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Review Article

Ecological best practice in decommissioning: a review of scientific research

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The Oslo and Paris Commissions (OSPAR) decision 98/3 prohibits the dumping of man-made structures (MMS) offshore. However, there are regions of the world where MMS are recognized as providing an ecological and societal benefit through the provision of ecosystem goods and services. This review provides a commentary on our current understanding of the ecological influence of man-made structures, the consequences of their decommissioning and recognizes that our knowledge is far from complete. It is known that a diverse and complex ecosystem of attached organisms develops on submerged structures which supports a localized food web that could not exist without them. However, our lack of detailed information makes modelling of system response to decommissioning very tentative. Ideally, we should use the best possible scientific information to reach a consensus as to whether the blanket removal of MMS (excepting derogations) is the most environmentally supportable option. The evidence available to-date shows both benefits and some risk in leaving MMS in place and this needs to be examined without preconception. On the UKCS, MMS as artificial habitats are not considered under the Habitats Directive, irrespective of the value or rarity of the species present. We conclude that a more comprehensive regulatory process, together with the recognition of the ecology associated with man-made structures, would allow science to play a role in the decision-making rather than supporting a blanket policy ignoring ecological context.

Keywords: decommissioning, ecosystem impacts, ecosystem services, man-made structures

Introduction

Any structure submerged in sea water quickly becomes colonized by marine biota. An ecological succession then follows, often leading to complex three dimensional and heterogeneous habitats of significant biodiversity and function. This includes man-made structures (MMS) placed within a marine environment. In the North Sea, the requirement to decommission existing MMS (OSPAR Commission Decision 98/3) introduces interesting questions around the ecological status of MMS. While technological advances have improved the planning and implementation of decommissioning, there remain more than 1 350 offshore installations in the OSPAR maritime area (OSPAR commission, 2015), many of which are mature. Despite this, there seems to be little concern over the ecology associated with MMS. The question of the best management of redundant resources is critical to the future of the offshore industry and also perhaps to the ecology of the region. Yet, management decisions are currently being made without sufficient knowledge of the potential ecological consequences. There is an urgent need to consider the purpose of decommissioning legislation in relation to ecological best practise for the future to the renewable energy sector and marine ecology.

The Oslo and Paris Commissions decision 98/3 (OSPAR, 1998), prohibits the dumping of whole or partial offshore structures and states that re-use, recycling, or disposal on land is the preferred option. “Dumping” encompasses structures that might be left in place after their commercial life is over. Derogations to this requirement are very limited, requiring most MMS to be wholly or partially removed. While the intentions of these regulations are clear, namely to protect the marine environment and ensure proper management of redundant resources, there is a growing body of evidence that offshore structures themselves become part of the ecology of the system, utilized by marine biota and providing useful ecosystem function and services and habitat diversity (Todd *et al.*, 2009; Consoli *et al.*, 2013; Bergmark and Jørgensen, 2014; Claisse *et al.*, 2015). Offshore man-made structures have also unintentionally served as *de facto* marine protected areas, providing a localized refuge from fishing activities (Fujii, 2015). Therefore, the ecology of decommissioning offshore structures requires evaluation and the implications locally, and in the wider context of the regional seas, should be acknowledged. This would allow scientific evidence to feed into a multi-criteria analysis of the optimal decommissioning outcomes for all sectors.

Methodology

Details of the literature search terms and search engines used are provided (Supplementary Appendix S1). The breadth of current knowledge is limited by research efforts which themselves reflect the priorities of research funding bodies, scientific expertise and policy drivers. This can create an "information bias". For example, subject areas where there are commercial drivers (e.g. fisheries science) may be better represented and have more background information than others (seabirds).

Features of the MMS environment

Man-made structures in the marine environment have a number of recognizable characteristics. The most obvious is that they are composed of non-natural substrata such as steel or concrete but, despite their artificial composition and without anti-fouling treatments, MMS quickly develop a succession of marine biota (Whomersley and Picken, 2003; De Mesel *et al.*, 2015). Both concrete and steel are suitable for settlement by invertebrate assemblages (Macreadie *et al.*, 2011) and the substratum can be a significant variable in determining the rate and extent of settlement. For example, growth of shallow water corals was greater on painted steel than on concrete (Fitzhardinge and Bailey-Brock, 1989). In addition, steel MMS have also a more complex spatial structure than concrete and therefore provide a more three-dimensional reef habitat with greater niche variation (Pickering and Whitmarsh, 1997; *in* Løkkeborg *et al.*, 2002).

The side elevations of the MMS can be considered as either "intertidal", which suggests regular wetting and drying on the basis of the tidal cycle, or fully submerged. Intertidal hard substrata are rare in the North Sea (van der Stap *et al.*, 2016) and given the vertical nature of MMS, the "intertidal" zone is spatially restricted, akin to a marine cliff, making competition for space intense. As for any marine systems, water depth and light availability have been shown to be significant factors in the distribution of the associated biota (Jones *et al.*, 2012; Fujii and Jamieson, 2016; van der Stap *et al.*, 2016). The placement of the MMS can also result in localized effects, where variations in current speeds and orientation provide shelter or focus passing currents for filter feeding epifauna (Løkkeborg *et al.*, 2002 and references therein).

A feature unique to MMS is the operational legacy including maintenance and cleaning regimes, disturbance and pollution. The operational activities of offshore MMS represent a focal point of disturbance to marine biota both in terms of noise and drilling activities. The level of disturbance will vary depending on the functional stage of the MMS with the most negative impacts associated with MMS construction (Russell *et al.*, 2016). However, there is a serious lack of data on disturbance due to decommissioning. While cessation of operations may result in the reduction of noise, the decommissioning operations involving the use of cutting equipment and/or explosives may require careful management to avoid unacceptable level of ecosystem damage.

The issue of chemical pollution from operations is more relevant to the offshore oil and gas industry than the renewable sector and can result in the contamination with hydrocarbons in production water and accidental spills to the water column. The impact of contaminants on marine biota is an active area of research with several recent articles describing the mechanisms and temporal and spatial extent of impacts (Table 1). Drill cuttings piles, produced around the base of wells are often contaminated with hydrocarbons and heavy metals (Breuer *et al.*, 2008). Air pollution also occurs due to the release of gases during operations including CO_2, NO_x, and small particulates (PM10). Also, grey water and ground food waste are allowable for discharge at sea (www 1) and these artificial nutrient subsidies may alter the ecological status of the locality but would not continue on decommissioning. Following cessation of operations, disturbance from noise, drilling and organic enrichment would also end. Little is known of how the MMS ecosystem would respond to this change (Fujii, 2015).

Understanding MMS ecosystems

MMS are challenging environments to study, often with additional limitations to research. As privately owned assets, permission must be sought to carry out ecological surveys (as well as to publish findings). Even with permission, access may be restricted due to operational, safety and weather factors. The assessment of fish abundance is important yet difficult at MMS locations as trawl-surveys are limited for safety reasons. Consequently, techniques have been developed and adapted for use at MMS including; underwater visual census, hydro-acoustic monitoring, photography/video footage, gill net surveys, and fish bait traps (Figure 1). The data derived from such surveys are difficult to compare as the methods may be selective for different species or sizes, depending on fish behaviour. For example, baited traps are not attractive for all species and may under-report fish diversity. A study of fish assemblages at the decommissioned Miller platform (Central North Sea) used baited fish traps and recorded relatively high numbers of saithe which were absent or rare at open water sites as assessed using bottom trawl surveys (International bottom trawl survey, IBTS, Fujii, 2015). Also, trawling vessels may have variable gears and selective mesh sizes (Løkkeborg *et al.*, 2002). Conversely, non-selective trawls, passive gill-netting, and ROV video footage may suggest other fish species such as ling (*Molva molva*) and flatfish (Fujii, 2015) are important. Smaller species that dwell in cavities may be underreported due to their secretive behaviour and non-commercial status. Thus, while all survey data is helpful, it is unclear what influence variable methodology has on the findings.

Monitoring the movement of fish over time is similarly limited by access and by weather conditions and studies are often conducted during summer months (Løkkeborg *et al.*, 2002; Soldal *et al.*, 2002). A longer period of monitoring has been achieved around the decommissioned Miller platform (2 years, Fujii, 2015) and a pilot study indicated diurnal movements of fish and their prey species (Fujii and Jamieson, 2016). Despite technical challenges, data from the baited fish traps do suggest turnovers of individual fish using MMS, perhaps regulated at seasonal scales (Fujii, 2015).

Table 1. Selected peer-reviewed scientific publications examining aspects of pollution and offshore oil production (note: this is not exhaustive and is limited for brevity to the most relevant to this review, literature search methodology, and criteria detailed in Supplementary Appendix S1).

Title	Reference	Purpose	Data type	Findings
Environmental aspect of oil and water-based drilling muds and cuttings from Dibi and Ewan off-shore wells in the Niger Delta, Nigeria	Adewole *et al.* (2010)	Drilling muds and cuttings derived from Ewan and Dibi off-shore wells in the Niger-Delta petroleum province of Nigeria was studied to evaluate their toxicity and possible environmental impacts that may result from their indiscriminate disposal	Heavy metals, THC, PAH	It is likely that the drill muds and cuttings wastes will increase the pollution problems in aquatic environment, thereby causing stress for the fish and other aquatic organisms
Biomarkers in natural fish populations indicate adverse biological effects of offshore oil production	Balk *et al.* (2011)	To examine samples from natural populations of haddock and cod in two areas with extensive oil production	Biomarkers	Exposure to and uptake of polycyclic aromatic hydrocarbons (PAHs) were demonstrated, and biomarker analyses revealed adverse biological effects, including induction of biotransformation enzymes, oxidative stress, altered fatty acid composition, and genotoxicity
Assessment of metal concentrations found within a North Sea drill cuttings pile	Breuer *et al.* (2008)	The analysis of geochemical carrier substances (Mn and Fe oxyhydroxides) and metal (Ba, Co, Cr, Cu, Mo, Pb, V) concentrations from a cuttings pile	Heavy metals in cuttings piles, pore water oxygen and sulfide	Results show a rapid removal of oxygen within the top few millimetres of the cuttings pile along with elevated concentrations of total hydrocarbons and solid phase metal concentrations compared to the surrounding environment
Historic scale and persistence of drill cuttings impacts on North Sea benthos	Henry *et al.* (2017)	To assess the temporal persistence and spatial scale of drill cutting pile impacts on benthic communities using industry survey database (UK Benthos)	Industry surveys of benthic macrofauna, sediment properties, total oil, aromatic hydrocarbons, and trace metals	Only 19 surveys out of 351 were standardized sufficiently to compare statistically. 12 of 19 showed significant benthic responses to drilling piles. Most effects were limited within 1 km and persisted up to 8 years post drilling.
Recovery of deep-water megafaunal assemblages from hydrocarbon drilling disturbance in the Faroe–Shetland Channel	Jones *et al.* (2012)	Recovery of benthic assemblages from physical disturbance at the Laggan deep-water hydrocarbon drilling site was assessed using ROV quantitative video survey	ROV video footage	Sessile faunal densities and richness increased significantly with increasing distance from drilling in all years, although both metrics were significantly higher close to drilling after 3 and 10 years when compared to immediately after drilling
Whole-body concentrations of elements in three fish species from offshore oil platforms and natural areas in the Southern California Bight, United States	Love *et al.* (2013)	To determine if offshore platforms are a major source of contamination by trace element in fish	Whole body samples for elemental analysis	None of the 21 elements measured consistently exhibited higher concentrations in fish from platforms compared to natural areas. Some elements were higher at natural sites. Some elements were found at toxic levels in both sites.
Hydrocarbon contamination affects deep-sea benthic oxygen uptake and microbial community composition	Main *et al.* (2015)	To examine how crude oil affected the oxygen consumption rate of a natural, deep-sea benthic community	Sediment core, microcosm, O_2 consumption, phospholipid fatty acids, stable carbon isotope	Sediment community oxygen consumption rates increased significantly in response to increasing levels of contamination in the overlying water of oil-treated microcosms
Crude oil exposures reveal roles for intracellular calcium cycling in haddock craniofacial and cardiac development	Sørhus *et al.* (2016)	To elucidate mechanism of crude oil disruption of fish development	PAH uptake, molecular expression, malformation observations	These data support a unifying hypothesis whereby depletion of intracellular calcium pools by crude oil-derived PAHs disrupts several pathways critical for organogenesis in fish

Figure 1. (a) A visual census of platform Gina showing anemones and kelp bass, Santa Barbara Channel, California (© James Forte, courtesy of Dr Milton Love, University of California at Santa Barbara). (b) Brambling, one of many migrating birds visiting oil platforms (courtesy of North Sea Bird Club). (c) Longeared owl at Murdoch Platform (image courtesy of NSBC). (d) Young-of-year Vermilion Rockfish (*Sebastes miniatus*) at platform Gilda.

The ecological baseline

A considerable difficulty in assessing the impact of MMS decommissioning is the lack of ecological information on the state of the marine environment prior to the MMS installation. The absence of baseline data makes it very difficult, if not impossible, to accurately assess the impact of the MMS on the host system or to provide a "target" for restoration post-decommissioning. Background or control sites some distance from oil and gas production are often used as a comparison (Jones *et al.*, 2012; Main *et al.*, 2015). However, under the Marine Strategy Framework Directive (MSFD) this implies that any selected comparative site represents "Good Ecologic Status" (GES, EU MSFD) which is often arguably not the case. The problem of a valid, or at least representative baseline, is a recurring one in environmental impact assessment. While there are no easy solutions, it is important to recognize this baseline problem and seek pragmatic answers. This is dealt with in some detail by Borja *et al.* (2013) highlighting four ways of determining the baseline or reference condition for the assessment of GES, namely:

(1) Find an area similar to the one under study but without the pressures (control area)
(2) Hind-cast conditions to a time before pressures were exerted
(3) Numerically model an "un-impacted" (control) condition
(4) Use expert judgement to gauge expected ecology.

With respect to decommissioning in the North Sea OSPAR region, these problems become very apparent. For (1), an area without an MMS may not reach GES where there are other pressures that affect the ecosystem, such as pollution, transport, noise, or fishing. The MMS area may have higher biodiversity and functionality and be closer to GES than an open region so that the baseline is confounded. For (2), how far do we have to hind cast to consider an untouched marine environment, such as the North Sea? This is hard to say and would this be correct, in any case, given that all systems change and adapt with time? For (3), while modelling is advancing there is still reason to require validation and in this context, that would be difficult though the modelling exercise may be valuable in increasing our understanding. Often, we revert to (4) as a workable solution. Therefore, the best pragmatic environment practise may be to aim to improve ecosystem functioning above the status quo and certainly do no damage. This approach suggests that the aim of decommissioning management could be to achieve an improving environmental

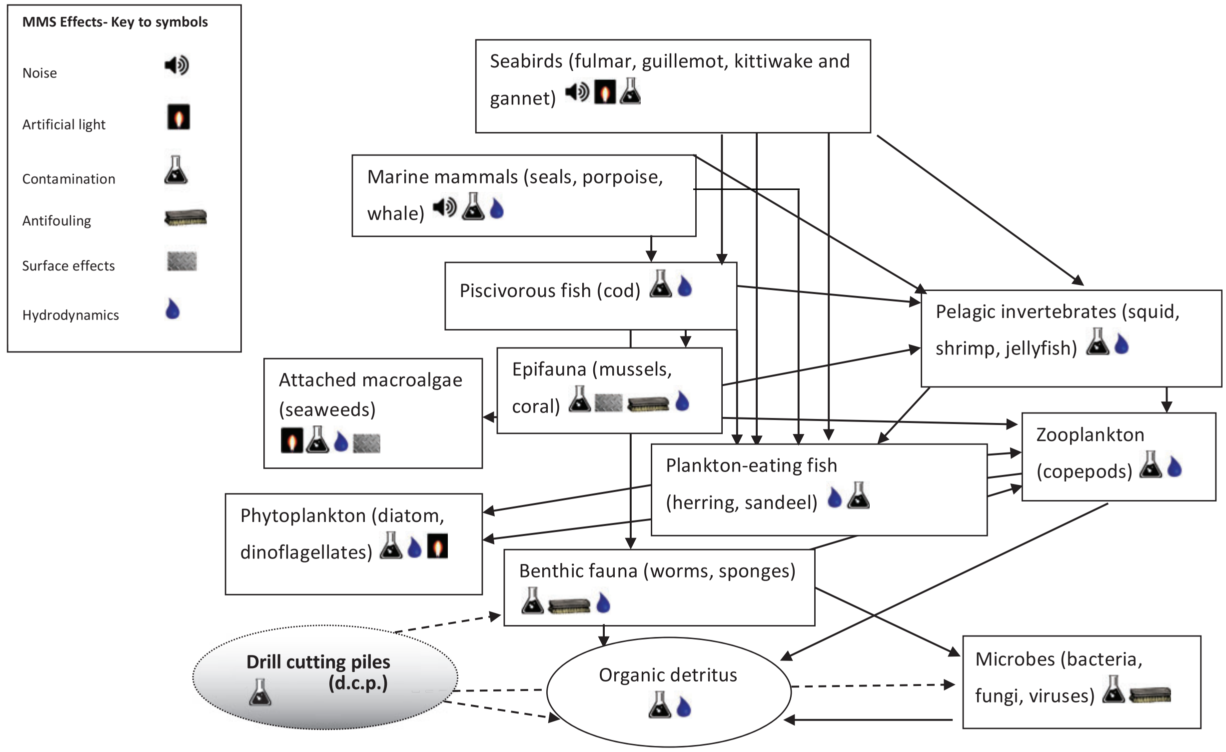


Figure 2. North Sea food web from both natural hard substratum and MMS are similar however there are impacts on the distribution and diversity of assemblages from operational activities including; pollution, noise, anti-fouling, and the presence of drill cuttings piles.

trajectory. Therefore, a clear question for environmental management is whether or not the local habitat would be improved by removing the MMS during decommissioning? However, any environmental change may benefit some species whilst being detrimental to others, such as those adapted to the "industrialized" conditions (e.g. *Capitella* spp.) and this would have to be recognized as part of the assessment process. Given the variability of geographical and hydrodynamic context between MMS, it seems only sensible to assess the individual circumstances of each platform and their ecology on a "case by case" basis.

MMS ecosystem structure

The most obvious MMS ecosystem components are attached to the structure. This highly visible epifauna can be identified from video footage or physical samples (Whomersley and Picken, 2003; Coolen *et al.*, 2016; van der Stap *et al.*, 2016). Less is known about other element of the ecosystem including mobile and cryptic species, meiofauna, plankton, and the microbial elements, including surface biofilms. In the Southern North Sea, sessile species richness (S) at offshore gas platforms increased from the surface to a depth of 15–20 m then decreased (van der Stap *et al.*, 2016). The lower S in shallow water may reflect the harshness of the intertidal system with periods of wetting and drying, the force of breaking waves and salinity change from rainfall, all factors observed in intertidal zonation. The lower S at greater depth may be related to competition from dominant taxa such as the plumose anemone (*Metridium dianthus*, synonym *senile*). This depth effect is in line with the "intermediate disturbance hypothesis" that at low levels of disturbance, strong competitors exclude inferior species, whereas at higher rates of disturbance, recruitment cannot compensate for high mortality (van der Stap *et al.*, 2016). Depth is therefore an important factor in the distribution of epifauna as well as variation in species richness on MMS (De Mesel *et al.*, 2015).

It is clear that the food webs associated with hard substrata are very different from those of open water. The question of how food webs on natural hard substrata vary from MMS is more subtle (Figure 2). The basics are similar; both are dominated by sessile life stages of a varied assemblage of marine forms. Differences in the community assemblages between natural and artificial systems will be driven by the physical nature of the surface, the three-dimensional conformation and the local environmental context. This does not account for deliberate measures to prevent or minimize colonization (anti-biofouling rings, anti-fouling treatments, materials, etc.) or local pollution. Differences will arise since settlement can be affected but direct comparative studies are lacking, however, it is clear a complex three-dimensional system develops on MMS and this habitat provisioning is an important ecosystem service. Scientists agree that there is a link between biodiversity and ecosystem function and services but also recognize the variability and context dependency of that link (Bulling *et al.*, 2010). Therefore, a local increase in biodiversity would be expected to alter the function of the ecosystem. This is clearly the case for MMS where new ecosystems that could not existed are now supported (Figure 2, De Mesel *et al.*, 2015). Considerable research effort has focused on evaluating the role of MMS for habitat provision, primarily for fish also as a substratum for epifauna such as cold water corals (Gass and Roberts, 2006; Fowler *et al.*, 2015).

MMS may serve as a refuge from fishing and higher levels of fish biomass are found at the MMS than in surrounding waters (Løkkeborg *et al.*, 2002; Claisse *et al.*, 2015). The quantification of fish is often assessed in conjunction with environmental variables such as depth, to gain an understanding of the dynamic relationships at play. For example, in the central North Sea, most fish caught at a "semi-cold" platform were at the lowest depth of 100 m compared to 10 and 50 m (Fujii, 2015). MMS size and orientation are important factors in determining the fish community present (Bartholomew *et al.*, 2008) with small artificial reefs having greater fish densities than larger artificial reefs, while larger reefs show higher fish biomass but fewer individuals. Soldal *et al.* (2002), noted cod (*Gadus morhua*) size increased in proximity to a decommissioned platform compared to those caught further away (1.25–5 nautical miles). While numbers of haddock (*Melanogrammus aeglefinus*) decreased in proximity to the platform, possibly as smaller fish were eaten or repelled by larger fish at the platform. Orientation of the MMS has been shown to be an important variable for fish abundance (Soldal *et al.*, 2002) perhaps affecting foraging and shelter. Also MMS may provide orientation cues and there is a need to understand the fish-habitat dependency in relation to changes in the number and distribution of MMS through decommissioning (Fujii, 2015).

Attraction vs. production debate

There is an ongoing debate about whether the higher fish biomass found at MMS results from an attraction to the MMS from the background area or whether the MMS facilitates the production of new biomass, through food provision and survivorship (Pickering and Whitmarsh, 1997; Osenberg *et al.*, 2002). The aggregation of fish at MMS has been attributed to a lower risk of predation, higher prey densities, and shelter from currents (Løkkeborg *et al.*, 2002). Some authors state that MMS attract and aggregate fish that would otherwise be widely dispersed, citing numerous studies finding higher levels of species richness and abundance associated with MMS (Consoli *et al.*, 2013). This has implications for the ecological management of MMS since attraction may concentrate fish stocks making them more vulnerable to predation or exploitation.

One study examining the attraction vs. production debate estimated the time spent by a fish species at an artificial reef (Smith *et al.*, 2016). These authors distinguish between "local" and "new" fish biomass production with "local" defined as fish attracted to the site and "new production" biomass that would not exist without the site. While the site was highly productive (211 kg y^{-1}), only 4-5% represented new production. Hence, the presence of MMS may not add significantly to net fish production. In the context of the North Sea, it has been suggested that the present areas closed to fishing (MPA, Platforms, etc.) would maintain the *status quo* of fish stocks and the conversion of existing structures into reefs is unlikely to further enhance fish stocks (Sayer and Baine, 2002).

The attraction/production debate is not relevant to "biofouling" organisms (anemones, bivalves, corals) as these settle on surfaces and fulfil a trophic function, facilitating the presence of carnivorous fish and larger predators. MMS may act as plankton accumulators through hydrodynamic and illumination effects (Keenan *et al.*, 2007) although there is uncertainty over the temporal significance of this impact. The presence of plankton is exploited by filter-feeding invertebrates, thus promoting biomass production. So, MMS are productive environments, especially for lower trophic levels, and attractive to other marine biota. The increased densities of fish and other marine life on MMS are exploited by sea mammals (Todd *et al.*, 2009; Russell *et al.*, 2014). A very small proportion of Grey and Harbour seals were found to follow subsea pipelines and to navigate between structures, presumably as a behavioural response to improve foraging success. These authors noted that burial or removal of such pipelines during decommissioning would remove these foraging opportunities (Russell *et al.*, 2014). The presence of top predators, such as the harbour porpoise (*Phocoena p. phocoena*), around North Sea MMS was shown to vary throughout a 24-h period with more encounters detected at night and indications that these visits were associated with hunting and feeding (Todd *et al.*, 2009).

Bird and MMS interactions

The effect of MMS on birds is not well understood with little peer-reviewed research (Ronconi *et al.*, 2015). The most commonly described direct effects are collision and attraction to lights and flares. This occurs in an unpredictable manner but often coincides with poor weather and limited visibility. MMS may be visited by significant numbers of migrating birds in the spring and autumn, especially if they are exhausted. Many of these migratory birds will be in poor condition and use MMS as an opportunistic resting site (Figure 1) and without a site they may have "ditched" into the ocean and died. Thus, MMS may increase the survivorship for some birds but others may perish after arrival. Starvation was the most common cause of mortality observed at offshore platforms in the Gulf of Mexico (Ronconi *et al.*, 2015). However, the initial benefits such as rest sites may be offset by disruption to the natural functioning of the ecosystem (Ronconi *et al.*, 2015). Other MMS effects on birds include; the provision of foraging and roosting sites, exposure to contaminants, and physical hazards. Light attraction is believed to be the most important factor driving nocturnal circulation of birds around offshore platforms and contributing to the mortality of high numbers of birds annually in the North Sea (Ronconi *et al.*, 2015). Mitigation strategies such as shielding and light reduction may be helpful. Weather conditions are also an important factor in the success or otherwise of migration flights. Anecdotally, poor visibility can increase the number of land birds visiting platforms but there is a lack of systematic data. One study on a wind energy platform found a correlation in call rates of migratory birds and fog, drizzle, and rain with 50% of strikes recorded occurred over a 2-day period of poor visibility (Ronconi *et al.*, 2015, and references therein).

Foraging activities by seabirds appear to be most notable in darkness when the lights and flares attract prey to surface waters (Ronconi *et al.*, 2015). Visiting corvids and raptors may be able to reside for some time if they prey on smaller migrants. Thus MMS provide a source of prey while increasing the exposure of smaller birds to predation (Figure 1). Information regarding the bird species and numbers is usually collected by observer-based measurements. This is time-consuming, expensive and of variable quality due to the lack of standard protocols. Also, access to MMS for systematic monitoring may be restricted and vessel-based observations are biased towards summer months. There is scope for improving data collected using improved technology including radar, camera, acoustics, and telemetry. Many small seabirds and most passerines are too small to carry satellite or GPS tags so VHF tags can be used and platforms fitted with receiver stations to record the presence/absence of tagged birds. This method requires an intervention to fit the tag and analysis will be limited by sample size. However, instruments operate continually and automatically in most conditions and could complement observer-based recording. Data from different sensors could be linked, validated and economical if integrated with existing technology (radar on platforms) (Ronconi *et al.*, 2015). A long-term continuous monitoring program is necessary if bird–MMS interactions and the full impacts of decommissioning are to be understood.

Connectivity and invasive species

Most species do not reside on platforms for their entire lives and may use the surrounding regions (seabed and water column), as well as parts of the platform at different life stages. Therefore, they are ecologically part of a wider regional community of interconnected populations (Schroeder and Love, 2004). Understanding the connections, both biological and physical, is important for determining the implications of the removal of structures. Connectivity information could be a useful addition to the environmental impact assessment of individual decommissioning plans. Only integrated regional-scale assessments can provide a complete insight of decommissioning impact. The biological traits of an organism such as mobility, planktonic larval stages, duration of larval viability (PLD), spawning timing, vertical migration behaviour, and life cycle length will influence the range of connectivity between MMS. Connectivity is also affected by abiotic factors such as water currents, wind speed and direction, density of MMS (available hard substrata), and anthropogenic vectors (vessel movements). The spatial isolation of an MMS may influence the ratio of resident to visitor fish. Structures which support large resident populations are more likely to offer value as a habitat than structures which support small or transient populations, and would therefore be more valuable in ecological terms for decommissioning options which involve leaving all or part of the structure in place (Fowler *et al.*, 2015). However, assessments of each individual MMS ecosystem is important to take account of particular geographic importance that even small structures may have where populations of rare or endangered species are involved.

A negative impact of connectivity is the potential spread of invasive non-native species (INNS). The dispersal of INNS is considered one of the greatest threats to ecological functioning of "native" ecosystems (Page *et al.*, 2006; Cloern and Jassby, 2012). In addition, the consequences of INNS can be severe for fisheries and aquaculture. Although more commonly associated with marinas and inshore infrastructure, INNS have been found on renewable infrastructure in the Orkney Island Archipelago and in the southern North Sea (Coolen *et al.*, 2016; Want *et al.*, 2017). In deeper waters, the lack of baseline data on species distribution hampers evaluation of the occurrences and impact of INNS. It is positive that the International Ballast Waters Directive has finally been ratified and action on the control of ballast water is more prominent and entered into law in 2017 (www 2).

The occurrence and potential spread of exotic invertebrates on offshore platforms in the pacific offshore continental shelf (POCS) was explored using biophysical models (Simons *et al.*, 2016). INNS were present in inverse proportion to native species, demonstrating competition for space. A finding of note was the enhanced dispersal of planktonic larvae from offshore structures compared to near shore sites (travelling up to 10 km cf. 100 m) due to high and sustained offshore advection. The presence of INNS on MMS would reduce the ecological value of the MMS and introduce risk. Monitoring for INNS is advisable and methods include rapid assessment surveys or settlement panels with scrape sampling (Cook *et al.*, 2015). A high risk of INNS occurring and dispersing could be an important factor in the decommissioning decision for MMS in that area.

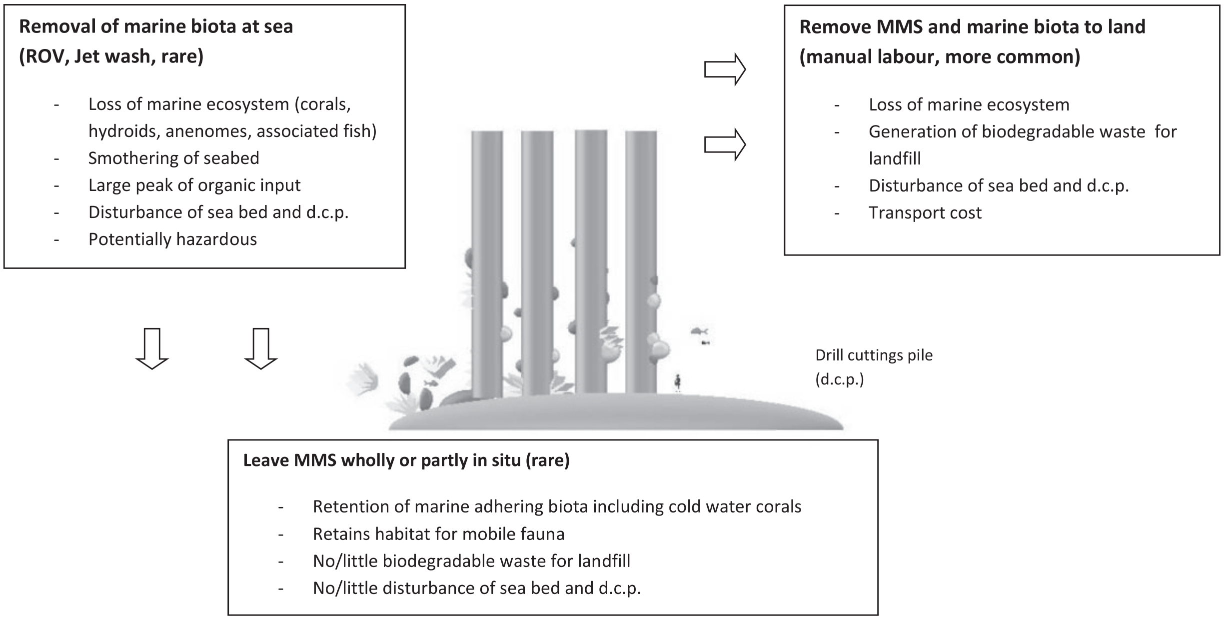
Environmental aspects of decommissioning options

The EIA process

The offshore industry undertakes environmental impact assessments (EIA) and produces an environmental statement as part of decommissioning to identify and assess likely impacts. However, in the United Kingdom, the BEIS "streamlined decommissioning programme template" specifically excludes consideration of all marine biota adhering to the structure. Instead, the EIA lists "environmental receptors" including; seabed, fish, fisheries, marine mammals, birds. So, for example, a marine worm living in the seabed is counted and the decommissioning impact upon it assessed, a marine worm attached to the structure is not. BEIS guidance states: "regulations do not apply to artificial habitats created by the infrastructure that is the subject of the decommissioning programme, and it will therefore be unnecessary to justify the removal of structures that have been colonized by protected or rare species". For example, the EIA for Ninian North Platform with respect to the protected coral species, *Lophelia pertusa*, states

> Lophelia covered 5 to 100% (in places) within the depth range 53 m to the seabed in 2011…CNRI have undertaken consultation with JNCC regarding the presence of L. pertusa on the legs of the NNP…JNCC advised, that under the Habitats Directive, it is clear that the habitats listed for protection should be natural, and therefore the marine growth on the infrastructure does not need to be considered by itself under the Habitats Directive… It is found that mortality as a result of decommissioning operations would not be considered as an issue of significant concern for the ES' (NNP, ES, CNR UK). (CNR International, 2017, decommissioning program p. 49)

Equally one could argue that the presence of rare, protected marine life or indeed an active and functioning ecosystem could be a valid reason for advocating that the MMS remain in place, particularly if the MMS is a candidate for derogation. There is no clear scientific or ecological basis for exclusion of epifauna and other adhering marine biota in the EIA, rather this is policy driven and is based on the assertion that any artificial substratum is not protected by legislation (i.e. 'Offshore Petroleum Activities—Conservation of Habitats 2001' regulations). Thus, a pragmatic route is to ignore biota living on the infrastructure. One may compare this to the protection given to rare plants whether they grow upon a stony outcrop or upon a man-made monument (The Wildlife and Countryside Act 1981, schedule 8). While a natural or artificial substratum in the marine environment might be considered not ecologically relevant, it is politically sensitive. As it stands, the regulatory framework does not provide provision for the protection of the whole ecosystem of MMS. This is an interesting potential contradiction to the EU Marine Framework Directive which seek to promote of Good Environmental Status (GES) and the use of the "ecosystem approach".



Removal of marine biota at sea (ROV, Jet wash, rare)

- Loss of marine ecosystem (corals, hydroids, anenomes, associated fish)
- Smothering of seabed
- Large peak of organic input
- Disturbance of sea bed and d.c.p.
- Potentially hazardous

Remove MMS and marine biota to land (manual labour, more common)

- Loss of marine ecosystem
- Generation of biodegradable waste for landfill
- Disturbance of sea bed and d.c.p.
- Transport cost

Leave MMS wholly or partly in situ (rare)

- Retention of marine adhering biota including cold water corals
- Retains habitat for mobile fauna
- No/little biodegradable waste for landfill
- No/little disturbance of sea bed and d.c.p.

Figure 3. Schematic diagram showing environmental aspects of marine growth management during decommissioning including "leave in place" scenario.

The aftermath of decommissioning

Currently, adhering biota termed, "marine growth" is categorized as a "waste stream" and is removed from decommissioned MMS at the onshore disposal facilities and land-filled (MT Cordah, 2013). As well as the loss of a marine ecosystem, this incurs additional transport and labour costs. Land-fill is the least preferable option of the waste management hierarchy and landfill of biodegradable waste such as this is increasingly restricted. However, there is a lack of capacity for composting/land spreading, resulting in operational challenges for disposal facilities (MT Cordah, 2013). Depending on the composition of the "marine growth", there may be scope for exploring potential re-use for example, as a soil conditioner, fuel for anaerobic digestion, or fish feed. For example, the gelatinous carcasses of marine organisms are known to form part of the diet of the economically important species, Norway lobster, *Nephrops norvegicus* (Dunlop *et al.*, 2017). A comparative assessment of waste management found onshore disposal of marine growth to be preferable, in expenditure and safety terms, than dumping at sea. In environmental and societal terms, on shore disposal was the least preferable option (MT Cordah, 2013). Note, this did not include a scenario for leaving the marine growth with the MMS (or part of it) in place. The environmental aspects of marine growth management scenarios are illustrated (Figure 3).

Whole removal

Whole removal is the option permitted and preferred through current OSPAR commission regulations and is also the default option in the Gulf of Mexico (GOM, Schroeder and Love, 2004). MMS removal may also cause damage to the environment through noise and disturbance of cuttings piles. There is a lack of quantitative assessments on the loss of biotic productivity during whole removal and the use of explosives can be contentious (Lakhal *et al.*, 2009). In general, all local demersal fish and many pelagic fish will be killed by the shock waves of explosive deconstruction. Those more likely to survive are species without swim bladders (i.e. gobies, blennies) but they would face considerable mortality as they relocate (Schroeder and Love, 2004). Attached invertebrates would have complete mortality when the structure is removed to shore. Biological surveys of the MMS, with estimates of biomass, would inform decision makers on the balance of benefits and losses of decommissioning options.

Also, there are notable emissions to air during decommissioning. For example, the removal of a large platform off California (Harmony, 365m depth) has been estimated to incur the release of 29 400 tonnes of CO_2, 600 tonnes NO_x, and 21 tonnes of fine particulates (PM10, Henrion *et al.*, 2015). Consideration of emissions is relevant in a holistic (ecosystem) approach to decommissioning. Indeed, an OSPAR strategic policy document states "where necessary, revise existing measures and/or develop and adopt new measures, taking climate change impacts into account". Although decommissioning generates general, special and clinical wastes, scrap metal, explosives and asbestos, 95% of wastes from decommissioning on the UKCS were re-used or recycled in 2015 (www 3. Oil & Gas Environmental Report, 2016).

The material and flows of decommissioning case studies were analysed along with the financial costs, to highlight the economic, social and environmental concerns (Ekins *et al.*, 2006). The conclusions of the authors remain pertinent in the present context. Namely that the advantages of whole removal are; a clear seabed and the conservation of material stocks (as recycling onshore avoids the extraction of virgin material i.e. steel). The disadvantages are; impacts on the marine environment including fish, health and safety concerns, the use of landfill for non-recyclables and expenditure (Ekins *et al.*, 2006). The removal of the footings is deemed to be particularly negative in terms of adverse impacts on the marine environment, technical effort and expense. The authors caution that the findings are based on a limited number of case studies available at the time of publication (Ekins *et al.*, 2006). Efforts are being made to develop more efficient and cost effective mechanisms of complete removal, by lifting larger sections of infrastructure to shore. Less attention has been paid to researching re-use as reefing programs (Lakhal *et al.*, 2009), presumably as they are not legally permissible in the present regulatory framework.

After whole removal is it expected that the marine biota will gradually shift towards a community typical of a soft sediment bottom and recovery rates (as defined by their likeness to ecosystems in similar substrates at a distance from the impact site) will depend on the ecological status at the point of decommissioning, disturbance rates (i.e. trawling), species migration rates (both larval and benthic stages) and the degree of contamination (Schroeder and Love, 2004). Related studies of ecosystem recovery from dredging sites indicate that it may take a decade or more for an impacted site to recover their normal functionality after the cessation of active dredging (Wan Hussin *et al.*, 2012).

Partial removal/leave in place

In decision 98/3, the definition of a disused offshore installation does not include an installation serving another legitimate purpose. While an artificial reef could be classed as such it would be subject to the OSPAR convention 1992 and article 8 therein (Sayer and Baine, 2002) and ‘Guidelines on Artificial Reefs in Relation to Living Marine Resources’ (OSPAR commission) which only allow virgin materials for artificial reef construction. These guidelines serve as a potential obstacle with respect to leaving MMS in place (Bergmark and Jørgensen, 2014).

There is general consensus that partial removal of the topsides to shore for recycling and disposal is the only “leave in place” option worthy of consideration (Ekins *et al.*, 2006) unless a viable re-use for the topsides is proposed (i.e. emergency bad weather shelter, night club!). The expense of cathodic protection and maintenance can be prohibitive for re-use (Schroeder and Love, 2004). Partial removal in the North Sea would require 55 m depth clearance between the structure and the sea surface (LAT, BEIS). In California, the clearance requirement is only 26 m (Claisse *et al.*, 2015). The remaining structure is then marked on navigation charts and/or with buoys. Partial removal of rigs has been used in the Gulf of Mexico (GOM) to leave sites for recreational fishing. When well-conductors are retained to the same depth as the jacket, additional complexity improves habitat quality.

Partial removal offers a compromise as the lower part of the platform is retained for artificial reefing and whole removal costs are reduced, although this saving may be small since the plugging of the wells is a significant proportion of the decommissioning cost. Also the use of explosives is unnecessary while access to maritime vessels is generally accommodated. However, there are implications for some commercial fishing such as bottom trawling which carries the risk of snagging. Indeed, safe navigation is enshrined in international legislation through the UN convention on the law of the sea (UNCLOS) and guidelines of the International Maritime Organisation (IMO). If MMS are left *in situ*, there are obvious benefits for the marine ecosystems associated with them. Claisse *et al.* (2015) estimated that while total removal would result in the total loss of fish associated with the MMS, partial removal would retain 80% of the biomass. This is because most of the fish were associated with depths that would remain after partial decommissioning.

A model of fish production at offshore oil platforms in Southern California was used to predict the outcome of the two decommissioning scenarios; namely whole removal or partial removal. Transect biometric data was used to estimate standing stock (total biomass), recruitment and production per species, per platform. While whole removal was predicted to result in the loss of most of the fish biomass, partial cutting would retain more that 90% of fish biomass at deep water platforms, due to the depth preference of the local species (predominantly rockfishes, Pondella *et al.*, 2015). For most platforms in this study, there was no significant effect on fish recruitment with partial removal but a 100% loss of young-of-year recruitment predicted for whole MMS removal (Figure 1, note, there was significant variation in fish standing stock between MMS due to location and depth). Furthermore, the ecological benefits may extend to non-resident (transient) biota, for example, as a feeding location for porpoise (Todd *et al.*, 2009). A cautionary note: the use of the MMS as artificial reefs for spawning or fish nursery grounds would require remaining levels of hydrocarbon contamination to be very low given the development abnormalities shown of some species (Sørhus *et al.*, 2016). In partial removal, species associated with the intertidal portion of the MMS are lost and the input of detritus from this layer (i.e. mussel shells, faecal pellets) to the seabed would cease which may cause alterations to the benthic community (Schroeder and Love, 2004). However, it’s important to note that several studies have shown the benthic community (protists, meio-, macro-, and megafauna) associated with MMS have changed in terms of biodiversity and density and biomass relative to reference sites (Cordes *et al.*, 2016 and references therein).

Repositioning of MMS

Re-positioning of MMS is defined as the removal and towing of a whole MMS to a new location or the toppling over of a MMS in its current location (Claisse *et al.*, 2015). The advantages of repositioning are that the MMS can be moved to a region deemed optimal for reef success, commercial re-use (lobster fishery) or away from contaminated drill cuttings piles, or to allow continued oil/gas production with a new structure at the original site (Schroeder and Love, 2004, Bergmark and Jørgensen, 2014). The negative aspects are the initial removal impacts noted above and the risk of introducing disturbance and invasive species to a new or pristine area. Long distance wet tows used in decommissioning could provide a marine pathway for INNS (Wanless *et al.*, 2010). Toppling the platform is considered to be less favourable than partial cutting due to the change in habitat depth and orientation of cross beams relative to the seabed (Pondella *et al.*, 2015).

Drill cuttings

In the context of the Central and Northern North Sea, relatively weak tidal currents allow the formation of drill cuttings piles (dcp, Breuer *et al.*, 2008; Henry *et al.*, 2017). On the UKCS, water-based fluid drill cuttings are usually permitted to be discharged to sea. However, there is a legacy of oil-based dcp and their constituents may include; barite and bentonite, heavy metals and hydrocarbons including polycyclic aromatic hydrocarbons (PAHs, Adewole *et al.*, 2010). Synergistic effects of multiple contaminants may be possible and toxicity data are often incomplete (Lakhal *et al.*, 2009). Microbially-mediated diagenetic reactions result in the removal of oxygen in the upper millimetres of the dcp. This creates an anoxic state within the pile that restricts the degradation of hydrocarbons. Metals that are released into the pore water then migrate into overlying water or they diffuse downward forming a potentially toxic sink (Breuer *et al.*, 2008). The marine diversity most acutely impacted by dcp is the benthos (Cordes *et al.*, 2016). This occurs initially through the physical smothering of the seabed (Jones *et al.*, 2012). Tidal pumping and faunal ventilation may also draw oil beneath the sediment surface (Main *et al.*, 2015). In sediments contaminated with hydrocarbons, an increase in benthic respiration have been measured, reflecting the up-regulation of compensatory mechanisms (Olsen *et al.*, 2007). Effects can be locally severe, leading to depauperated sediment dominated by anaerobic bacterial assemblages. However, the wider effects of contamination have also been shown in the pelagic environment; cod (*G. morhua*) and haddock (*M. aeglefinus*) from the North Sea showed evidence of the uptake of PAHs and adverse biological consequences including oxidative stress and genotoxicity. The responses were highest in the vicinity of intensive production but were also noted in an area of decommissioned infrastructure indicating background contamination (Balk *et al.*, 2011).

There are established on-shore methods for cleaning dcp however this is limited to situations when treatment rates and potential reuse of recovered oil are economically viable. Treatments include thermal separation of oil and re-use of cuttings as road and construction materials (Lakhal *et al.*, 2009). Opinion among scientists is divided on the best management for dcp with some advocating removal to shore for cleaning and re-use during decommissioning or reefing and others of the view that they should be left undisturbed (Henry *et al.*, 2017). Environmental monitoring of the dredging, and hence disturbance, of cuttings piles in Norway reported a decline in water and sediment quality at the dredging site and dispersal of fine particles up to 1 km but recovery to a state prior to dredging was expected within a few years (OSPAR Commission, 2016). This concludes that leaching from dcp and disturbance from over-trawling are unlikely to have significant impact on marine biota and that cuttings should be left in place. This is partly due to low levels of contaminant in the upper 10 cm of the piles and the already poor condition of the seabed in the vicinity of the cutting piles. A major concern for the scenario of leaving MMS is that they may be a source of contamination to the surrounding environment perhaps from leaching of hydrocarbons, heavy metals, drill cuttings piles or degradation of the structure. To assess this risk, Love *et al.* (2013), measured concentrations of 21 trace elements in 3 fish species caught at oil platforms and at natural reefs in California. Statistical comparison found the concentrations of trace elements were not significantly greater at platforms than at natural reefs. A recent study using benthic survey data suggested that any decommissioning activity that causes disturbance to a drill cuttings pile should be monitored for at least 8 years (Henry *et al.*, 2017). Given the variability in MMS, operational legacy and local conditions, the risk of residual contamination of potential artificial reefs must be assessed on an individual basis.

Lifetime stewardship, ongoing monitoring, and obligations

In the GOM, the state of Louisiana assumes long-term liability for rigs-to-reefs and operators donate the structure to a reefing program and also 50% of the cost savings for removal are paid to the state to be added to a rigs-to-reef trust fund. Although the state (via a fisheries agency) pays for navigational aid/buoys this comes from the reefing account and is not funded by the state or federal government (Schroeder and Love, 2004). On the UKCS, derogations to OSPAR 98/3 (OSPAR, 1998) represent oil and gas infrastructure decommissioned *in situ* and all the licensees relating to it are subject to the provisions of The Petroleum Act 1998.

It is clear that great variability exists in the habitat value of MMS and individual assessments must be carried out to establish the specific ecosystem qualities and context. The current environmental status of the MMS and of the associated ecosystem will play a role in the potential ecological value of MMS. The location of the MMS and connectivity to other natural or artificial reefs is also important for the capacity to sustain mobile fauna without producing an overlap of depleted prey zones (prey "halos", Campbell *et al.*, 2011). In California, rigs-to-reef guidelines call for enhancement of MMS reef habitat, for example, by adding rocks to increase niche complexity (Schroeder and Love, 2004; Ajemian *et al.*, 2015).

Knowledge gaps and future research

Future research should be driven by the need to complete basic biological insight that restrict our knowledge of MMS ecology. Limited access to MMS locations and a lack of baseline environmental data restrict our understanding of the impacts of decommissioning on the marine environment. Nevertheless, future decommissioning projects could provide important opportunities for research, as has been shown with the BP Miller platform (Fujii, 2015). A qualitative review of the scientific literature indicates little published information on; the impact of decommissioning on the ecology associated systems, the benthic habitat of MMS, foodwebs associated with MMS and systematic data for birds/MMS interactions. 156 decommissioning projects have been completed (as of 2015) in the OSPAR maritime area in the absence of this understanding and there is a risk that individual EIA do not consider the full impact on the ecology of MMS on the wider system, for example system connectivity and interaction with MPAs. Variability in marine biodiversity associated with MMS prevents a general prediction of the consequences of the different decommissioning scenarios and requires each decommissioning program to be considered individually.

The oil and gas industry are improving autonomous underwater vehicle (AUV) technology (such as autonaut passive acoustic monitoring) and there is an opportunity for this technology to be better utilized for understanding MMS ecology. For example, using AUV with smart technology, such as real-time biochemical sensors and eDNA samplers and the potential installation of "smart buoys" that are relatively cheap to maintain and can return pre-processed data via satellite.

Finally, oil and gas exploration and production is expanding into deeper waters and environmental assessments must be improved and better baseline data collected to assess potential impacts under more difficult conditions. Ecosystems here are particularly sensitive to disturbance and a precautionary approach is recommended in the management of deep water resources (Cordes *et al.*, 2016) with limitations recommended on the type and timing of operations and appropriate spatial buffer zones such as an 'ecologically or biologically significant area' (ESBA, United Nations Convention on Biological Diversity). Gathering information on benthic biota and processes remains a challenge, the most promising emerging approach uses multi-beam echo sounder to provide acoustic data. However, acoustic data alone will not be sufficient unless supported by significant *in situ* sampling or imagery (photographic or video) to characterize the biological structures and assemblages of the MMS benthos compared to reference sites.

Conclusions

This review highlights our knowledge of the ecology of MMS and recognizes that this is far from complete. The loss of platforms due to decommissioning may be positive or negative in ecological terms and should be examined without preconception. The quality of the individual MMS as a reef habitat determines whether the removal of the structure would improve or degrade the marine environment.

In the UKCS, The BEIS decommissioning EIA protocols excludes the inclusion of organisms or ecosystems on platforms, making a clear distinction between biological life on natural and artificial substrates. Comparisons can be made with other post-industrial man-made sites, such as shale-oil bings colonized by unique biological assemblages. This marine exclusion prevents a balanced debate on the biological costs and benefits of decommissioning and the exclusion has no ecological validity. Thus, there is an urgent need to quantify the ecosystem services that they provide. A more comprehensive EIA process together with the recognition of the ecology associated with man-made structures would allow science to play a role in the decision-making process as opposed to a blanket policy ignoring the ecological context. Thus a policy review may be warranted for management of ecosystems of MMS by OSPAR and its' signatories.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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