea. Scientists from JNCC (CNR International, 2016) argue that *D. pertusum* would have not colonised the Ninian Northen Platform if the structure had not been installed and therefore, removing the structure and destroying the species would not be considered as an issue. This is partly supported by scientists interviewed by Fowler et al. (2018)

TABLE 9 Protection from trawling (part 2): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Impact of decom-missioning options	• Full removal of O&G will result in the loss of the exclusion zone and extend the trawling pattern again.	Supplementary Table 17
	• There is no science-based evidence that reopening fishing areas will increase the fishing pressure. However, the loss of the protected area will clearly have an impact on the local ecosystem (e.g. newly introduced disturbance).	n.a.
	• Compared to partial removal, full removal would reduce the risk of snagging.	Supplementary Table 17
	• If "leaving intact" the O&G substructure would mean that the exclusion zone must be renewed to further protect the O&G reef. Reducing the extend of the exclusion zone may have an impact on the fishing effort near the boundaries, though.	Supplementary Table 17
	• If "leaving intact" the O&G substructure would mean that neither the current snagging risk nor the remaining drill cuttings would be effected.	Supplementary Tables 17, 1
	• Normally, it is preferred that drill cuttings naturally degrade. However, this may be an issue for the options "full removal", "topping and deploy top next to structure", and "toppling", since any kind of disturbance (incl. shing) can lead to leaching.	Supplementary Tables 17, 1
	• Partial removal of O&G, incl. both options "topping" and "toppling", may result in a higher risk of snagging depending on the water depth.	Supplementary Table 17
	• There is no science-based evidence that partial removal of O&G, incl. both options "topping" and "toppling", would adequately protect the remaining O&G reef from trawling.	n.a.
Ecologically or commercially important species	• Studies clearly highlight that 36% of all fishing trips of Scottish demersal fleet occur within 200 m of a pipeline over a 5-year period. Most vessel incidents are related to debris, wires, or pipelines and occur near pipelines or wrecks.	Supplementary Table 17
	• Almost all Atlantic cod fish found at O&G/OWF have been observed within 50 m.	Supplementary Table 11
	• There is no science-based evidence that the trawling effort is greater at the boundaries of O&G exclusion zones.	n.a.
	• There is no science-based evidence that catches of commercially important species are greater at O&G exclusion zones.	n.a.

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red). n.a., Not available.

who stated that it is ethically acceptable to destroy such species because they say this hard substrate does not belong there. Where and how much hard substrate there was before trawling began in the NS is unknown, so there is no way to understand where hard substrate 'should be'. On the other hand, the same scientists (Fowler et al., 2018) also argue that O&G structures should not automatically be removed; showing that some in the science community are making decisions and providing policy advice without understanding the entire picture. Many authors and some NGOs, including van Elden et al. (2019) and Schläppy and Hobbs (2019), now argue that O&G reefs could be valued as novel ecosystems.

4 Discussion

The results show that the majority of the key ecological criteria to determine the impact of MMS on the marine environment are

TABLE 10 Colour-coded illustration of the qualitative analysis: traffic light rating of the current knowledge status – mature science-based (green), immature (grey) and no science-based (red) – with regards to the key ecological considerations (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature
Provision of reef habitat	• O&G reef vs. natural reef
	• O&G reef vs. other artificial reef
	• Ecologically or commercially important species
	• Non-native or invasive species
	• Rare and/or threatened species
	• Impact on soft-bottom ecosystem
	• Impact of decommissioning options
Productivity of offshore ecosystems	• Sessile invertebrates
	• Motile invertebrates
	• Behaviour of important fish species for fisheries
	• Reproduction & nursery grounds
	• Local growth rates
	• Regional total productivity
Enhancement of biodiversity	• Physical and environmental impacts
	• Regional impact
	• O&G reef vs. natural reef
	• Trade-offs: O&G reef vs. soft-bottom ecosystem
	• O&G reef vs. other artificial reef
	• Local vs. regional biodiversity
	• Regional total productivity
Protection of the seabed from trawling	• Protected vs. non-protected seabed
	• Ecologically or commercially important species
	• Rare and/or threatened species
	• Fishing effort near O&G reef
	• Impact of decommissioning options
Enhancement of connectivity	• Connectivity through larval dispersal
	• Larval dispersal mechanism
	• Rare and/or threatened species
	• Non-native or invasive species
	• Impact of decommissioning options

The colour brightness relates to the maturity of the evidence available.

green in the traffic light system, meaning that in general the current research knowledge status can be considered as mostly mature, science-based evidence and that existing O&G platform substructures can and do act as multipurpose artificial reefs.

The results presented demonstrate that the current knowledge about the impact of manmade structures on the marine environment is mature enough to show that it is no longer justifiable to mandatory remove all O&G platform substructures without proper assessment of each of the five ecological considerations as described here and in Fowler et al. (2020).

Furthermore, to ensure that an unbiased comparative assessment is conducted, it is vital that the five key criteria are included and are critically assessed so that the results are used to determine the best decommissioning option, including the decision about whether to remove O&G structures or to leave them *in situ*.

For example, are all criteria generally relevant or do they need to be adapted on a case by case basis? Do all identified knowledge gaps need to be closed before conducting a comparative assessment? These questions can only be addressed in an iterative process and full stakeholder collaboration (Tung, 2020). The Brent Spar experience (Side, 1997) has demonstrated that only a transparent assessment method (Martins et al., 2020) and sound decision criteria (Fowler et al., 2020) can lead to success. To deal with this it is recommended to set up an integrated scientific team as suggested by Shaw et al. (2018) and a survey similar to Fowler et al. (2018) could be conducted with all stakeholders involved. This would help to find common ground and define team goals rather than individual discipline goals.

Some limitations within the study come from the limited number and type of research available, with benthic fauna dominating the research and a bias towards the Southern North Sea. The main knowledge gaps are identified (grey and red colour) in the traffic light system and are in relation to the following key criteria; 2) *protection of the seabed from trawling, 4) enhancement of connectivity*, and *5) productivity of offshore ecosystems* and are in some part due to the complexities of these studies as well as a lack of available data. In future, new tools such as eDNA (Harper et al., 2020) could facilitate and improve the research work. Meanwhile, data gaps could be mitigated by granting access to the large number of not yet published industry monitoring data (Macreadie et al., 2018; Murray et al., 2018). In particular, monitoring data of the derogation cases, where the footings were left *in situ* such as the Ninian Northern platform (CNR International, 2016) and the Murchison platform (CNR International, 2013), would give some insight into the short-term and long-term effects on the habitat provision. Any changes to the benthic fauna and the behaviour of fish and marine mammals at the remaining O&G reef could be determined. This information could also be used to investigate knowledge gaps related to partial removal impacts. For example, what is the impact on the local and regional biodiversity including the surrounding soft-bottom ecosystem? How is the fishing effort near the O&G reefs? And does the remaining O&G reef provide protection from trawling?

Finally, It should be highlighted that other environmental considerations, especially GHG emissions from decommissioning operations (Davies and Hastings, 2023a, 2023) and hence compliance to net zero (Oil & Gas Authority, 2020a) need to also be evaluated when conducting a comparative assessment of various decommissioning options. In this respect, it is worth examining how other countries are dealing with this issue (Scarborough Bull and Love, 2019).

5 Conclusions and policy implications

This study demonstrates that a new clearly structured regulatory framework with clear environmental objectives based on scientific evidence is required for future decommissioning of O&G industry infrastructure in the UK North Sea. This new framework should also include specific expectations of decommissioning within MPAs and if endangered, protected or endangered species are present.

This review concludes that the current research knowledge status of the impact of MMS on the marine environment can be considered as mostly mature, science-based evidence. Evidence that shows that existing O&G platform substructures can and do act as multipurpose artificial reefs and that a clear sea-bed policy is no longer justifiable in the UK North Sea.

The results show that an unbiased comparative assessment using the five key criteria should be undertaken for each decommissioning program, on case-by-case basis, and that decommissioning *in situ* should be considered within these comparative assessments.

The study clearly shows that the precautionary principle of OSPAR 98/3 (OSPAR Commission, 1992) should be reversed.

Finally, the study postulates that adherence to the current version of the OSPAR Decision 98/3 is driven by politics and not by marine environmental sciences.

Author contributions

NP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. AD: Methodology, Project administration, Resources, Validation, Writing – review & editing. AH: Supervision, Validation, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This research is funded by the UK Net Zero Technology Centre (NZTC) and the University of Aberdeen, through their partnership in the UK National Decommissioning Centre (NDC) through a PhD Scholarship for AD. AH was funded by two UKRI funded projects: the NERC funded FAB-GGR project (NE/P01995/1) and the EPSRC funded UKERC-4 project (EP/S029575/1). The NDC funded this publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1264892/full#supplementary-material

References

Bergmark, P., and Jørgensen, D. (2014). Lophelia pertusa conservation in the North Sea using obsolete offshore structures as artificial reefs. *Mar. Ecol. Prog. Ser. (Inter-Research Sci. Center)* 516, 275–280. doi: 10.3354/meps10997

Birchenough, S. N.R., and Degraer, S. (2020). Science in support of ecologically sound decommissioning strategies for offshore man-made structures: taking stock of current knowledge and considering future challenges. Edited by Howard Browman. *ICES J. Mar. Sci.* 77, 1075–1078. doi: 10.1093/icesjms/fsaa039

Burdon, D., Barnard, S., Boyes, S. J., and Elliott, M. (2018). Oil and gas infrastructure decommissioning in marine protected areas: System complexity, analysis and challenges. *Mar. pollut. Bull. (Elsevier BV)* 135, 739–758. doi: 10.1016/j.marpolbul.2018.07.077

CNR International (2013). *Murchison Facilities Decommissioning Environmental Statement* (Aberdeen, United Kingdom: CNR International provided by BMT Cordah Ltd.). Tech. rep., (320 pp.).

CNR International (2016). *Ninian Northern Platform EIA Scoping Report* (Aberdeen, United Kingdom: CNR International provided by BMT Cordah Ltd.). Tech. rep., (63 pp.).

Coolen, J. W.P., Bittner, O., Driessen, F. M.F., van Dongen, U., Siahaya, M. S., de Groot, W., et al. (2020). Ecological implications of removing a concrete gas platform in the North Sea. *Journal of Sea Research*. 166, 101968. doi: 10.1101/2020.04.16.044263

Coolen, J. W.P., Lengkeek, W., Degraer, S., Kerckhof, F., Kirkwood, R., and Lindeboom, H. (2016). Distribution of the invasive Caprella mutica Schurin 1935 and native Caprella linearis (Linnaeus 1767) on artificial hard substrates in the North Sea: separation by habitat. *Aquat. Invasions* 11, 437–449. doi: 10.3391/ai.2016.11.4.08

Coolen, J. W.P., van der Weide, B. E., Cuperus, J., Blomberg, M., Van Moorsel, G. W.N.M., Faasse, M. A., et al. (2018). Benthic biodiversity on old platforms, young wind farms, and rocky reefs. Edited by Joanna Norkko. *ICES J. Mar. Sci.* 77, 1250–1265. doi: 10.1093/icesjms/fsy092

Dannheim, J., Bergström, L., Birchenough, S. N.R., Brzana, R., Boon, A. R., Coolen, J. W.P., et al. (2020). Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. *ICES J. Mar. Sci.* 77, 1092–1108. doi: 10.1093/icesjms/fsz018

Davies, A. J., and Hastings, A. (2023a). Greenhouse gas emissions from decommissioning manmade structures in the marine environment; current trends and implications for the future. *J. Mar. Sci. Eng.* 11, 1133. doi: 10.3390/jmse11061133

Davies, A. J., and Hastings, A. (2023b). A first estimate of blue carbon associated wth oil & gas infrstructure. *Environ. Sci.: Adv.* 12, 1708–1726. doi: 10.1039/D3VA00204G

Department for Business, Energy & Industrial Strategy (2018). *Decommissioning of Offshore Oil and Gas Installations and Pipelines* (London, United Kingdom: UK Government), 137 pp.

Ekins, P., Vanner, R., and Firebrace, J. (2006). Decommissioning of offshore oil and gas facilities: A comparative assessment of different scenarios. *J. Environ. Manage.* 79, 420–438. doi: 10.1016/j.jenvman.2005.08.023

European Environment Agency (2013). *Conservation status of habitat types and species (Article 17, Habitats Directive 92/43/EEC) - Annex I habitat distribution filtered for Reefs, (1170).* Available online at: https://www.eea.europa.eu/data-and-maps/data/article-17-database-habitats-directive-92-43-eec-1.

Fabi, G. (2015). *Practical guidelines for the use of artificial reefs in the Mediterranean and the Black Sea* (Rome, Italy: Food and Agriculture Organization of the United Nations).

Fairfield Energy Limited (2019). *Dunlin Alpha Substructure Decommissioning Environmental Appraisal Report* (Aberdeen, United Kingdom: Fairfield Energy Limited provided by Xodus). Tech. rep., (176 pp.).

Falcone, G. (2020). Can the offshore energy sector be transformed to help the UK become a net-zero nation? *Sci. Parliament* 76, 16–20.

Fam, M. L., Konovessis, D., Ong, L. S., and Tan, H. K. (2018). A review of offshore decommissioning regulations in five countries – Strengths and weaknesses. *Ocean Eng. (Elsevier BV)* 160, 244–263. doi: 10.1016/j.oceaneng.2018.04.001

Fortune, I. S., and Paterson, D. M. (2020). Ecological best practice in decommissioning: a review of scientific research. *ICES J. Mar. Sci.* 77, 1079–1091. doi: 10.1093/icesjms/fsy130

Fowler, A. M., Jørgensen, A.-M., Coolen, J. W. P., Jones, D. O. B., Svendsen, J. C., Brabant, R., et al. (2020). The ecology of infrastructure decommissioning in the North Sea: what we need to know and how to achieve it. *ICES J. Mar. Sci.* 77, 1109–1126. doi: 10.1093/icesjms/fsz143

Fowler, A. M., Jørgensen, A.-M., Svendsen, J. C., Macreadie, P. I., Jones, D. O.B., Boon, A. R., et al. (2018). Environmental benefits of leaving offshore infrastructure in the ocean. *Front. Ecol. Environ.* 16, 571–578. doi: 10.1002/fee.1827

Fowler, A. M., Macreadie, P. I., Jones, D. O. B., and Booth, D. J. (2014). A multi-criteria decision approach to decommissioning of offshore oil and gas infrastructure. *Ocean Coast. Manage.* 87, 20–29. doi: 10.1016/j.ocecoaman.2013.10.019

Gates, A. R., Horton, T., Serpell-Stevens, A., Chandler, C., Grange, L. J., Robert, K., et al. (2019). Ecological role of an offshore industry artificial structure. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00675

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., et al. (2008). A global map of human impact on marine ecosystems. *Science* 319, 948–952. doi: 10.1126/science.1149345

Harper, K. J., Goodwin, K. D., Harper, L. R., LaCasella, E. L., Frey, A., and Dutton, P. H. (2020). Finding crush: environmental DNA analysis as a tool for tracking the green sea turtle chelonia mydas in a marine estuary. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00810

Henry, L.-A., Mayorga-Adame, C. G., Fox, A. D., Polton, J. A., Ferris, J. S., McLellan, F., et al. (2018). Ocean sprawl facilitates dispersal and connectivity of protected species. *Sci. Rep.* 8. doi: 10.1038/s41598-018-29575-4

Jørgensen, D. (2012). OSPAR's exclusion of rigs-to-reefs in the North Sea. *Ocean Coast. Manage.* 58, 57–61. doi: 10.1016/j.ocecoaman.2011.12.012

Kaiser, M. J., and Pulsipher, A. G. (2005). Rigs-to-reef programs in the gulf of Mexico. *Ocean Dev. Int. Law* 36, 119–134. doi: 10.1080/00908320590943990

Kerckhof, F., Coolen, J. W.P., Rumes, B., and Degraer, S. (2018). Recent findings of wild European flat oysters Ostrea edulis (Linnaeus 1758) in Belgian and Dutch offshore waters: new perspectives for offshore oyster reef restoration in the southern North Sea. *Belgian J. Zool.* 148, 79–89. doi: 10.26496/bjz.2018.16

Klunder, L., Lavaleye, M. S., Filippidi, A., Van Bleijswijk, J. D., Reichart, G. J., Van Der Veer, H. W., et al. (2020). Impact of an artificial structure on the benthic community composition in the southern North Sea: assessed by a morphological and molecular approach. *ICES Journal of Marine Science.* 77 (3), 1167–1177. doi: 10.1093/icesjms/fsy114

Lindeboom, H. J., Kouwenhoven, H. J., Bergman, M. J. N., Bouma, S., Brasseur, S., Daan, R., et al. (2011). Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environ. Res. Lett. (IOP Publishing)* 6, 35101. doi: 10.1088/1748-9326/6/3/035101

Macreadie, P. I., Fowler, A. M., and Booth, D. J. (2011). Rigs-to-reefs: will the deep sea benefit from artificial habitat? *Front. Ecol. Environ.* 9, 455–461. doi: 10.1890/100112

Macreadie, P. I., McLean, D. L., Thomson, P. G., Partridge, J. C., Jones, D. O.B., Gates, A. R., et al. (2018). Eyes in the sea: Unlocking the mysteries of the ocean using industrial, remotely operated vehicles (ROVs). *Sci. Total Environ.* 634, 1077–1091. doi: 10.1016/j.scitotenv.2018.04.049

Martins, I. D., Moraes, F. F., Távora, G., Soares, H. L. F., Infante, C. E., Arruda, E. F., et al. (2020). A review of the multicriteria decision analysis applied to oil and gas decommissioning problems. *Ocean Coast. Manage.* 184, 105000. doi: 10.1016/j.ocecoaman.2019.105000

McLean, D. L., Bond, T., Partridge, J. C., Rouse, S., and Love, M. (2020). The impact of oil and gas infrastructure in marine ecosystems: a global vision for informing decommissioning decisions. *APPEA J.* 60, 476. doi: 10.1071/AJ19153

Murray, F., Needham, K., Gormley, K., Rouse, S., Coolen, J. W.P., Billett, D., et al. (2018). Data challenges and opportunities for environmental management of North Sea oil and gas decommissioning in an era of blue growth. *Mar. Policy* 97, 130–138. doi: 10.1016/j.marpol.2018.05.021

National Audit Office (2019). *Oil and gas in the UK – offshore decommissioning* (London, United Kingdom: Department for Business, Energy & Industrial Strategy, HM Revenue & Customs, HM Treasury provided by the Comptroller and Auditor General). Tech. rep., (34 pp.).

OGUK (2019). *Decommissioning Insight 2019* (London, United Kingdom: The UK Oil and Gas Industry Association Limited), 68 pp.

Oil & Gas Authority (2020a). *Oil and Gas infrastructure - Surface*. Available online at: https://data.ogauthority.co.uk/arcgis/rest/services/OGA_Public_WGS84/OGA_Infrastructure_WGS84/FeatureServer (Accessed 30 October 2020).

Oil & Gas Authority (2020b). *UKCS Decommissioning: Cost Estimate 2020* (London, UK: North Sea Transition Authority). 32 pp.

OSPAR Commission (1992). "OSPAR Convention for the protection of the marine environment of the Nort-East Atlantic," in *Ministerial Meeting of the OSPAR Commission*, Paris, France (London, UK: OSPAR Commission), 22 September.

OSPAR Commission (1998). "OSPAR decision 98/3 on the disposal of disused offshore installations," in *Ministerial Meeting of the OSPAR Commission*, Sintra, Portugal (London, UK: OSPAR Commission), 22-23 July. 15–24.

OSPAR Commission (2012). *OSPAR Guidelines on Artificial Reefs in relation to Living Marine Resources* (Bonn). 5 pp.

OSPAR Commission (2017). *OSPAR Inventory of Offshore Installations*. Available online at: https://odims.ospar.org/layers/geonode:ospar_offshore_installations_2017_01_001 (Accessed 30 October 2020).

OSPAR Commission (2019a). *OSPAR MPA Network filtered for United Kingdom*. Available online at: https://carto.maia-network.org/en/1/ospar.map (Accessed 30 October 2020).

OSPAR Commission (2019b). *Status of the OSPAR Network of Marine Protected Areas in 2018, Assessment Sheets (2 pp.)*. (London, UK: OSPAR Commission).

Ounanian, K., van Tatenhove, J. P.M., and Ramírez-Monsalve, P. (2019). Midnight at the oasis: does restoration change the rigs-to-reefs debate in the North Sea? *J. Environ. Policy Plann.* 22, 211–225. doi: 10.1080/1523908X.2019.1697657

Reeds, K. A., Smith, J. A., Suthers, I. M., and Johnston, E. L. (2018). An ecological halo surrounding a large offshore artificial reef: sediments, infauna, and fish foraging. *Marine Environmental Research.* 141, 30–38. doi: 10.1016/j.marenvres.2018.07.011

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

Rouse, S., Hayes, P., and Wilding, T. A. (2020). Commercial fisheries losses arising from interactions with offshore pipelines and other oil and gas infrastructure and activities. Edited by Silvana Birchenough. *ICES J. Mar. Sci.* 77, 1148–1156. doi: 10.1093/icesjms/fsy116

Sammarco, P. W., Lirette, A., Tung, Y. F., Boland, G. S., Genazzio, M., and Sinclair, J. (2014). Coral communities on artificial reefs in the Gulf of Mexico: standing vs. toppled oil platforms. *ICES J. Mar. Sci.* 71, 417–426. doi: 10.1093/icesjms/fst140

Scarborough Bull, A., and Love, M. S. (2019). Worldwide oil and gas platform decommissioning: A review of practices and reefing options. *Ocean Coast. Manage.* 168, 274–306. doi: 10.1016/j.ocecoaman.2018.10.024

Schläppy, M.-L., and Hobbs, R. J. (2019). A triage framework for managing novel, hybrid, and designed marine ecosystems. *Global Change Biol.* 25, 3215–3223. doi: 10.1111/gcb.14757

Shaw, J. L., Seares, P., and Newman, S. J. (2018). *Decommissioning offshore infrastructure: a review of stakeholder views and science priorities* (Perth, WA, Australia: WAMSI). Tech. rep., (66 pp.).

Shell U.K. Limited (2017). *Brent Decommissioning Programmes Environmental Statement* (Aberdeen, United Kingdom: Shell U.K. Limited provided by DNV GL LTD.). Tech. rep., (444 pp.).

Side, J. (1997). The future of North Sea oil industry abandonment in the light of the Brent Spar decision. *Mar. Policy* 1, 45–52. doi: 10.1016/S0308-597X(96)00045-0

Sommer, B., Fowler, A. M., Macreadie, P. I., Palandro, D. A., Aziz, A. C., and Booth, D. J. (2019). Decommissioning of offshore oil and gas structures – Environmental opportunities and challenges. *Sci. Total Environ.* 658, 973–981. doi: 10.1016/j.scitotenv.2018.12.193

Tung, A. (2020). "A comparison of stakeholder engagement strategies for offshore decommissioning projects in the United Kingdom and Australian landscape," in *Offshore Technology Conference*. doi: 10.4043/30824-MS

Vad, J., Kazanidis, G., Henry, L.-A., Jones, D. O. B., Gates, A. R., and Roberts, J. M. (2020). Environmental controls and anthropogenic impacts on deep-sea sponge grounds in the Faroe-Shetland Channel, NE Atlantic: the importance of considering spatial scale to distinguish drivers of change. *ICES J. Mar. Sci.* 77 (1), 451–461. doi: 10.1093/icesjms/fsz185

van Elden, S., Meeuwig, J. J., Hobbs, R. J., and Hemmi, J. M. (2019). Offshore oil and gas platforms as novel ecosystems: A global perspective. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00548

Wood, M. (2018). Upstream decommissioning: where's next and who pays? (Edinburgh, United Kingdom) 8 pp. Available at: https://www.woodmac.com/reports/upstream-oil-and-gas-upstream-decommissioning-wheres-next-and-who-pays-22918/.

Supplementary Material

Is OSPAR 98/3 science-based politics or politics-based science?

Nicole Paces[1], Abigail J. Davies[2,3*], Astley Hastings[,4]

[1]University of Aberdeen, Aberdeen, Scotland, United Kingdom

[2]The National Decommissioning Centre, University of Aberdeen, Newburgh, Scotland, United Kingdom

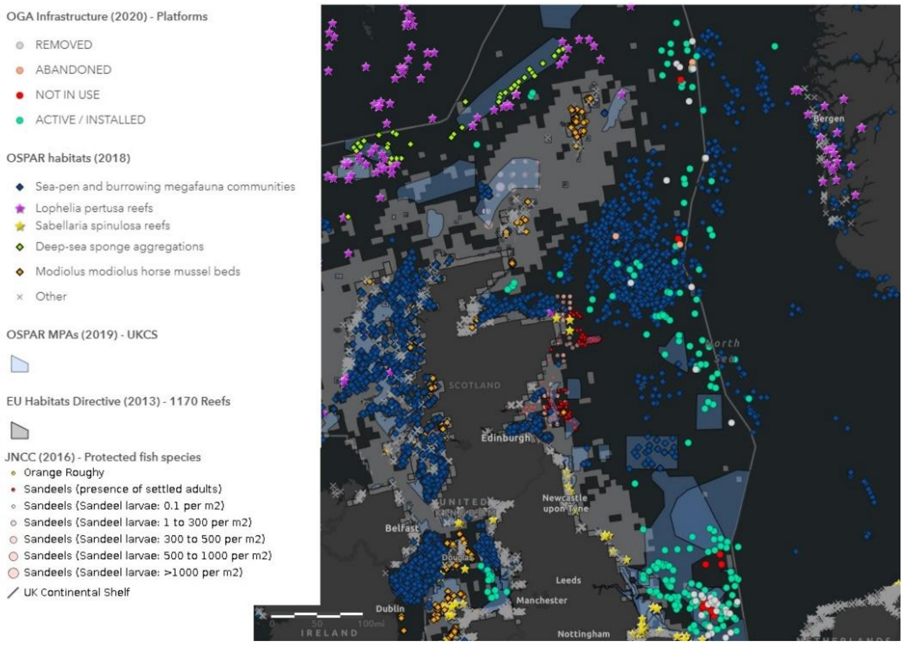
[3]Aberdeen Business School, Robert Gordon University, Aberdeen, Scotland, United Kingdom

[4]The School of Biological Sciences, University of Aberdeen, Aberdeen, Scotland, United Kingdom

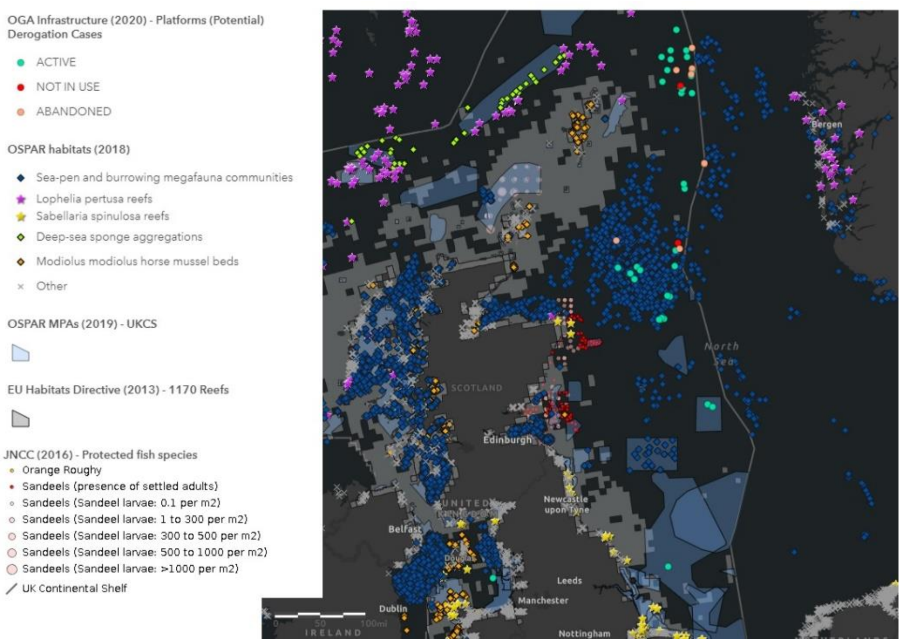
*** Correspondence:**
Corresponding Author
a.davies.1@rgu.ac.uk

1 Supplementary Figures and Tables

1.1 Supplementary Figures



(a)



(b)

Supplementary Figure 1. Locations and status (Oil & Gas Authority 2020a) of (a) all UK platforms and (b) potential candidates for derogation under OSPAR Decision 98/3; Surrounded by threatened and/or declining habitats (OSPAR Commission 2018), designated MPAs (OSPAR Commission 2019a), protected reefs by EEA (2013), and protected fish species (JNCC 2016) in the North Sea. Geospatial layers are overlapped and based on the respective official metadata.

1.2 Supplementary Tables

Supplementary Table 1: Impact on water quality and seabed condition: List of contaminants deriving from O&G installations and surrounding drill cuttings.

Contaminants/ Disturbances	Findings due to substrate degradation and disturbances	Research References
Chemicals	• risk of potential release of legacy chemicals during or after decommissioning	(Sühring, et al. 2020)
Sacrificial anodes	• used to protect platform substructures against corrosion and consist mainly of aluminum and/or zinc	(Picken, Curtis and Elliott 1997)
	• release of contaminants steadily decrease after abandonment	(Pors, et al. 2011)
	• no significant increase of aluminum concentration found in water, but in surrounding sediments	(Gabelle, et al. 2012)
	• low environmental impact expected, however, evidence limited due to lack of monitoring	(Kirchgeorg, et al. 2018)
Paintings & coatings	• organic compounds slowly released, but at very low concentrations	(Kirchgeorg, et al. 2018)
Steel corrosion & deterioration	• platform substructures consist mainly of steel and some traces of aluminum and copper or concrete for GBS	(Pors, et al. 2011)
	• substructures will ultimately deteriorate and fall apart into iron oxide pieces that will accumulate on the seabed	(Tornero and Hanke 2016)
	• estimations: +500 years for steel to fully corrode or concrete legs to fully fall apart	(Shell U.K. Limited 2017)
Drill cuttings	• natural degradation and intensive monitoring is the preferred option	(Tornero and Hanke 2016)
	• disturbance (fishing, cable-laying) lead to leaching and spreading of contaminants	(Henry, Harries, et al. 2017)
Dredging operations	• enable oxygen entering the sediment, hence enhancing aerobic microbial processes leading to behaviour changes of species *L. conchilega*	(Mestdagh, et al. 2020)

Supplementary Table 2: List of recent research works dealing with the influence of man-made structures including O&G installations and OWFs on the benthic fauna in the Southern North Sea.

Key species	location max depth	Substrate type	sampling method/period/analysis	Research References
M. acherusicum *J. herdmani* *P. marina* *S. monoculoides*	SNS 25 m	O&G (GBS)	taxa collection by diving period n.a. statistical analysis, data used and compared to (Coolen, van der Weide, et al. 2018)	(Coolen, Bittner, et al. 2020)
M. edulis	SNS 25 m	various[a]	taxa collection by diving 2014–2016 statistical analysis and PTM incl. model validation with sample data	(Coolen, Boon, et al. 2020)
M. edulis *P. miliaris* *M. dianthus* Tubulariidae[b]	SNS 32 m	O&G OWF Natural reefs	taxa collection by diving 2014–2015 statistical analysis	(Coolen, van der Weide, et al. 2018)
C. linearis *C. mutica*	SNS 45 m	various[a]	taxa collection by diving 2013–2015 statistical analysis, complemented with other published research data	(Coolen, Lengkeek and Degraer, et al. 2016)
C. smithii	SNS 32 m	shipwrecks	taxa collection by diving 2014, species detection only	(Coolen, Lengkeek and Lewis, et al. 2015)
O. edulis	SNS n.a.	various[a]	meta-analysis 2001-ctd.	(Kerckhof, Coolen, et al. 2018)
C. pagurus	SNS 29 m	OWF	taxa collection by diving 2012–2014 statistical analysis	(Krone, et al. 2017)
M. edulis Anthozoa[c] *Jassa spp.*	SNS 28 m	research platform	taxa collection by diving 2005–2007 statistical analysis	(Krone, et al. 2013)
J. herdmani	SNS 28 m	various[a]	taxa collection by diving 2015–2016 statistical analysis, DNA extracted	(Luttikhuizen, et al. 2019)
M. edulis *M. senile* *A. rubens*	SNS/CNS 46 m 66 m	O&G	visual by ROV 2015–2016 statistical analysis	(Schutter, et al. 2019)
Asteroidea[c] *C. pagurus* *B. undatum* *L. holsatus* *P. bernhardus*	SNS depth n.a.	O&G pipeline	visual by ROV 2015 statistical analysis	(Todd, Williamson, et al. 2020)
Variation of sessile/motile invertebrates	SNS 49 m	fixed& mobile O&G	visual by ROV 2014 statistical analysis	(Todd, Lavallin and Macreadie 2018)
M. edulis *M. senile* *A. digitatum*	SNS 43 m	O&G	visual by ROV period n.a. statistical analysis	(van der Stap, Coolen and Lindeboom 2016)

[a]various substrate types include any kind of anthropogenic hard substrate and natural reefs; correct taxonomic rank of marine invertebrates: [b]family, [c]class

Supplementary Table 3: List of recent research works dealing with the influence of man-made structures including O&G installations and OWFs on the benthic fauna in the Central and Southern North Sea (NS).

Key species	location max depth	Substrate type	sampling method/period/analysis	Research References
F. foliacea	West-coast Scotland depth n.a.	artificial reef	taxa collection by diving period n.a. statistical analysis	(Rouse, Porter and Wilding 2020)
L. pertusa	NNS depth n.a.	O&G	meta-analysis period n.a	(Bergmark and Jørgensen 2014)
Cnidaria[b] Mollusca[b] Annelida[b] Arthropoda[b] Echinodermata[b]	NNS 185 m	O&G	taxa collection by diving and visual by ROV 2009–2018 statistical analysis, observation	(Gates, et al. 2019)
C. smithii Bryozoa[b] Hydrozoa[c] Actiniaria[d] *S. triqueter* *A. rubens* Paguridae[e]	CNS NNS 164 m	pipeline	visual by ROV 2012–2013 statistical analysis	(Lacey and Hayes 2020)
L. pertusa	NS from 80 m to 200 m	O&G	simulation based on research data 2010–2012 PTM modelling only	(Henry, Mayorga-Adame, et al. 2018)
A. digitatum *E. esculentus* *L. pertusa* *M. dianthus* *C. fornicata* *Porifera spp.*	NS depth n.a.	various[a]	simulation based on research data 2001–2010 PTM modelling only, based on (van der Molen, et al. 2018)	(Tidbury, et al. 2020)

[a]various substrate types include any kind of anthropogenic hard substrate and natural reefs; correct taxonomic rank of marine invertebrates: [b]phylum, [c]class, [d]order, [e]family

Supplementary Table 4: List of epifauna species with greatest abundance on man-made structures in the Southern North Sea including O&G installations and OWFs.

Species & community ecology		Findings of species' significant behaviour	Research References
M. acherusicum *J. herdmani* *P. marina* *S. monoculoides*	abundance	• significant on O&G (GBS = concrete)	(Coolen, Bittner, et al. 2020)
M. senile	abundance biomass	• dominated community biomass on O&G (GBS)	(Coolen, Bittner, et al. 2020)
Non-native spp.	detection	• low percentage on O&G (GBS), not registered in the Netherlands, but native in NS	(Coolen, Bittner, et al. 2020)
M. edulis *P. miliaris* *M. dianthus* Tubulariidae[a]	abundance	• *M. edulis*: pos. correlation with richness • *P. miliaris*: pos. correlation with richness • *M. dianthus*: neg. correlation with richness • all significant on O&G/OWF/natural reefs	(Coolen, van der Weide, et al. 2018)
C. mutica (non-native)	detection	• only on nearshore OWF	(Coolen, Lengkeek and Degraer, et al. 2016)
C. smithii	detection	• first record on shipwreck offshore	(Coolen, Lengkeek and Lewis, et al. 2015)
O. edulis	detection recovery	• relict populations on O&G/OWF • potential to recover	(Kerckhof, Coolen, et al. 2018)
C. pagurus *Liocarcinus spp.* *P. bernhardus*	abundance reproduction	• significant among crustaceans on OWF • *C. pagurus*: using OWF as nursery grounds	(Krone, et al. 2017)
M. edulis Anthozoa[b] *Jassa spp.*	abundance	• significant on research platform	(Krone, et al. 2013)
M. edulis	biomass	• dominated community biomass on structure • significant production/export: "*Mytilusation*"	(Krone, et al. 2013)
M. edulis *M. senile* *A. rubens*	abundance	• significant on O&G	(Schutter, et al. 2019)
M. leidyi (non-native)	detection	• in CNS on O&G • occur seasonally due to rising temperatures	(Schutter, et al. 2019)
P. bernhardus	abundance	• significant on newly installed O&G	(Todd, Williamson, et al. 2020)
A. rubens *E. esculentus* *C. pagurus* *P. bernhardus*	abundance	• significant on O&G	(Todd, Lavallin and Macreadie 2018)
M. senile	abundance biomass	• dominated community biomass on O&G	(Todd, Lavallin and Macreadie 2018)
B. undatum	reproduction	• egg masses found on O&G	(Todd, Lavallin and Macreadie 2018)
M. edulis *M. senile* *A. digitatum*	abundance	• significant on O&G	(van der Stap, Coolen and Lindeboom 2016)

correct taxonomic rank of marine invertebrates: [a]family, [b]class

Supplementary Table 5: List of epifauna species with greatest abundance on man-made structures in the Central and Northern North Sea including O&G and OWFs.

Species & community ecology		Findings of species' significant behaviour	Research References
C. smithii Bryozoa[a] Hydrozoa[b] Actiniaria[c] *S. triqueter* *A. rubens* Paguridae[d]	abundance	• significant on pipelines	(Lacey and Hayes 2020)
Cnidaria[a] Mollusca[a] Annelida[a] Arthropoda[a] Echinodermata[a]	biomass richness	• significant on O&G	(Gates, et al. 2019)
L. pertusa	recovery reproduction	• strong potential to form cold-water coral reefs on obsolete O&G in NNS	(Bergmark and Jørgensen 2014)
L. pertusa	recovery reproduction	• strong potential to form cold-water coral reefs on obsolete O&G in NS	(Henry, Mayorga-Adame, et al. 2018)

correct taxonomic rank of marine invertebrates: [a]phylum, [b]class, [c]order, [d]family

Supplementary Table 6: List of epifauna species and their community ecology influenced by water depth in relation to man-made structures including O&G installations and OWFs across the North Sea.

Species & community ecology		Findings due to water depth	Research References
M. edulis *P. miliaris* *M. dianthus*	richness	• buildup of vertical zonation: non-linear distribution, peak at intermediate depths	(Coolen, van der Weide, et al. 2018)
Non-native spp.	detection	• higher percentage in the intertidal zone	(Coolen, van der Weide, et al. 2018)
M. edulis	abundance	• highest in the upper 10 m	(Krone, et al. 2017)
M. edulis Anthozoa[a] *Jassa spp.*	abundance	• buildup of vertical zonation (from surface to bottom): Mytilus, Mytilus-Jassa, Anthozoa-Jassa, Anthozoa	(Krone, et al. 2013)
Variation of species	richness diversity	• higher in bottom zone compared to surface zone	(Schutter, et al. 2019)
Motile invertebrates	abundance richness diversity	• highest in bottom zone	(Todd, Lavallin and Macreadie 2018)
Sessile invertebrates	abundance richness diversity	• buildup of vertical zonation (from surface to bottom): infralittoral, circalittoral, epi-benthic assemblages	(Todd, Lavallin and Macreadie 2018)
M. edulis *M. senile* *A. digitatum*	richness	• buildup of vertical zonation: non-linear distribution, peak at intermediate depths	(van der Stap, Coolen and Lindeboom 2016)
Variation of species	abundance	• strong correlation with depth and latitude	(Lacey and Hayes 2020)

correct taxonomic rank of marine invertebrates: [a]class

Supplementary Table 7: List of epifauna species and their community ecology influenced by substrate type effects in relation to man-made structures including O&G installations and OWFs across the North Sea.

Species & community ecology		Findings due to substrate material/type	Research References
Variation of species	abundance	• large overlap in communities between GBS (=concrete) and steel O&G/OWF • low overlap in communities between GBS and sandy seabed • relative large overlap in communities between GBS and natural reefs in Borkum Reef Grounds	(Coolen, Bittner, et al. 2020)
Variation of species	uniqueness	• 23 % of species on GBS locally unique	(Coolen, Bittner, et al. 2020)
M. senile	biomass	• 12 times higher on GBS than in sandy seabed	(Coolen, Bittner, et al. 2020)
M. edulis *P. miliaris* *M. dianthus*	richness	• no great differentiation between rock and steel • gradient from deep rocks to shallow steel • no great differentiation between artificial and natural substrates	(Coolen, van der Weide, et al. 2018)
Variation of species	abundance	• large overlap in communities on steel and rock • large overlap in communities between young OWF and old O&G	(Coolen, van der Weide, et al. 2018)
C. linearis (native) *C. mutica* (non-native)	abundance	• minor overlap of habitat preference (offshore vs. nearshore) leading to co-existing potential	(Coolen, Lengkeek and Degraer, et al. 2016)
C. pagurus	abundance	• highest at monopiles with scour protection: two times higher than on tripod and six times higher than on jacket (all OWF)	(Krone, et al. 2017)
Sessile invertebrates	abundance	• low overlap in communities between fixed and mobile O&G	(Todd, Lavallin and Macreadie 2018)
F. foliacea	productivity	• higher in complex, voided reef block habitats compared to simple blocks (all artificial)	(Rouse, Porter and Wilding 2020)
Variation of invertebrates	abundance	• large overlap in communities between O&G and surrounding coarse/mixed seabed	(Gates, et al. 2019)
Porifera spp.	abundance	• high in surrounding seabed, not found on O&G	(Gates, et al. 2019)
Variation of invertebrates	richness abundance	• higher on Link-lok/concrete mattresses • low overlap in communities between pipelines and sandy seabed	(Lacey and Hayes 2020)
L. pertusa	abundance	• not only found on natural reefs, but also on O&G far offshore	(Henry, Mayorga-Adame, et al. 2018)

Supplementary Table 8: List of epifauna species and their community ecology influenced by location or substrate inter-connectivity effects in relation to man-made structures including O&G installations and OWFs across the North Sea.

Species & community ecology		Findings due to location and inter-connectivity	Research References
M. edulis	dispersal	• no clear connectivity pattern between hard substrates in SNS: PTM showing connectivity that is not validated by genetic data • PTM predicts locations greater than 85 km offshore to be isolated from coastal communities, but actual species found 181 km offshore • no correlation between isolation and distance	(Coolen, Boon, et al. 2020)
J. herdmani	dispersal	• no correlation between isolation and distance • no correlation between artificial substrates and genetic connectivity	(Luttikhuizen, et al. 2019)
Variation of species	abundance	• higher in CNS than in SNS • medium overlap in communities between CNS and SNS, significant clustering	(Schutter, et al. 2019)
L. pertusa	dispersal	• PTM showing strong potential of O&G infrastructure to form highly interconnected coral ecosystem networks	(Henry, Mayorga-Adame, et al. 2018)
Variation of species	dispersal	• PTM showing clear connectivity between all kind of hard substrates across NS: (1) Full removal of all O&G infrastructure leading to 60 % reduction in connectivity across NS (2) Decommissioning as per OSPAR Convention leading to complete loss of connectivity in CNS (3) SNS is well connected, removal of O&G infrastructure in SNS leading to loss of connectivity between CNS/SNS	(Tidbury, et al. 2020)

PTM: Particle Tracking Model; SNS/CNS/NNS: Southern/Central/Northern North Sea

Supplementary Table 9: List of epifauna species and their community ecology influenced by temporal and disturbance effects in relation to man-made structures including i.a. Oil & Gas (O&G) installations and offshore wind farms (OWF) across the North Sea.

Species & community ecology		Findings due to temporal and disturbance effects	Research References
M. edulis *P. miliaris* *M. dianthus*	richness	• no difference between old O&G and young OWF differences between sampling months	(Coolen, van der Weide, et al. 2018)
O. edulis	abundance	• sensitive to bottom trawling or sand/gravel extractions	(Kerckhof, Coolen, et al. 2018)
M. edulis Anthozoa[a] *Jassa spp.*	biomass	• differences between sampling months	(Krone, et al. 2013)
M. edulis *M. senile* *A. digitatum*	richness	• increases with community age	(van der Stap, Coolen and Lindeboom 2016)
Variation of species	abundance richness diversity	• no differences between pre/post installation of mobile O&G • differences between laid and trenched pipeline: significant decrease after trenching	(Todd, Williamson, et al. 2020)

correct taxonomic rank of marine invertebrates: [a]class

Supplementary Table 10: List of recent research works dealing with the influence of man-made structures including O&G installations and OWFs on various fish species across the North Sea.

Key species*	location max depth	Substrate type	sampling method/period/analysis	Research References
Variation of flatfishes	SNS/CNS depth n.a.	OWF	simulation based on research data 2010–2012 Particle tracking modelling only	(Barbut, et al. 2020)
Variation of fish species	SNS Depth n.a.	OWF wrecks	taxa collection by dive transects & line fishing 2001–2017, descriptive analysis	(Kerckhof, Rumes and Degraer 2018)
Atlantic cod Pouting	SNS 24 m	OWF steel & concrete	taxa collection by line gear & data collection by tagging, acoustic telemetry & visual observation 2011–2012, statistical analysis	(Reubens, Degraer and Vincx 2014) (Reubens, et al. 2013)
Whiting Common dab Sandeels	SNS 13.5 m	OWF	taxa collection by gillnets 2001 (pre-installation) & 2009 (post-installation), statistical analysis	(Stenberg, et al. 2015)
Variation of fish species	depth n.a.	O&G pipeline	visual by ROV 2015 statistical analysis	(Todd, Williamson, et al. 2020)
Atlantic cod Pollack Common ling	SNS 49 m	fixed & mobile O&G	visual by ROV 2014 statistical analysis	(Todd, Lavallin and Macreadie 2018)
Common dab Common sole Atlantic cod	SNS 21 m	OWF	taxa collection by gillnets & data collection by sonar 2011, statistical analysis	(van Hal, Griffioen and van Keeken 2017)
Saithe	CNS 103 m	ceased O&G	data collection by monitoring system: oceanographic instrumentation & time-lapse photography 2014, statistical analysis	(Fujii and Jamieson 2016)
Saithe Haddock Atlantic cod	CNS NNS 103 m	ceased O&G & open water	taxa collection by fish traps at O&G, data collection by using bottom trawl survey at open water 2010-2014 (2012 survey) statistical analysis	(Fujii 2016) (Fujii 2015)
Atlantic cod European plaice Thornback ray	CNS NNS depth n.a.	O&G OWF Cables wrecks	data collection by electronic tags & fisheries surveys 1993–2010, statistical analysis	(Wright, et al. 2020)

**scientific names*: Atlantic cod (*G. morhua*), Common dab (*L. limanda*), Common ling (*M. molva*), Common sole (*S. solea*), European plaice (*P. platessa*), Haddock (*M. aeglefinus*), Pollack (*P. pollachius*), Pouting (*T. luscus*), Saithe (*P. virens*), Sandeels (*Ammodytidae spp*), Thornback ray (*R. clavata*), Whiting (*M. merlangus*)

Supplementary Table 11: List of fish species with greatest abundance at man-made structures including O&G installations and OWFs across the North Sea.

Species & community ecology		Findings of species' significant behaviour	Research References
Variation of fish species	richness	• 25 different species observed at OWF and less at wrecks	(Kerckhof, Rumes and Degraer 2018)
Variation of fish species	detection	• first records of obligate hard substrate fish species uncommon to Belgian Sea though	(Kerckhof, Rumes and Degraer 2018)
Atlantic cod	abundance	• showing high residency, site fidelity at OWF, confirming early work (Jørgensen, Løkkeborg and Soldal 2002)	(Reubens, Degraer and Vincx 2014)
Atlantic cod Pouting	abundance	• strongly attracted towards OWF	(Reubens, Degraer and Vincx 2014)
Atlantic cod Pouting	food web	prey dominated in stomach for both species: • *J. herdmani* and *P. longicornis* (good quality)	(Reubens, Degraer and Vincx 2014)
Atlantic cod	abundance	• significant within 50 m of OWF (97 % of all records)	(Reubens, et al. 2013)
Whiting Common dab Sandeels	abundance	• significant at OWF	(Stenberg, et al. 2015)
Atlantic cod Common ling Pollack	abundance	• significant at O&G, dominated by Atlantic cod	(Todd, Lavallin and Macreadie 2018)
Atlantic cod Lumpsucker	reproduction	• Lumpsucker brooding eggs on O&G and juveniles of Atlantic cod spotted at O&G	(Todd, Lavallin and Macreadie 2018)
Common sole Atlantic cod	abundance	• significant at OWF	(van Hal, Griffioen and van Keeken 2017)
Goldsinny wrasse Grey triggerfish	detection	• first records in Belgian Sea	(van Hal, Griffioen and van Keeken 2017)
Saithe	biological rhythm	• showing diurnal rhythm of vertical movements at O&G, confirming early work (Soldal 2002)	(Fujii and Jamieson 2016)
Saithe Haddock Atlantic cod	abundance	• significant at O&G, dominated by saithe	(Fujii 2016)
Saithe Haddock Atlantic cod	food web	prey dominated in stomach in respective order: • Euphausiacea (O&G) & pouting (trawl) • Ophiuroidea (O&G) • unidentified fish (O&G)	(Fujii 2016)

Supplementary Table 12: List of fish species and their community ecology influenced by water depth and temporal effects in relation to man-made structures including O&G installations and OWFs across the North Sea.

Species & community ecology		Findings due to water depth and temporal effects	Research References
Variation of fish species	abundance	• buildup of vertical zonation: benthic fish (bottom zone), benthopelagic fish (live in bottom zone but do not rest there), pelagic fish (live in mid-depth or surface zone)	(Kerckhof, Rumes and Degraer 2018)
Atlantic cod Common ling Pollack	abundance	• highest in bottom zone, pollack also significant in surface zone	(Todd, Lavallin and Macreadie 2018)
Saithe	abundance	• peak at around 3–4 am at mid-depth and 34 pm at bottom of O&G, confirming early work (Soldal 2002)	(Fujii and Jamieson 2016)
Saithe Haddock Atlantic cod	abundance	• highest in bottom zone varying with season and year (correlated with temperature)	(Fujii 2015)
Atlantic cod	abundance	• spatial-temporal movement pattern: highest in surface zone in winter/spring and highest in bottom zone in autumn/winter	(Wright, et al. 2020)
European plaice	abundance	• highest in surface zone	(Wright, et al. 2020)

Supplementary Table 13: List of fish species and their community ecology influenced by temporal and disturbance effects in relation to man-made structures including O&G installations and OWFs across the North Sea.

Species & community ecology		**Findings due to temporal and disturbance effects**	**Research References**
Atlantic cod	abundance	• seasonal movement pattern: high in summer/ autumn (feeding season), very low in winter (spawning season)	(Reubens, et al. 2013)
Whiting Common dab Sandeels	abundance	• no significant changes due to installation of OWF (long term)	(Stenberg, et al. 2015)
Variation of fish species	abundance richness diversity	• significant increase from pre-installation to post-installation of mobile O&G (short term) • differences between laid and trenched pipeline: significant increase after trenching except for whiting	(Todd, Williamson, et al. 2020)
Variation of fish species	aggregation	• fish schools in April observed at OWF, none in summer	(van Hal, Griffioen and van Keeken 2017)
Saithe Haddock Atlantic cod	food web	• differences in stomach content between species varying seasonally	(Fujii 2016)
Saithe Haddock Atlantic cod	abundance	• seasonal movement pattern: high and constant from spring to autumn, very low in winter except for saithe	(Fujii 2015)

Supplementary Table 14: List of fish species and their community ecology influenced by substrate site/type and temporal effects in relation to man-made structures including O&G installations and OWFs across the North Sea.

Species & community ecology		Findings due to site/type and temporal effects	Research References
Variation of flatfishes	dispersal	• PTM showing potential overlap between potential spawning grounds and future OWF sites	(Barbut, et al. 2020)
Variation of fish species	diversity	• OWF: higher at turbines, decline with distance	(Stenberg, et al. 2015)
Common dab Sandeels	abundance	• OWF: higher at turbines, decline with distance	(Stenberg, et al. 2015)
Whiting	abundance	• OWF: lower at turbines, increase with distance	(Stenberg, et al. 2015)
Atlantic cod	body size	• larger at OWF than on sandy bottom varying seasonally	(van Hal, Griffioen and van Keeken 2017)
Atlantic cod Pouting	abundance	• higher at OWF than on sandy bottom	(van Hal, Griffioen and van Keeken 2017)
Flatfish species Whiting	abundance	• higher on sandy bottom than at OWF	(van Hal, Griffioen and van Keeken 2017)
Saithe	food web	• stomach content varies between O&G and open water across CNS/NNS, but showing seasonal overlap	(Fujii 2016)
Saithe	abundance	• higher and more constant over the seasons at O&G than in open water	(Fujii 2015)
Haddock Atlantic cod	abundance	• higher and more constant over the seasons in open water than at O&G	(Fujii 2015)
Atlantic cod	abundance	• positive correlation with density of cables varying seasonally • negative correlation with density of wrecks varying seasonally	(Wright, et al. 2020)
European plaice	abundance	• positive correlation with density of O&G and cables varying seasonally	(Wright, et al. 2020)
Thornback ray	abundance	• positive correlation with density of wrecks varying seasonally • negative correlation with density of O&G and cables varying seasonally	(Wright, et al. 2020)

Supplementary Table 15: List of recent research works dealing with the influence of man-made structures including O&G installations and OWFs on various fish species across the North Sea.

Mammals/sharks	location max depth	Substrate type	sampling method/period/analysis	Research References
Harbour porpoise	CNS 46 m 66 m	manned & unmanned O&G	visual observation & acoustic detection by PAM (2 y) & taxa identification by eDNA continued work (Delefosse, Rahbek, et al. 2018) descriptive statistics	(Delefosse, Jacobsen, et al. 2020)
Harbour porpoise Dolphins Whales Seals	CNS 46 m 66 m	manned & unmanned O&G	visual observation 2013–2015 statistical analysis	(Delefosse, Rahbek, et al. 2018)
Seals	SNS	new OWF pipeline	GPS tracking data 2008–2012: different tagging periods descriptive statistics	(Russell, et al. 2014)
Dolphins Seals Sharks	NS N-E Atlantic 353 m	O&G subsea pipeline	visual/acoustic detection by ROV 1998–2019 descriptive statistics	(Todd, Lazar, et al. 2020)
Harbour porpoise Whales Dolphins Seals, Sharks	SNS 30 m	fixed & mobile O&G	visual observation during daylight & acoustic detection by PAM 2004–2014 (PAM in 2014) descriptive statistics	(Todd, Warley and Todd 2016)
Harbour porpoise	SNS 48 m	fixed & mobile O&G	acoustic detection by PAM 2004–2006 statistical analysis	(Todd, Pearse, et al. 2009)

PAM: Passive Acoustic Monitoring

Supplementary Table 16: List of marine mammals and sharks sighted at man-made structures including O&G installations and OWFs across the North Sea.

Species*	**Findings of species' behaviour due to interactions with anthropocentric hard substrate**	**Research References**
Harbour porpoise	• highest abundance of mammals at/near O&G in NS • mainly observed during night by PAM from July to January, while eDNA confirmed presence of prey species (mackerel, whiting) at O&G • pronounced diel pattern in echolocation activity: foraging at O&G during night; not supported by observations (Osiecka, Jones and Wahlberg 2020) • sightings increased from North to South in CNS • sightings increased with areal footprint of O&G	(Delefosse, Jacobsen, et al. 2020) (Delefosse, Rahbek, et al. 2018) (Todd, Warley and Todd 2016) (Todd, Pearse, et al. 2009)
White-sided White beaked dolphins	• sightings increased with depth	(Delefosse, Rahbek, et al. 2018) (Todd, Warley and Todd 2016)
Minke/Killer Pilot whales	• significant abundance of minke whales at/near O&G	(Delefosse, Rahbek, et al. 2018) (Todd, Warley and Todd 2016)
Common seal Grey seal	• strongly associated with pipelines using for navigation and foraging confirmed by observation & GPS data • sightings increased with depth • foraging at OWF showing grid-like movement pattern	(Delefosse, Rahbek, et al. 2018) (Russell, et al. 2014) (Todd, Lazar, et al. 2020) (Todd, Warley and Todd 2016)
Basking shark Porbeagle shark	• travelling along pipeline	(Todd, Lazar, et al. 2020) (Todd, Warley and Todd 2016)

* *scientific names*: Harbour porpoise *(P. phocoena)*, Atlantic white-sided dolphin *(L. acutus)*, White beaked dolphin *(L. albirostris)*, Common dolphin *(D. delphis)*, Bottlenose dolphin *(T. truncatus)*, Minke whale *(B. acutorostrata)*, Killer whale *(O. orca)*, Pilot whales *(Globicephala spp.)*, Common seal *(P. vitulina)*, Grey seal *(H. grypus)*, Basking shark *(C. maximus)*, Porbeagle shark *(L. nasus)*

Supplementary Table 17: List of recent research works dealing with the interactions between fisheries and man-made structures including O&G installations and OWFs across the North Sea.

Interaction	Findings due to interactions with anthropocentric hard substrate	Research References
Safety zones	• also called exclusion zones of 500 m automatically established around O&G installations (active/non-active) • any fishing activities prohibited in such zones • no restrictions applied to pipelines; restrictions may be defined for OWF on a case-by-case basis	(Petroleum Act 1987)
Hazardous incidents	• majority of incidents occur in NNS and on muddy substrate • 80 % of incidents related to debris/wires/pipelines and occur near pipelines or wrecks • probability of fishing gear incident with pipeline: 7.86E-5	(Rouse, Hayes and Wilding 2020)
Deliberate, regular interactions	• 36 % of all fishing trips of Scottish demersal fleet occur within 200 m of a pipeline over a 5-year period • compromise pipeline integrity, increase risk of gear snagging	(Rouse, Kafas, et al. 2018)
Co-location potential	• high for crab/lobster fisheries within OWF • fisheries concerns: site-specific risk and safety issues • no existing collaboration of stakeholders	(Hooper, Ashley and Austen 2015)

Supplementary Table 18: List of threatened and/or declining species & habitats (OSPAR) filtered for protected species and habitats recently found on, at or in the close vicinity of O&G installations.

Species & habitats	Findings in literature	Research References
Invertebrates		
Ocean quahog	• found near O&G, especially in designated MPAs	**Invalid source specified.**
Ostrea edulis	• found on O&G	Supplementary Table 4
Fish		
Atlantic cod	• shown significant residency at O&G	Supplementary Table 11
Thornback ray	• sighted near O&G, but prefers wrecks	Supplementary Table 14
Mammals and sharks		
Harbour porpoise	• sighted regularly at O&G, especially in designated MPAs	Supplementary Table 16
Basking shark	• sighted near pipelines	Supplementary Table 16
Porbeagle shark	• sighted near pipelines	Supplementary Table 16
Habitats		
Deep-sea sponge aggregations	• found next to O&G, abundance potentially increased due to the proximity of designated MPAs and using O&G as “stepping stones”	Supplementary Table 7 Supplementary Figure 1
Intertidal *Mytilus edulis* beds on mixed and sandy sediments	• massive colonies found on O&G, due to biomass export to surrounding sediment potentially form Mytilus beds in shallower water	Supplementary Table 4
Lophelia pertusa reefs	• colonies found on O&G, reefs found near O&G, strong potential to form reefs around O&G	Supplementary Table 5 Supplementary Figure 1
Modiolus modiolus beds	• abundance potential near/at O&G	Supplementary Figure 1
Ostrea edulis beds	• potential to recover and form beds around O&G	Supplementary Table 4
Sabellaria spinulosa reefs	• abundance potential near/at O&G	Supplementary Figure 1
Sea-pen and burrowing megafauna communities	• abundance potential near/at O&G	Supplementary Figure 1

2 Supplementary References

Barbut, Léo, Berthe Vastenhoud, Laurence Vigin, Steven Degraer, Filip A. M. Volckaert, and Geneviève Lacroix. 2020. "The proportion of flatfish recruitment in the North Sea potentially affected by offshore windfarms." Edited by Silvana Birchenough. *ICES Journal of Marine Science* (Oxford University Press (OUP)) 77: 1227–1237. doi:10.1093/icesjms/fsz050.

Bergmark, P., and D. Jørgensen. 2014. "Lophelia pertusa conservation in the North Sea using obsolete offshore structures as artificial reefs." *Marine Ecology Progress Series* (Inter-Research Science Center) 516: 275–280. doi:10.3354/meps10997.

Coolen, Joop W. P., Arjen R. Boon, Richard Crooijmans, Hilde Pelt, Frank Kleissen, Daan Gerla, Jan Beermann, Silvana N. R. Birchenough, Leontine E. Becking, and Pieternella C. Luttikhuizen. 2020. "Marine stepping-stones: Connectivity of Mytilus edulis populations between offshore energy installations." *Molecular Ecology* (Wiley) 29: 686–703. doi:10.1111/mec.15364.

Coolen, Joop W. P., B. E. van der Weide, J. Cuperus, Maxime Blomberg, Godfried W. N. M. Van Moorsel, Marco A. Faasse, Oscar G. Bos, Steven Degraer, and Han J. Lindeboom. 2018. "Benthic biodiversity on old platforms, young wind farms, and rocky reefs." Edited by Joanna Norkko. *ICES Journal of Marine Science* (Oxford University Press (OUP)) 77: 1250–1265. doi:10.1093/icesjms/fsy092.

Coolen, Joop W. P., Oliver Bittner, Floor M. F. Driessen, Udo van Dongen, Midas S. Siahaya, Wim de Groot, Ninon Mavraki, Stefan G. Bolam, and Babeth van der Weide. 2020. "Ecological implications of removing a concrete gas platform in the North Sea." *bioRxiv*. doi:10.1101/2020.04.16.044263.

Coolen, Joop W. P., Wouter Lengkeek, Gareth Lewis, Oscar G. Bos, Lodewijk Van Walraven, and Udo Van Dongen. 2015. "First record of Caryophyllia smithii in the central southern North Sea: artificial reefs affect range extensions of sessile benthic species." *Marine Biodiversity Records* (Cambridge University Press (CUP)) 8. doi:10.1017/S1755267215001165.

Coolen, Joop W. P., Wouter Lengkeek, Steven Degraer, Francis Kerckhof, Roger Kirkwood, and Han Lindeboom. 2016. "Distribution of the invasive Caprella mutica Schurin, 1935 and native Caprella linearis (Linnaeus, 1767) on artificial hard substrates in the North Sea: separation by habitat." *Aquatic Invasions* (Regional Euro-Asian Biological Invasions Centre Oy (REABIC)) 11: 437–449. doi:10.3391/ai.2016.11.4.08.

Delefosse, Matthieu, Magnus W. Jacobsen, Jeppe D. Balle, Brian K. Hansen, Anne Lise Middelboe, Einar E. Nielsen, and Jonas Teilmann. 2020. "Marine Mammal Biodiversity Around Oil and Gas Platforms - Challenges and Successes of Long-Term Monitoring." *SPE International Conference and Exhibition on Health, Safety, Environment, and Sustainability.* Society of Petroleum Engineers. doi:10.2118/199479-ms.

Delefosse, Matthieu, Malene Louise Rahbek, Lars Roesen, and Karin Tubbert Clausen. 2018. "Marine mammal sightings around oil and gas installations in the central North Sea." *Journal of the Marine Biological Association of the United Kingdom* (Cambridge University Press (CUP)) 98: 993–1001. doi:10.1017/s0025315417000406.

European Environment Agency. 2013. "Conservation status of habitat types and species (Article 17, Habitats Directive 92/43/EEC) - Annex I habitat distribution filtered for Reefs (1170)." *Conservation status of habitat types and species (Article 17, Habitats Directive 92/43/EEC) - Annex I habitat distribution filtered for Reefs (1170).* https://www.eea.europa.eu/data-and-maps/data/article-17-database-habitats-directive-92-43-eec-1.

Fujii, Toyonobu. 2016. "Potential influence of offshore oil and gas platforms on the feeding ecology of fish assemblages in the North Sea." *Marine Ecology Progress Series* (Inter-Research Science Center) 542: 167–186. doi:10.3354/meps11534.

Fujii, Toyonobu. 2015. "Temporal variation in environmental conditions and the structure of fish assemblages around an offshore oil platform in the North Sea." *Marine Environmental Research* (Elsevier BV) 108: 69–82. doi:10.1016/j.marenvres.2015.03.013.

Fujii, Toyonobu, and Alan J. Jamieson. 2016. "Fine-scale monitoring of fish movements and multiple environmental parameters around a decommissioned offshore oil platform: A pilot study in the North Sea." *Ocean Engineering* (Elsevier BV) 126: 481–487. doi:10.1016/j.oceaneng.2016.09.003.

Gabelle, C., F. Baraud, L. Biree, S. Gouali, H. Hamdoun, C. Rousseau, E. van Veen, and L. Leleyter. 2012. "The impact of aluminium sacrificial anodes on the marine environment: A case study." *Applied Geochemistry* (Elsevier BV) 27: 2088–2095. doi:10.1016/j.apgeochem.2012.07.001.

Gates, Andrew R., Tammy Horton, Amanda Serpell-Stevens, Chester Chandler, Laura J. Grange, Katleen Robert, Alexander Bevan, and Daniel O. B. Jones. 2019. "Ecological Role of an Offshore Industry Artificial Structure." *Frontiers in Marine Science* (Frontiers Media SA) 6. doi:10.3389/fmars.2019.00675.

Henry, Lea-Anne, Claudia G. Mayorga-Adame, Alan D. Fox, Jeff A. Polton, Joseph S. Ferris, Faron McLellan, Chris McCabe, Tina Kutti, and J. Murray Roberts. 2018. "Ocean sprawl facilitates dispersal and connectivity of protected species." *Scientific Reports* (Springer Science and Business Media LLC) 8. doi:10.1038/s41598-018-29575-4.

Henry, Lea-Anne, Dan Harries, Paul Kingston, and J. Murray Roberts. 2017. "Historic scale and persistence of drill cuttings impacts on North Sea benthos." *Marine Environmental Research* (Elsevier BV) 129: 219–228. doi:10.1016/j.marenvres.2017.05.008.

Hooper, Tara, Matthew Ashley, and Melanie Austen. 2015. "Perceptions of fishers and developers on the co-location of offshore wind farms and decapod fisheries in the UK." *Marine Policy* (Elsevier BV) 61: 16–22. doi:10.1016/j.marpol.2015.06.031.

JNCC. 2016. "Protected fish in offshore MPAs – WMS layers." *Protected fish in offshore MPAs – WMS layers.* https://ows.jncc.gov.uk/mpa_mapper/wms?

Jørgensen, Terje, Svein Løkkeborg, and Aud Vold Soldal. 2002. "Residence of fish in the vicinity of a decommissioned oil platform in the North Sea." *ICES Journal of Marine Science* (Oxford University Press (OUP)) 59: S288–S293. doi:10.1006/jmsc.2001.1165.

Kerckhof, Francis, Bob Rumes, and Steven Degraer. 2018. "Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Assessing and Managing Effect Spheres of Influence." Chap. 6: A closer look at the fish fauna of artificial hard substrata of offshore renewables in Belgian waters, 79–89. Ed. by S. Degraer, R. Brabant, B. Rumes & L. Vigin. Royal Belgian Institute of Natural Sciences, Brussels, Belgium.

Kerckhof, Francis, Joop W. P. Coolen, Bob Rumes, and Steven Degraer. 2018. "Recent findings of wild European flat oysters Ostrea edulis (Linnaeus, 1758) in Belgian and Dutch offshore waters: new perspectives for offshore oyster reef restoration in the southern North Sea." *Belgian Journal of Zoology* (Royal Belgian Institute of Natural Sciences (RBINS)) 148. doi:10.26496/bjz.2018.16.

Kirchgeorg, T., I. Weinberg, M. Hörnig, R. Baier, M. J. Schmid, and B. Brockmeyer. 2018. "Emissions from corrosion protection systems of offshore wind farms: Evaluation of the potential impact on the marine environment." *Marine Pollution Bulletin* (Elsevier BV) 136: 257–268. doi:10.1016/j.marpolbul.2018.08.058.

Krone, R., G. Dederer, P. Kanstinger, P. Krämer, C. Schneider, and I. Schmalenbach. 2017. "Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment - increased production rate of Cancer pagurus." *Marine Environmental Research* (Elsevier BV) 123: 53–61. doi:10.1016/j.marenvres.2016.11.011.

Krone, Roland, Lars Gutow, Tanja J. Joschko, and Alexander Schröder. 2013. "Epifauna dynamics at an offshore foundation – Implications of future wind power farming in the North Sea." *Marine Environmental Research* (Elsevier BV) 85: 1–12. doi:10.1016/j.marenvres.2012.12.004.

Lacey, Nichola C., and Peter Hayes. 2020. "Epifauna associated with subsea pipelines in the North Sea." Edited by Silvana Birchenough. *ICES Journal of Marine Science* (Oxford University Press (OUP)) 77: 1137–1147. doi:10.1093/icesjms/fsy196.

Luttikhuizen, P. C., J. Beermann, R. P. M. A. Crooijmans, R. G. Jak, and J. W. P. Coolen. 2019. "Low genetic connectivity in a fouling amphipod among man-made structures in the southern North Sea." *Marine Ecology Progress Series* (Inter-Research Science Center) 615: 133–142. doi:10.3354/meps12929.

Mestdagh, Sebastiaan, Tom Ysebaert, Tom Moens, and Carl Van Colen. 2020. "Dredging-induced turbid plumes affect bio-irrigation and biogeochemistry in sediments inhabited by Lanice conchilega (Pallas, 1766)." Edited by Joanna Norkko. *ICES Journal of Marine Science* (Oxford University Press (OUP)) 77: 1219–1226. doi:10.1093/icesjms/fsy122.

Oil & Gas Authority. 2020a. *Oil and Gas infrastructure - Surface.* Accessed Official public reference dataset. Retrieved from [last accessed 30 October 2020]. https://data.ogauthority.co.uk/arcgis/rest/services/OGA_Public_WGS84/OGA_Infrastructure_WGS84/FeatureServer.

Osiecka, Anna N., Owen Jones, and Magnus Wahlberg. 2020. "The diel pattern in harbour porpoise clicking behaviour is not a response to prey activity." *Scientific Reports* (Springer Science and Business Media LLC) 10. doi:10.1038/s41598-020-71957-0.

OSPAR Commission. 2019a. *OSPAR MPA Network filtered for United Kingdom.* Accessed Offcial public reference dataset. Retrieved from [last accessed 30 October 2020]. https://carto.maia-network.org/en/1/ospar.map.

—. 2018. "OSPAR threatened and/or declining habitats." *OSPAR threatened and/or declining habitats.* https://www.emodnet-seabedhabitats.eu/access-data/download-data/?linkid=ospar2018_poly.

Petroleum Act 1987. . "UK Government, London, United Kingdom." *UK Government, London, United Kingdom.*

Picken, Gordon, Tim Curtis, and Alan Elliott. 1997. "An Estimate of the Cumulative Environmental Effects of the Disposal in the Deep Sea of Bulky Wastes from the Offshore Oil and Gas Industry." *Offshore Europe.* Aberdeen, United Kingdom, 9-12 September: Society of Petroleum Engineers. doi:10.2118/38510-ms.

Pors, Janneke, Stephanie Verbeek, George Wurpel, Piet Briët, Anne-Mette Jørgensen, and Wouter van Dieren. 2011. "Decommissioning of North Sea oil and gas facilities: An introductory assessment of potential impacts, costs and opportunities." Tech. rep., LNS_{2}{0}{0}, (107 pp.), for IMSA Amsterdam provided by Living North Sea Initiative, Amsterdam, Netherlands.

Reubens, J. T., S. Degraer, and M. Vincx. 2014. "The ecology of benthopelagic fishes at offshore wind farms: a synthesis of 4 years of research." *Hydrobiologia* (Springer Science and Business Media LLC) 727: 121–136. doi:10.1007/s10750-013-1793-1.

Reubens, Jan T., Francesca Pasotti, Steven Degraer, and Magda Vincx. 2013. "Residency, site fidelity and habitat use of Atlantic cod (Gadus morhua) at an offshore wind farm using acoustic telemetry." *Marine Environmental Research* (Elsevier BV) 90: 128–135. doi:10.1016/j.marenvres.2013.07.001.

Rouse, Sally, Andronikos Kafas, Rui Catarino, and Hayes Peter. 2018. "Commercial fisheries interactions with oil and gas pipelines in the North Sea: considerations for decommissioning." Edited by Steven Degraer. *ICES Journal of Marine Science* (Oxford University Press (OUP)) 75: 279–286. doi:10.1093/icesjms/fsx121.

Rouse, Sally, Joanne S. Porter, and Thomas A. Wilding. 2020. "Artificial reef design affects benthic secondary productivity and provision of functional habitat." *Ecology and Evolution* (Wiley) 10: 2122–2130. doi:10.1002/ece3.6047.

Rouse, Sally, Peter Hayes, and Thomas A. Wilding. 2020. "Commercial fisheries losses arising from interactions with offshore pipelines and other oil and gas infrastructure and activities." Edited by Silvana Birchenough. *ICES Journal of Marine Science* (Oxford University Press (OUP)) 77: 1148–1156. doi:doi:10.1093/icesjms/fsy116.

Russell, Deborah J. F., Sophie M. J. M. Brasseur, Dave Thompson, Gordon D. Hastie, Vincent M. Janik, Geert Aarts, Brett T. McClintock, Jason Matthiopoulos, Simon E. W. Moss, and Bernie McConnell. 2014. "Marine mammals trace anthropogenic structures at sea." *Current Biology* (Elsevier BV) 24: R638–R639. doi:10.1016/j.cub.2014.06.033.

Schutter, Miriam, Martijn Dorenbosch, Floor M. F. Driessen, Wouter Lengkeek, Oscar G. Bos, and Joop W. P. Coolen. 2019. "Oil and gas platforms as artificial substrates for epibenthic North Sea fauna: Effects of location and depth." *Journal of Sea Research* (Elsevier BV) 153: 101782. doi:10.1016/j.seares.2019.101782.

Shell U.K. Limited. 2017. "Brent Decommissioning Programmes Environmental Statement." Tech. rep., (444 pp.), for Shell U.K. Limited provided by DNV GL LTD., Aberdeen, United Kingdom.

Soldal, A. 2002. "Rigs-to-reefs in the North Sea: hydroacoustic quantification of fish in the vicinity of a ``semi-cold" platform." *ICES Journal of Marine Science* (Oxford University Press (OUP)) 59: S281–S287. doi:10.1006/jmsc.2002.1279.

Stenberg, C., J. G. Støttrup, M. van Deurs, C. W. Berg, G. E. Dinesen, H. Mosegaard, T. M. Grome, and S. B. Leonhard. 2015. "Long-term effects of an offshore wind farm in the North Sea on fish communities." *Marine Ecology Progress Series* (Inter-Research Science Center) 528: 257–265. doi:10.3354/meps11261.

Sühring, R., A. Cousins, L. Gregory, C. Moran, A. Papachlimitzou, C. Phillips, R. Rowles, S. Supple, M. Wilczynska, and S. N. R. Birchenough. 2020. "The past, present, and future of the regulation of offshore chemicals in the North Sea—a United Kingdom perspective." Edited by Mark Gibbs. *ICES Journal of Marine Science* (Oxford University Press (OUP)) 77: 1157–1166. doi:10.1093/icesjms/fsz172.

Tidbury, Hannah, Nick Taylor, Johan Molen, Luz Garcia, Paulette Posen, Andrew Gill, Susana Lincoln, Adrian Judd, and Kieran Hyder. 2020. "Social network analysis as a tool for marine spatial planning: Impacts of decommissioning on connectivity in the North Sea." Edited by Nessa O\textquotesingleConnor. *Journal of Applied Ecology* (Wiley) 57: 566–577. doi:10.1111/1365-2664.13551.

Todd, Victoria L. G., Edward W. Lavallin, and Peter I. Macreadie. 2018. "Quantitative analysis of fish and invertebrate assemblage dynamics in association with a North Sea oil and gas installation complex." *Marine Environmental Research* (Elsevier BV) 142: 69–79. doi:10.1016/j.marenvres.2018.09.018.

Todd, Victoria L. G., Jane Clare Warley, and Ian Boyer Todd. 2016. "Meals on Wheels? A Decade of Megafaunal Visual and Acoustic Observations from Offshore Oil & Gas Rigs and Platforms in the North and Irish Seas." Edited by Michael L. Fine. *PLOS ONE* (Public Library of Science (PLoS)) 11. doi:10.1371/journal.pone.0153320.

Todd, Victoria L. G., Laura D. Williamson, Sophie E. Cox, Ian B. Todd, and Peter I. Macreadie. 2020. "Characterizing the first wave of fish and invertebrate colonization on a new offshore petroleum platform." Edited by Silvana Birchenough. *ICES Journal of Marine Science* (Oxford University Press (OUP)) 77: 1127–1136. doi:10.1093/icesjms/fsz077.

Todd, Victoria L. G., Laura Lazar, Laura D. Williamson, Ingrid T. Peters, Aimee L. Hoover, Sophie E. Cox, Ian. B. Todd, Peter I. Macreadie, and Dianne L. McLean. 2020. "Underwater Visual Records of Marine Megafauna Around Offshore Anthropogenic Structures." *Frontiers in Marine Science* (Frontiers Media SA) 7. doi:10.3389/fmars.2020.00230.

Todd, Victoria L. G., William D. Pearse, Nick C. Tregenza, Paul A. Lepper, and Ian B. Todd. 2009. "Diel echolocation activity of harbour porpoises (Phocoena phocoena) around North Sea offshore gas installations." *ICES Journal of Marine Science* (Oxford University Press (OUP)) 66: 734–745. doi:10.1093/icesjms/fsp035.

Tornero, Victoria, and Georg Hanke. 2016. "Chemical contaminants entering the marine environment from sea-based sources: A review with a focus on European seas." *Marine Pollution Bulletin* (Elsevier BV) 112: 17–38. doi:10.1016/j.marpolbul.2016.06.091.

van der Molen, Johan, Luz María García-García, Paul Whomersley, Alexander Callaway, Paulette E. Posen, and Kieran Hyder. 2018. "Connectivity of larval stages of sedentary marine communities between hard substrates and offshore structures in the North Sea." *Scientific Reports* (Springer Science and Business Media LLC) 8. doi:10.1038/s41598-018-32912-2.

van der Stap, Tim, Joop W. P. Coolen, and Han J. Lindeboom. 2016. "Marine Fouling Assemblages on Offshore Gas Platforms in the Southern North Sea: Effects of Depth and Distance from Shore on Biodiversity." Edited by Andrew Davies. *PLOS ONE* (Public Library of Science (PLoS)) 11. doi:10.1371/journal.pone.0146324.

van Hal, R., A. B. Griffioen, and O. A. van Keeken. 2017. "Changes in fish communities on a small spatial scale, an effect of increased habitat complexity by an offshore wind farm." *Marine Environmental Research* (Elsevier BV) 126: 26–36. doi:10.1016/j.marenvres.2017.01.009.

Wright, Serena R., Christopher P. Lynam, David A. Righton, Julian Metcalfe, Ewan Hunter, Ainsley Riley, Luz Garcia, Paulette Posen, and Kieran Hyder. 2020. "Structure in a sea of sand: fish abundance in relation to man-made structures in the North Sea." Edited by Steven Degraer. *ICES Journal of Marine Science* (Oxford University Press (OUP)) 77: 1206–1218. doi:10.1093/icesjms/fsy142.