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Challenges of evidence-informed offshore decommissioning: an environmental perspective

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Many offshore artificial structures are at or nearing their ends of life, and society faces the considerable challenge that is decommissioning. Current scientific evidence of the ecological and environmental consequences of decommissioning is insufficient to reliably and accurately inform decision-making and policy development. Thus, we must strengthen the scientific basis for evidence-informed decommissioning.

Overview of the decommissioning landscape

Worldwide, governments and political agendas are promoting **decarbonisation** (see Glossary) accompanied by ambitious objectives for **energy transition** [1,2]. While fundamental to mitigating anthropogenically induced global climate change [1,2], decarbonisation is also driving rapid acceleration in demand for alternative green energy sources. In marine environments, this is manifested as the addition of marine renewable energy infrastructure (MREI), such as offshore wind farms (OWFs) [3]. These marine artificial structures (MAS) alongside oil and gas (O&G) installations are widespread features of marine ecosystems with apparent hotspots [4]. Yet many offshore MAS are now at or nearing their operational end of life introducing the considerable challenge that is **decommissioning**.

How best to tackle the urgent but complex decommissioning problem is an ongoing challenge. The majority of scientific evidence related to decommissioning stems, unsurprisingly, from the O&G industry experience, but many first-generation structures from the 1950s to 1960s were neither built nor deployed with decommissioning considerations in mind. In fact, discussion of decommissioning did not begin in earnest until the late 1980s [5], despite the known scale of the issue. By necessity, decommissioning involves multiple sectors and stakeholders with often-conflicting priorities and agendas creating management challenges. Additionally, decommissioning involves a complex suite of logistical, technical, safety, economic, social, and environmental considerations. Potential options range widely, from complete removal to complete abandonment *in situ*, or 'middle-ground' options involving partial removal, partial or complete relocation, and repurposing as artificial reefs, dive resorts, mariculture facilities, and so forth [6]. In the case of O&G, stakeholders value sustainable decommissioning options such as reuse and multi-repurposing, which can minimise negative impacts and maximise potential environmental, social, and economic value [7]. From a legal standpoint, there is no comprehensive and coherent international/global legal framework for decommissioning, but rather a fragmented one with much regional divergence [5]. While in some areas decommissioning is legally restricted only to complete removal of structures (with some specific derogations) [15], elsewhere legal provisions allow for the consideration and adoption of alternative options [5,6]. As such, uncovering which option might be 'best' and 'acceptable' is anything but straightforward.

Glossary

Decarbonisation: refers to the process of removing, reducing, or suppressing carbon dioxide (CO_2) emissions into the atmosphere resulting from human activity.
Decommissioning: is a general term for a formal process to remove something from an active status. In the case of offshore oil and gas, decommissioning may have different meanings for different people or sectors, but generally it refers to the fate of a structure following cessation of operations and/or activities for which it was originally deployed. It encompasses all possible strategies and options from removal and disposal to repurposing and recycling.
Direct evidence: evidence stemming from real-world case studies of decommissioned marine artificial structures.
Energy transition: refers to the global energy sector's shift from fossil-based systems of energy production and consumption (oil, natural gas, and coal) to low-carbon energy sources such as renewable energy sources (wind, wave, solar).
Indirect evidence: evidence stemming from the presence of marine artificial structures prior to decommissioning, rather than from case studies of decommissioned structures. This type of evidence does not depict the effects of decommissioning *stricto sensu*, but rather the effects of structures being present in the sea. It may be used to infer the environmental effects of some decommissioning options.
Reefing: also referred to as 'toppling', whereby the upper section of the oil and gas jacket is removed and deployed on the seabed next to the remaining jacket, turning the structure into an artificial reef.
Systematic map: a systematic evidence synthesis output created following a rigorous, objective, and transparent evidence synthesis methodology. It aims to collate and describe all the available evidence into a 'catalogue'. It focusses on the nature and distribution of evidence.
Systematic review: a systematic evidence synthesis output created following a rigorous, objective, and transparent evidence synthesis methodology. It aims to systematically search, critically appraise, and synthesise all available evidence. It focusses on the effects shown by the evidence.
Toppling: laying the entire oil and gas jacket structure on its side *in situ*.

Like O&G infrastructure, OWFs will require decommissioning at end of life. However, the limited number of decommissioned OWFs to date (<10 as of 2021, although >1800 offshore turbines will likely need decommissioning between 2020 and 2030 [8]) provides limited **direct evidence** of decommissioning effects, prohibiting standardisation in OWF decommissioning protocols and redaction of informed EIAs [9]. Nevertheless, as OWF decommissioning will likely be constrained by challenges and considerations similar to those of O&G [10], there is significant potential for it to be informed by the O&G decommissioning experience making it essential to get O&G decommissioning as 'right' as possible.

Irrespective of the MAS type, experts and stakeholders have been advocating for an evidence-based approach to decommissioning, but scientists informing decommissioning face multiple challenges associated with evidence-informed decision-making that are common in the fields of environmental management and policy (Box 1).

In the following section, we discuss the evidence needs and availability, from an environmental standpoint, to inform MAS decommissioning. While the evidence for effects on other sectors (economic, social, technical, etc.) are not discussed, we acknowledge that they are, nonetheless, crucial to decision-making processes with regard to decommissioning.

Environmental effects of decommissioning: 'direct' and 'indirect' evidence bases

To support policy development and implementation, reliable, robust, and unbiased evidence must have been generated, collated, and made available to decision-makers, which might be easier said than done. Evidence can take many forms, from the analysis of existing and new data to expert opinion and advice. The various forms, however, vary both in validity and reliability and may not be equally persuasive depending on context. Indeed, evidence typically used in key environmental decision-making processes (such as those related to MAS) often originates from the grey literature [12], which alongside personal experience, anecdotal evidence and advice of colleagues, may be viewed as less robust, unreliable, or biased. In the case of MAS decommissioning, evidence is also gathered from literature generated by industry-contracted research, which one could argue may not always be transparent and agenda-free. At present, there seems to be a general assumption that an abundance of evidence relevant to the matter at hand exists and is available – but is this assumption substantiated? Hence we ask: what really is the state of the evidence base when it comes to MAS decommissioning?

To overcome the challenges of evidence-informed decision-making and facilitate the integration of high-quality evidence, evidence synthesis tools are available, such as **systematic maps** and **systematic reviews**. Recent systematic map work [13] helped build the evidence base by collating the available peer-reviewed primary literature (published until early 2021) around the ecosystem effects of the presence and decommissioning of selected offshore MAS (O&G infrastructure, OWFs, MREI, artificial reefs, shipwrecks, pipelines, and cables).

Just 57 articles assessing the effects of decommissioning options on marine ecosystems through case studies (referred to as 'direct' evidence here) were found, with articles originating predominantly from the USA (Gulf of Mexico and off California) and the North Sea region but missing for most of Asia and the southern hemisphere, highlighting clear regional disparities (Figure 1A). The studies, categorised across nine decommissioning options, focussed in majority on effects on fish and invertebrates (Figure 1B,C). An update to this map using the same search string used in [13] entered into Web of Science in March 2023 and screened to title and abstract level only found just ten additional articles reporting on O&G decommissioning studies. Mirroring the findings of [13], these ten articles predominantly originated from the Gulf of Mexico, USA (n = 6) and focussed primarily on fish (n = 7) and invertebrates (n = 3). Clearly, the direct evidence base is much more limited and disparate than might be assumed given the importance of the industries involved leading to several questions: (i) 'can robust quantitative estimates of decommissioning effects be made based on this limited amount of direct evidence?'; (ii) 'can region-specific direct evidence (e.g., Gulf of Mexico) be applied to other evidence-limited regions?';

Box 1. Common challenges associated with evidence-informed decision-making in the fields of environmental and societal management and policy

Challenge 1: incomplete and disparate evidence bases

Ecosystem science, which depends on progress across disciplines, develops and matures slowly. Therefore, the resultant evidence that informs decision-making is, inevitably, grounded primarily in what we have previously known, and as such is incomplete. Adapted from [11].

Challenge 2: rapidly evolving evidence needs

Because evidence bases are incomplete, expert knowledge and what we have previously understood weigh heavily in the evidence we generate and, importantly, the advice we provide. Applying this to an evolving, uncertain, and at times unprecedented present, requires us to acknowledge and clearly communicate the boundaries of our knowledge. Adapted from [11].

Challenge 3: contentious socio-political contexts

The at-times contentious socio-political contexts into which we are feeding evidence and advice, and in which policy decisions must be made, can represent an important challenge. Our scientific evidence is only one, albeit critical, piece of the decision-making puzzle and needs to both be recognised, and recognise itself, as such. Adapted from [11].

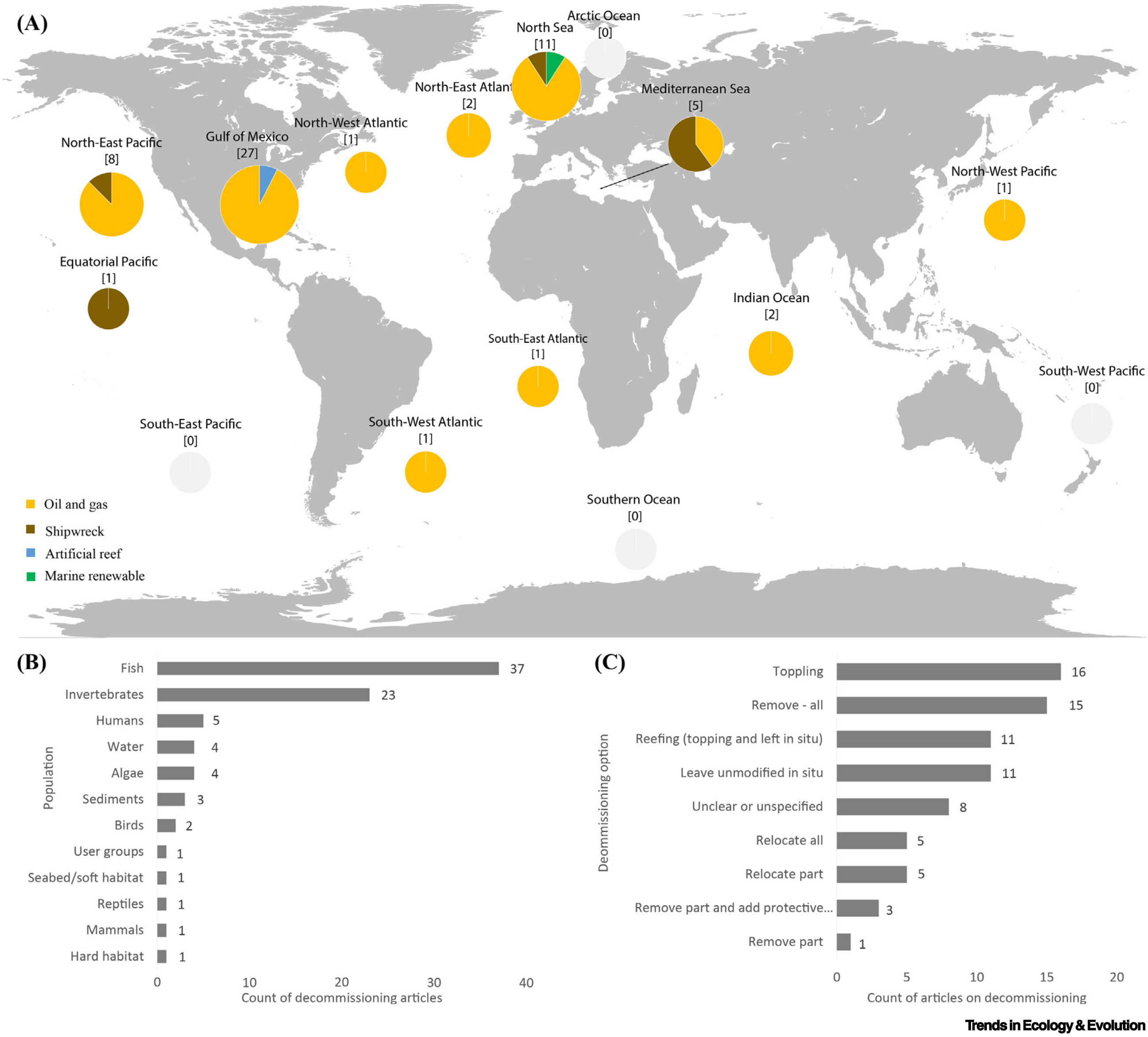

Figure 1. Overview of the disparate and limited (n = 57 articles) direct evidence base related to the effects of decommissioning offshore artificial structures. (A) Geographical distribution of research articles highlighting regional differences in evidence availability, with apparent evidence clusters (e.g., Gulf of Mexico, North Sea) and evidence gaps (e.g., Australia, South-East Asia). The Antarctic Treaty, which prohibits oil and gas exploration in the Southern Ocean, explains the absence of decommissioning evidence for that region. Although we are not aware of the exact numbers, there is likely to be some decommissioned structures from oil-producing regions such as Australia, Russia, the Far-East, and South America (see global distribution map of offshore oil and gas structures in [3]), but as the time [13] was produced, no decommissioning case studies were evidenced for these areas. Pie charts present the split of articles for each artificial structure type per oceanographic area. (B) Distribution of articles by taxonomic groups showing that the majority of evidence relates to fish and invertebrates. (C) Distribution of articles per decommissioning option. See Glossary for definitions of '**reefing**' and '**toppling**'. Adapted from [13].

and if not, (iii) 'how else can we complement this limited direct evidence base in order to assess the potential effects of decommissioning options?' As 'direct' evidence from real-world decommissioning case studies is greatly limited, can **'indirect' evidence** be used instead? For instance by using articles relating to the presence of MAS prior to decommissioning (*sensu* 'indirect' evidence that does not depict the effects of decommissioning *stricto sensu* but the effects of the structures being present in the sea), which are considerably more abundant (942 catalogued in [13], another potential 151 identified in our update). By investigating 'presence' effect(s) of a given structure, the environmental effects of decommissioning structures can be inferred. If considered with caution and in appropriate socio-ecological contexts, this extensive body of indirect evidence might be critical in predicting the probable effects of offshore MAS decommissioning on biodiversity and natural capital. However, this alternative may not be applicable to every decommissioning option but only a select few, such as complete removal where the total loss of 'presence' effects is assumed, or leaving whole structures in place that likely maintain 'presence' effects. Using this method to assess other options may omit certain effects not encompassed by 'presence' effects, such as effects of transportation in the case of relocation. Ultimately and ideally, direct evidence for specific decommissioning options would be preferable.

Recommendations for decision-making and future effort investment

It is widely argued that complete removal may not be the most beneficial option for decommissioning MAS and that societal or environmental benefits can be achieved by choosing alternative options [6]. Given the clearly limited direct evidence available (Figure 1), is this widespread acceptance justified?

Moving forward, we must challenge our own preconceptions of what the effects of MAS may be and which decommissioning option might be optimal by looking more closely and critically at both direct and indirect evidence. Although it remains the preferable type of evidence, direct evidence from decommissioning case studies is still greatly limited; thus, we recommend that policy-developers and decision-makers use the available and plentiful indirect evidence base (in combination with direct evidence) to support decommissioning choices. However, given the amount and quality of evidence varies both geographically and depending on structure type, the efficacy of any decommissioning option(s) is potentially uncertain. Thereby, decommissioning is likely to require localised, context-dependent recommendations. While it may be difficult, even unwise, to provide a 'one-fits-all' recommendation to policy-developers and decision-makers, an assessment of the available evidence base (direct and indirect) placed in context coupled with a degree of expert judgement to fill data gaps may be sufficient to facilitate effective decision-making. This may manifest in evidence-rich contexts with policy-developers and decision-makers choosing from optimal decommissioning options, while in evidence-poor contexts, the precautionary principle might be applied (e.g., leaving structures *in situ*) until sufficient robust evidence becomes available to indicate the benefits or costs of different options [14].

The last few years have seen an important increase in the number of studies tackling the environmental aspects of offshore MAS decommissioning. This surge highlights the global recognition that research efforts are critically needed to make significant progress. To assist this international endeavour and ensure effort and funding are used optimally, we recommend: (i) investments in research assessing direct decommissioning effects, for example, before-and-after or BACI case studies of planned decommissioning, to strengthen the scientific basis for evidence-informed decommissioning; and (ii) improved scientific collaborations between industry, government, and academia, especially where resources or expertise are limited, to facilitate the publication of all relevant, quality-assured data and information regardless of whether they originate from academic, government, or industry sources.

Data and materials availability

All data used to produce Figure 1 are available from [13].

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Author contributions

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Declaration of interests

The authors declare that they have no competing interests.

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