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Introduction to the Themed Section: '*Decommissioned offshore man-made installations*'

Introduction

Science in support of ecologically sound decommissioning strategies for offshore man-made structures: taking stock of current knowledge and considering future challenges

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The blue growth agenda has spurred an accelerating exploitation and continued development of the coastal and marine environment. This is also driven by the increasing need to generate renewable energy. In most cases, this has resulted in a large number of man-made structures (MMSs) across several soft sediment environments. The nature of these structures ranges from oil and gas installations to harbour walls, anchored buoys, pipelines and offshore wind farms. These structures host fouling communities that are often new to offshore regions, potentially serving as stepping stones for range-expanding (non-indigenous) species and providing habitat and shelter for a variety of marine species. The altered local biodiversity also affects biological and biogeochemical processes from the water column to the seafloor, either directly (e.g. scouring, organic matter export from piles) or indirectly (e.g. closure or displacement of fisheries) and, hence, ecosystem functioning at various spatial and temporal scales. A proper understanding of the effects of artificial hard substrate and the consequences of its removal (e.g. through decommissioning) to marine biodiversity has yet to develop to maturity. This themed article set contributes to the scientific knowledge base on the impacts of MMSs on marine ecosystems with the specific aim to fertilize and facilitate an evidence-based debate over decommissioning. This discussion will become ever more vital to inform marine spatial planning and future policy decisions on the use and protection of marine resources.

Keywords: artificial hard substrata, artificial reef, decommissioning debate, ecological effects, evidence knowledge base, fisheries exclusion

Introduction

Man-made structures (MMSs), such as buoys for marking and safe shipping, harbour walls for access to harbours, and constructions related to aquaculture or dikes and groynes for protection against inundations, have been present in the coastal environment for centuries. More recently, MMSs have been placed further off the coast; this is not least with the aim of generating renewable sources of energy, mainly wind. While oil and gas platforms have been present offshore for decades (Olsgard and Gray, 1995), the growing necessity to generate renewable marine energy has prompted the exploration of alternative energy sources worldwide in support of blue growth developments (Degraer *et al.*, 2019).

The introduction of a large variety of MMSs in soft sediment areas has resulted in locally altered biodiversity. A multitude of typical hard substrate species now finds suitable habitat in a formerly hostile environment. MMSs are colonized by a suite of fouling species, many of which occur in high densities. These mainly comprise common, suspension feeding species like mussels, anemones, and amphipods (Wilhelmsson and Malm, 2008). In turn, MMSs and their fouling communities attract mobile organisms. Mobile benthic and demersal species like Atlantic cod (*Gadus morhua*), pouting (*Trisopterus luscus*), European lobster (*Homarus gammarus*), and edible crab (*Cancer pagurus*), as well as pelagic fish like mackerel (*Scomber scombrus*), seabirds like sandwich tern (*Thalasseus sandvicensis*), and marine mammals such as the harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*), are often detected in higher densities close to MMSs compared to the open sea (e.g. Soldal *et al.*, 2002; Krone *et al.*, 2013; Reubens *et al.*, 2014; Russell *et al.*, 2014; Vanermen *et al.*, 2017). These species benefit from locally enhanced shelter and feeding opportunities around MMSs. The combined effect is generally referred to as the artificial reef effect (Dannheim *et al.*, 2020). Aside from the common species attracted to MMSs, the artificial reefs may also provide habitat to rare and/or red listed species, such as the solitary coral (*Caryophillia smithii*) (Coolen *et al.*, 2015) and the colonial cold-water coral (*Lophelia pertusa*) (Gass and Roberts, 2006; Henry *et al.*, 2018), or species that are only seldomly observed such as tadpole fish (*Raniceps raninus*), tompot blenny (*Parablennius gattorugine*), longspined bullhead (*Taurulus bulbalis*), and ballan wrasse (*Labrys bergylta*) (Kerckhof *et al.*, 2018). However, the artificial reef effect is more than just a locally altered species pool. A suite of knock-on effects into biological and biogeochemical processes has been described from the water column to the seafloor. For example, organic matter export from the fouling community to the seafloor is assumed to affect local nutrient cycling in the surrounding soft sediments (Coates *et al.*, 2014). On the other hand, the altered species pool affects trophic interactions (Mavraki *et al.*, 2019) and secondary production and MMSs may also serve as stepping stones for range-expanding (sometimes non-indigenous; Kerckhof *et al.*, 2011) species altering the connectivity patterns of populations (Henry *et al.*, 2018; Coolen *et al.*, 2020a). Last but not least, in the case of fixed MMSs, the highly complex artificial reef effect is often complemented by the effects of the *de facto* closure for fisheries within a 500-m radius of the construction (UNCLOS Art. 60, paragraph 5), allowing the surrounding seafloor to eventually recover from anthropogenic disturbance. This is often referred to as the fisheries exclusion effect.

MMSs such as oil and gas platforms and offshore wind farms are temporary constructions most often allowed to occupy marine space for a specified period after which they are deemed to be decommissioned. In the Northeast Atlantic, the present-day commitment under the OSPAR Convention is to fully remove the MMSs when they are decommissioned (OSPAR Decision 98/3). However, derogations from the general principle of complete removal may apply to, for example steel installations weighing more than 10 000 tonnes in air and gravity-based concrete installations.

The expected ecological effects associated with decommissioning practices will comprise, for example the removal of the established artificial hard substrate community, elevated turbidity (e.g. resulting from dredging), elevated underwater sound (e.g. from boat traffic and decommissioning operations), and an increased risk of ship collisions and pollution, all of which can be detrimental to marine ecosystems. On the other hand, the removal of the MMSs will allow restoration of the natural habitat, reversing the artificial reef effect, but at the same time also the protection of the *de facto* fisheries exclusion.

A new challenge for industry, regulators, and governments worldwide is the planning and execution of decommissioning of MMSs. This process will have to be judged by whether it is socially, economically, and ecologically beneficial to apply derogation (e.g. “rigs-to-reefs”) or, to partially or completely remove these infrastructures. To date, there are notable gaps in the knowledge base required to support science-based decisions on this topic. These knowledge gaps are: (i) how the introduction of these structures has modified the ecosystem, locally and beyond, and an assessment of the potential negatives and positives of MMSs and, hence, the effect of the removal of the artificial reef and fisheries exclusion effect and (ii) how the activities related to decommissioning may further affect the marine ecosystem.

To fill these knowledge gaps, the *ICES Journal of Marine Science* solicited contributions to a themed article set “Science in support of ecologically sound decommissioning strategies for offshore man-made structures”. The call attracted 24 submissions, 14 of which were accepted for publication. These papers contribute significantly to the knowledge base, reviewing existing literature, covering new targeted research on the ecological effects of MMSs, and providing regulatory perspectives and recommendations for future research efforts.

This themed article set

Fortune and Paterson (2020) conducted a review of the current understanding of the ecological influence of MMSs and the consequences of decommissioning. Their paper acknowledges that the current knowledge is still very far from complete. Dedicated research on, e.g. food web assessments, ecological consequences resulting from decommissioning practices, and consideration on decommissioning options will have considered. Similarly, Dannheim *et al.* (2020) identify knowledge gaps by presenting an exhaustive literature analysis of 233 publications with the aim of summarizing the current knowledge on how marine renewable energy installations affect marine benthic systems. Their analysis provides a mechanistic insight into how marine renewable energy installations affect the marine biogeochemical reactor, food production, and biodiversity and concludes with a summary of priority hypothesis-driven research needs. The need for an in-depth understanding of the impacts of MMSs is also supported by Fowler *et al.* (2020), who review environmental policy objectives in the North Sea and summarize existing knowledge about ecological effects of oil and gas rig, and offshore wind farm decommissioning. Their work issues a plea for science–industry partnerships to efficiently and effectively create the necessary knowledge base, which would be equally relevant to the debate on oil and gas rig and offshore windfarm decommissioning. A first example of the value of opportunistic data collected by the industry with remotely operated vehicles—of which terabytes are held by oil and gas companies—is given by Todd *et al.* (2020) characterizing the pioneer wave of fish and invertebrate colonization of an oil and gas rig. Lacey and Hayes (2020) present another example of the benefit of an industry–science collaboration utilizing industry-collected footage from remotely operated vehicle inspections of pipelines in the northern and central North Sea. By focusing on the epifauna colonizing pipelines, they assess the interactions of benthic epifauna with pipelines, and their associated structures, demonstrating the high species richness of MMSs.

Aside from overviewing the existing knowledge base and scoping for added value through improved industry–science interactions, this themed article set also provides insights into societal and regulatory issues relevant to the decommissioning debate. Rouse *et al.* (2020) demonstrate the damage to fishing gear, loss of fishing time, and considerable risks to health and safety due to oil and gas infrastructure by analysing 1590 incidents between fishing activities and oil and gas infrastructure. Sühring *et al.* (2020) analyse the regulatory frameworks governing offshore chemicals used by the oil and gas industry, particularly focusing on the North Sea and the new set of risk assessments as applied in the United Kingdom. This work offers insights into how a sustainable and cost-effective assessment of offshore chemical use can be achieved in the North Sea.

This themed article set further adds to the knowledge base of the ecological effects of MMSs. Targeting the surrounding mobile sediments of MMSs and using morphological and molecular species identification techniques, Klunder *et al.* (2020) report on the long-term effects of a gas platform on the benthic community in the Southern North Sea. They found that it is linked to an altered abiotic environment (e.g. sediment organic matter content) close to the platform, particularly in the direction of the predominant currents. However, when installed on natural rocky reefs, MMSs such as rock armouring of cables may support assemblages like those inhabiting the surrounding habitat, at least provided that material similar to the natural reef is used to construct the MMS as shown by Sheehan *et al.* (2020). This is consistent with the findings of Coolen *et al.* (2020a, b), who reported a high comparability between the epifouling community of erosion protection layers of oil and gas platforms and offshore wind farms and that of natural gravel beds. On these MMSs extending vertically from bottom to surface; however, they found the epifouling communities to drastically change and hence deviate from natural rock over the depth gradient. Comparative work on a suite of artificial structures (e.g. wrecks, wind turbines, cables, and oil and gas structures) was also conducted by Wright *et al.* (2020), who investigated the local abundance of three fish species, cod (*G. morhua*), plaice (*Pleuronectes platessa*), and thornback ray (*Raja clavata*). Their results showed that aside from correlations with, for example temperature and depth, all species showed seasonal increases in their abundance in areas with high densities of MMSs.

Aside from effects on the community composition (e.g. abundances and species composition), effects of MMSs on the ecosystem include altered ecosystem functioning. Mestdagh *et al.* (2020) mimicked the effect of increased turbidity due to dredging operations that may occur during decommissioning activities. They conclude that extreme increases in turbidity can have a significant impact on the benthic biogeochemical fluxes through changes in the behaviour of bio-irrigators such as *Lanice conchilega*. Using a particle tracking model coupled with a three-dimensional hydrodynamic model, Barbut *et al.* (2020) showed clear differences in the spatial overlap of offshore windfarms and the spatial distribution of the spawning grounds of six flatfish species. They showed that, with the planned proliferation of offshore wind farms, the North Sea spawning grounds of European plaice, common dab, and brill may be impacted.

Evidently, both ecosystem structure and function are important and knowledge on both should be combined to inform the decommissioning debate in an integrated manner. Acknowledging the existence of good knowledge on various aspects of the environmental effects of MMSs, Pezy *et al.* (2020), therefore, promotes adopting a systemic approach (e.g. Ecological Network Analysis) to unravel the structural and functional effects of offshore wind farms.

Forward look

While a large knowledge base already exists, we still lack information to accurately inform the decommissioning debate. This is particularly true for how these artificial habitats contribute to the wider resilience of marine ecosystems. Such knowledge, however, is crucial to allow for a science-based assessment of the positives and negatives of the removal of MMSs and, hence, to decide on decommissioning strategies. The increased knowledge base should further form the basis for revising the current regulatory frameworks on decommissioning so as to ensure the inclusion of scientific knowledge in marine policy and management. We acknowledge that, aside from the science–industry–policy–management interactions, the wider public (e.g. environmental NGOs) needs to engage in the discussion on decommissioning strategies to ensure an outcome that is accepted by all stakeholders and society. This themed article set has helped to set the stage for the initial direction of this discussion and highlights that further progress is needed to assess the wider ecological aspects of a modified MMSs environment. While this themed article set was being compiled, several industry-sponsored initiatives have driven efforts to gather further scientific evidence. For example, in 2012, the initiative "the INfluence of man-made Structures In The Ecosystem" (https://www.insitenorthsea.org/) was launched. The INSITE Programme was conceived to produce independent science that would lead to a better understanding of the influence of MMSs on the North Sea ecosystem so as to inform the decommissioning debate. At the end of 2017, the research funded under INSITE Phase I helped to target further efforts for a follow-up stage in collaboration with academics (https://nerc.ukri.org/research/funded/programmes/insite/).
Elsewhere (e.g. Australia and the United States), efforts have been made to continue to expand on the science to provide evidence to inform advisors, industry, and regulators (https://nerc.ukri.org/research/funded/programmes/insite/).

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