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Research article

To what extent can decommissioning options for marine artificial structures move us toward environmental targets?

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ABSTRACT

Switching from fossil fuels to renewable energy is key to international energy transition efforts and the move toward net zero. For many nations, this requires decommissioning of hundreds of oil and gas infrastructure in the

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marine environment. Current international, regional and national legislation largely dictates that structures must be completely removed at end-of-life although, increasingly, alternative decommissioning options are being promoted and implemented. Yet, a paucity of real-world case studies describing the impacts of decommissioning on the environment make decision-making with respect to which option(s) might be optimal for meeting international and regional strategic environmental targets challenging. To address this gap, we draw together international expertise and judgment from marine environmental scientists on marine artificial structures as an alternative source of evidence that explores how different decommissioning options might ameliorate pressures that drive environmental status toward (or away) from environmental objectives. Synthesis reveals that for 37 United Nations and Oslo-Paris Commissions (OSPAR) global and regional environmental targets, experts consider repurposing or abandoning individual structures, or abandoning multiple structures across a region, as the options that would most strongly contribute toward targets. This collective view suggests complete removal may not be best for the environment or society. However, different decommissioning options act in different ways and make variable contributions toward environmental targets, such that policy makers and managers would likely need to prioritise some targets over others considering political, social, economic, and ecological contexts. Current policy may not result in optimal outcomes for the environment or society.

1. Introduction

The Anthropocene is characterised by significant environmental changes emanating from human activity, including, habitat degradation, loss and homogenization of biodiversity, and global climate change from fossil fuel emissions (Comte and Lenoir, 2020; Schmeller et al., 2020). Given the pace and scale at which these changes are now occurring, there has been international recognition that urgent actions must be taken to prevent and mitigate further environmental deterioration. In response, nation states/governments have set various environmental targets, including targets for habitat protection, biodiversity, and emission levels (Sovacool et al., 2022), commitment to halt and reverse biodiversity loss and to protect 30% of land and seas (30 × 30) (G7 Cornwall UK), and reach net-zero emissions by 2050 (e.g. North Sea Transition Authority, 2022). These targets echo established hopes and goals for environmental protection and sustainable development, such as those expressed both at international level in the United Nations' Sustainable Development Goals (SDG, https://sdgs.un.org/goals) and UN Rio+20 "Future We Want" report (FWW, link to document), and regionally, such as within the OSPAR "North-East Atlantic Environment Strategy 2030" (NEAES, link to document).

Reduced reliance on fossil fuels and increased use of renewable energies is a highlighted goal in UN FWW and SDG reports, and one frequently used by governments in their energy transition and pathway to meeting emission targets (Camarasa et al., 2022). For coastal nations, this can translate to the extensive addition of artificial structures into our seas, such as offshore wind farms (OWFs) and other offshore renewable energy (OREs) installations (Gourvenec et al., 2022; Martins et al., 2023) to generate the capacity needed to replace fossil fuels. These marine artificial structures (herein referred to as MAS) join older, established or well-known structures such as shipwrecks, purpose-built artificial reefs (ARs), and oil and gas (O&G) infrastructure, as widespread features of marine ecosystems (Bugnot et al., 2020; Gourvenec et al., 2022).

Concomitantly, a number of energy-producing MAS, notably oil and gas, and some offshore wind farms, are at or reaching the end of operational life. Decisive choices must soon be made when it comes to MAS decommissioning (Invernizzi et al., 2020), not least given the financial and environmental cost of their removal (Raimi et al., 2021). From a legal standpoint, several existing international instruments dictate that structures must be fully removed (e.g. the 1958 Geneva Convention, with some derogations granted under the United Nations Convention on the Law of the Sea (1982) and guidelines of the International Maritime Organisation (1989)) to "ensure safety of navigation …. [and] have due regard to fishing, the protection of the marine environment and the rights and duties of other States" (UNCLOS, 1982, Article 60 paragraph 3). More locally, such as within regional seas, requirements can vary and decommissioning options other than full removal may be considered. For instance, in the Gulf of Mexico and off the coast of California (USA) the repurposing of O&G installations as ARs is allowed through the "Rigs-to-Reefs" (RtR) programme (Bull and Love, 2019; da Fonseca et al., 2020; Trevisanut, 2020). Conversely, in the north-east Atlantic, OSPAR Decision 98/3 (1998) states that any artificial structures should be entirely removed at end-of-life (except for exceptional derogations). Oftentimes, the socio-political context in which local restrictions have been imposed (e.g. OSPAR Decision 98/3 and the Brent Spar debacle (Löfstedt and Renn, 1997)) have led to scientists contesting the decisions and calling for the consideration of alternative decommissioning options to complete removal (Ounanian et al., 2020). Several options for O&G decommissioning have been proposed, most of which are also applicable to OWFs and OREs (Smyth et al., 2015). These range from complete removal to various reefing options, alternative use (repurposing), or complete abandonment *in situ* (Sommer et al., 2019); each expected to bring its own environmental and societal consequences (Knights et al. submitted).

At time of writing, there was no international consensus (scientific, political or otherwise) on which decommissioning option(s) will bring the most desirable outcomes for the environment and society, and it remains unclear how different decommissioning options might affect the marine systems and assist nations in reaching their environmental and sustainable development targets. Despite several scientific reviews and overviews providing information and debate on the range of possible effects of MAS decommissioning (Elliott and Birchenough, 2022; Fortune and Paterson, 2020; Sommer et al., 2019; Bull and Love, 2019), recent systematic synthesis work highlighted the paucity of case studies describing the ecological effects of different decommissioning options (Lemasson et al. 2022a, 2022b). Lemasson et al. (2023) argue that the sparsity of evidence of real-world case studies makes deciphering the environmental effects of different decommissioning options a considerable challenge for evidence-informed decommissioning; a position that could prevent decision-makers from taking defensible and decisive action regarding structures at end-of-life, and crucially, could also hinder potential support for policy change. Consequently, deciding which option(s) will move environmental status toward targets and environmental net gain (i.e. the use of environmental management options which give additional benefits, e.g. Hooper et al., 2021) remains a challenge, with selection of specific options expected to be a trade-off between desirable and undesirable effects (Knights et al. submitted).

MAS decommissioning is now being recognised worldwide as a global challenge (Watson et al., 2023). Its strategic planning, management and governance requires a strong evidence base (Lonsdale et al., 2022), but few additional empirical data from real-world decommissioning are being produced to inform decommissioning decisions (Lemasson et al., 2023). In light of this significant knowledge gap, we used expert knowledge as an alternative source of evidence, as this can play a crucial role in decision-making. A more detailed explanation behind our decision to use expert opinion/knowledge is provided in Knights et al. submitted). This type of evidence can be particularly

Table 1
Summary of decommissioning options considered.

Decommissioning Option	Number of Structures	Description
A	Single	Abandonment (leave in place)
B	Single	Repurpose (in place)
C	Single	Partial removal (partial abandonment)
D	Single	Repurpose (relocate)
E	Single	Total removal
F	Multiple	Abandonment of all
G	Multiple	Repurpose/relocate all
H	Multiple	Partial removal of all
I	Multiple	Partial removal of some, repurpose/relocate others
J	Multiple	Complete removal of some, abandonment of others
K	Multiple	Complete removal of some, repurpose/relocated others
L	Multiple	Complete removal of all

valuable when the state of knowledge is insufficient to effectively inform decision-making but the issue is time-sensitive and requires decisions to be taken in spite of uncertainty (McBride and Burgman, 2011; Knights et al., 2014), which is precisely the case with energy infrastructure decommissioning.

Given the urgency with which the decommissioning challenge must be addressed, we asked an international panel of scientists to provide their expert opinion with regards to the decommissioning challenge. Specifically, we were interested in answering the following three questions: 1) How do different decommissioning options affect (ameliorate/enhance) pressures emanating from the presence of the structures? (2) To what extent do different decommissioning options move the marine system toward environmental targets, and does this vary with scale (single structure vs. regional decommissioning approach)? 3) Which decommissioning option(s) will lead to optimal outcomes with respect to environmental targets? Using a set of pre-defined questions presented in a structured workshop, we provide an international scientific consensus on the potential of various decommissioning options to move marine ecosystems and societies toward environmental targets.

2. Methods

The workshop captured expert opinion with data collected using the World Café methodology (Brown, 2002; Elliot et al., 2005; Knights et al., 2015; Löhr et al., 2020). Invitations were extended to individuals with international reputations in marine biology, ecology and physics, marine policy, ecosystem services and socio-ecological systems, and resulted in a total of 36 participants from 28 academic and government institutions, across three continents and six countries.

Twelve decommissioning options were presented (Table 1), with each participant asked to provide their opinion on the ability of decommissioning options to ameliorate pressures and affect environmental targets from two standpoints: (1) considering single structures, and (2) as multiple structures across any region. Of the 12 options, five considered single structures, and seven considered multiple structures representing regional management. Options ranged from the abandonment of structure(s) *in situ* (e.g. in the Gulf of Mexico, see Quigel and Thornton, 1989), to the complete removal of all infrastructure (e.g. OSPAR region) (Fig. 1) and represent the range of options currently implemented (Jagerroos and Krause, 2016; Sommer et al., 2019).

We identified 37 marine-related environmental targets for evaluation that could be affected by MAS decommissioning. These 37 targets were contained within three international documents: (1) 14 from the UN Rio+20 'Future We Want', (2) 10 from the UN Sustainable Development Goals (SDG); and (3) 13 from the OSPAR North-East Atlantic Environment Strategy 2030 (Table A1).

We also identified 10 pressures through which MAS can affect the marine environment (Table 2 and taken from Knights et al. submitted). A pressure is defined as the mechanism through which an activity or structure impacts the marine environment and its ecological characteristics (*sensu* Knights et al., 2013). Pressures can be modified by a decommissioning option in one of three ways: **enhanced** (e.g.

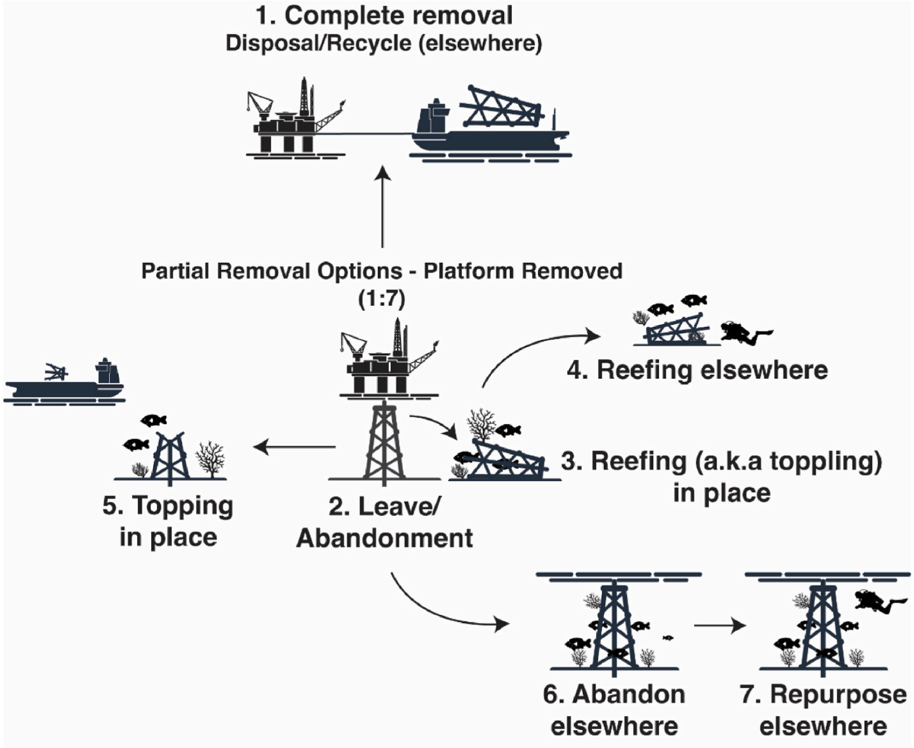

Fig. 1. Conceptual figure of decommissioning options for MAS at end-of-life including complete removal and partial removal options.

Table 2
List of pressures associated with marine artificial structures in the sea and their definitions.

Pressure	Description	Example Effect
Chemical contamination	Introduction of chemical contaminants (e.g. synthetic/ non-synthetic) into the marine environment arising from the operation or decommissioning of marine artificial structures.	The effect of drill cutting piles on sediment geochemistry (Breuer et al., 2008)
Connectivity	Introduction of substrate/ species affecting the ecological functioning and structure of marine ecosystems as connectivity (gene/propagule transfer) is altered.	Offshore renewable energy devices acting as stepping stones for dispersal (connectivity) linking habitat patches across space (Adams et al., 2014)
Electromagnetic field (EMF)	Creation of electromagnetic fields from sub-sea electrical conduits.	Change in foraging behaviour and dispersal of marine species (Hutchison et al., 2020)
Food availability	Change in primary/secondary productivity.	Increased standing stock and productivity of 'fouling' organisms (Wolfson et al., 1979)
Hydrodynamics	Change to local hydrodynamics as a result of modified habitat complexity/ bathymetry associated with structures.	Strong currents interacting with MAS generate complex 3-dimensional wakes that can make prey more accessible (Lieber et al., 2019)
Light	Introduction of artificial light (e.g. artificial light at night (ALAN)) into the marine environment.	ALAN changes behaviour and aggregations of seabirds around oil drilling platforms and rigs (Wiese et al., 2001)
Noise	Introduction of artificial noise into the marine environment.	Elevated nocturnal levels of anthropogenic noise interfere with acoustic feeding in odontocete species (Todd et al., 2009)
Nutrients	Accumulation of nutrients around structures.	Structures can aggregate nutrients by modifying currents (Yanagi and Nakajima, 1991)
Other human activity	Modification of other human activities (e.g. commercial fishing) in the sea due to structural hazards or exclusion areas.	Structures act as *de facto* Marine Protected Areas displacing other human activities (Schroeder and Love, 2002)
Physical structure	Introduction of alternative habitat or modification of natural habitat.	Provision of 'novel' hard substrate into soft sediment environments (Bulleri and Chapman, 2010)

resuspension of chemical contamination following the disturbance of sediments on structure removal); **maintained** (e.g. habitat is maintained by the complete abandonment of a structure); or, **reduced** (e.g. removal of chemical contamination following the complete removal of a structure).

Prior to the workshop, we created a unique workbook for each participant containing 13/37 (35%) targets, randomly selected from the complete list to allow completion of the assessment in the time available. All 37 targets were assessed by a minimum of five independent participants. Using a 5-point Likert scale, participants were asked to assess to what extent each decommissioning option might move environmental status toward a specified environmental target ('strongly toward' or 'toward'), to move away from it ('strongly away' or 'away'), or to have no effect ('neutral') on it. For each decommissioning option, participants could select only one of the five scale points. Herein, this is referred to as 'Option Performance'. Then for each target, using a 3-point Likert scale, participants were asked to assess each of the decommissioning options would affect each of the 10 pressures, where present, selecting 'enhanced', 'maintained', or 'reduced'. Hereafter, this is referred to as the 'Pressure Assessment'.

For analysis, opinion data were collated in R by merging individual respondent files into a single data file using the libraries *openxlsx* (Schauberger and Walker, 2022), *readxl* (Wickham and Bryan, 2022) and *reshape 2* (Wickham, 2007) packages. For option performance data, each scale point was then converted to an ordinal score as follows: Strongly toward = +2, Toward = +1, Neutral = 0, Away = −1, Strongly Away = −2. For pressure assessment data, each scale point was awarded an ordinal score as follows: enhanced = +1, maintained = 0, reduced = −1. The library *dplyr* (Wickham et al., 2022) was then used to summarise score data grouped by **Target** (1–37, Table A1) and **Option** (e.g., Abandonment (leave in place), Repurpose (in place) etc.). Descriptive summary statistics were then derived including mean, minimum, and maximum score (range), and standard error for both option performance and pressure assessment data. Analysis of variance (ANOVA) and Tukey *posthoc* pairwise comparison tests were used to compare the performance of each option against targets.

3. Results

3.1. Decommissioning options as pressure ameliorators

Respondents assessed whether each of the 10 pressures were maintained, enhanced, or reduced under each single structure and multi-structure decommissioning scenarios (options A:L; Fig. 2 legend gives the options). All options with the exception of Option A (Abandonment-leave in place (single structure)) and Option F (Abandonment of all (multi-structure)) had a significant effect on pressures. In most cases, pressure was reduced by decommissioning options but to varying degrees (Fig. 2). Greatest pressure reduction from different options was to artificial light (Artificial light at night (ALAN); −0.65 ± 0.04) followed by electromagnetic forces (−0.63 ± 0.04) (Fig. S1).

Some pressures were enhanced by decommissioning: the introduction of chemical contamination (G), food availability (A, F & G), nutrients (F), and 'Other Human Activities' (except E – Total removal) (Fig. 2). Partial removal of all structures (H) led to the greatest enhancement of pressure (Other human activity; 0.37 ± 0.12), and the overall mean change in Other Human Activities, irrespective of decommissioning option, was 0.13 ± 0.03 (Fig. S1). In contrast, pressures were maintained for a number of decommissioning options. Examples include chemical contamination (Options A and F) and Connectivity (Options A, F and G) (Fig. 2).

3.2. Which decommissioning option(s) best meet environmental targets?

There were significant differences in the potential to move environmental status toward target objectives depending on the choice of decommissioning option, target, and spatial scale of management (see Fig. S2 for option performance for individual targets) indicating objectives may need to be prioritised and trade-offs acknowledged. Integrating data across all 35 targets to identify which option(s) would lead to optimal environmental outcomes considering all targets identified clear differences in option performance ($F_{11,2794} = 12.6$, $p < 0.001$) (Fig. 3). Although there was some variation in opinion between respondents (Fig. 3 standard deviation), single structure management Options A (Abandonment (leave in place)), B (Repurpose in place), and regional management option F (Abandonment of all) were identified as the options best placed to move environmental status toward targets. Options considered to be most likely to move environmental status away from a given target were single structure Option E (Total removal), and L (Complete removal of all) (Fig. 3). A number of options (C, G:J) had similar, marginal positive effects toward environmental targets. Comparison of the change in pressures associated with different options and targets revealed no discernible pattern (Fig. S4).

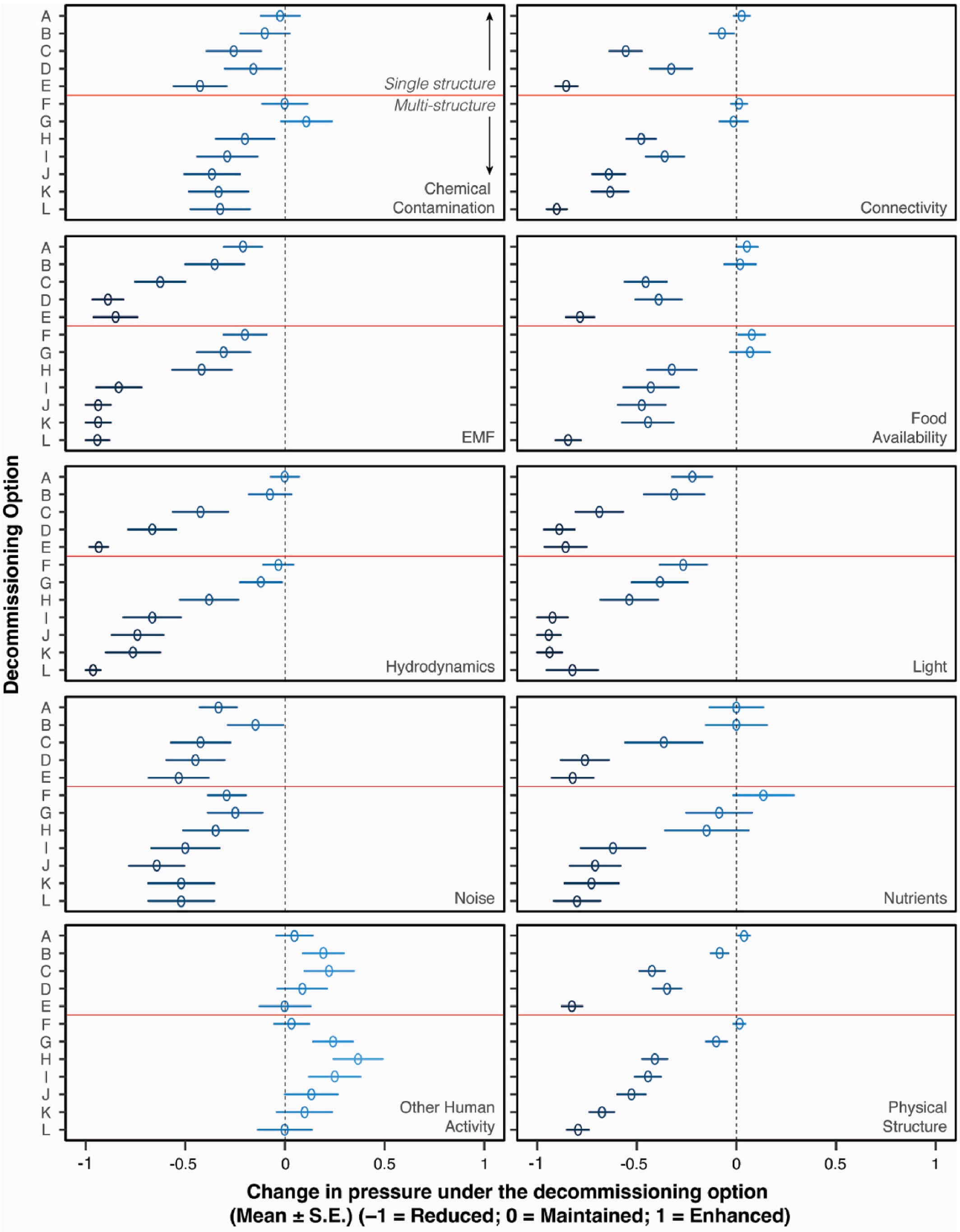

Fig. 2. Change in 10 pressures under 12 decommissioning options (A:L). Data shown are Mean ± S.E. based on an ordinal score. Positive values indicate the pressure is enhanced, negative values indicate the pressure is reduced, and a value of zero indicates the pressure is maintained at ‘current’ levels. Decommissioning Options A:E are single structure options, and F:L are multi-structure (regional) options, as follows: A - Abandonment (leave in place); B - Repurpose (in place); C - Partial Removal (partial abandonment); D - Repurpose (relocate); E – Total Removal; F - Abandonment of all; G - Repurpose/relocate all; H - Partial removal of all; I - Partial removal of some, repurpose/relocate others; J - Complete removal of some, abandonment of others; K - Complete removal of some, repurpose/relocate others; L - Complete removal of all.

4. Discussion

Expert opinion is that the performance of decommissioning options to move environmental status towards environmental targets will vary with the scale considered (single vs multiple structures), the decommissioning options applied, and the environmental target being considered. While there was a degree of variation in opinion of the extent to which different options might support (or hinder) environmental targets, either individually or combined, three options were considered as best performing options for meeting all targets. These were: abandonment in place, either as single structures (Option A) or regionally (Option F) or repurpose individual structures in place (Option B). The total removal of single or structures regionally (Option E and L, respectively) were, on average, considered to be the two worst performing options with respect to targets but best for adhering to current policy (i.e. OSPAR 98/3) of not leaving being a legacy of dumping in the marine environment. In terms of options affecting pressures on the environment, the majority (91/120; 76%) were predicted to reduce

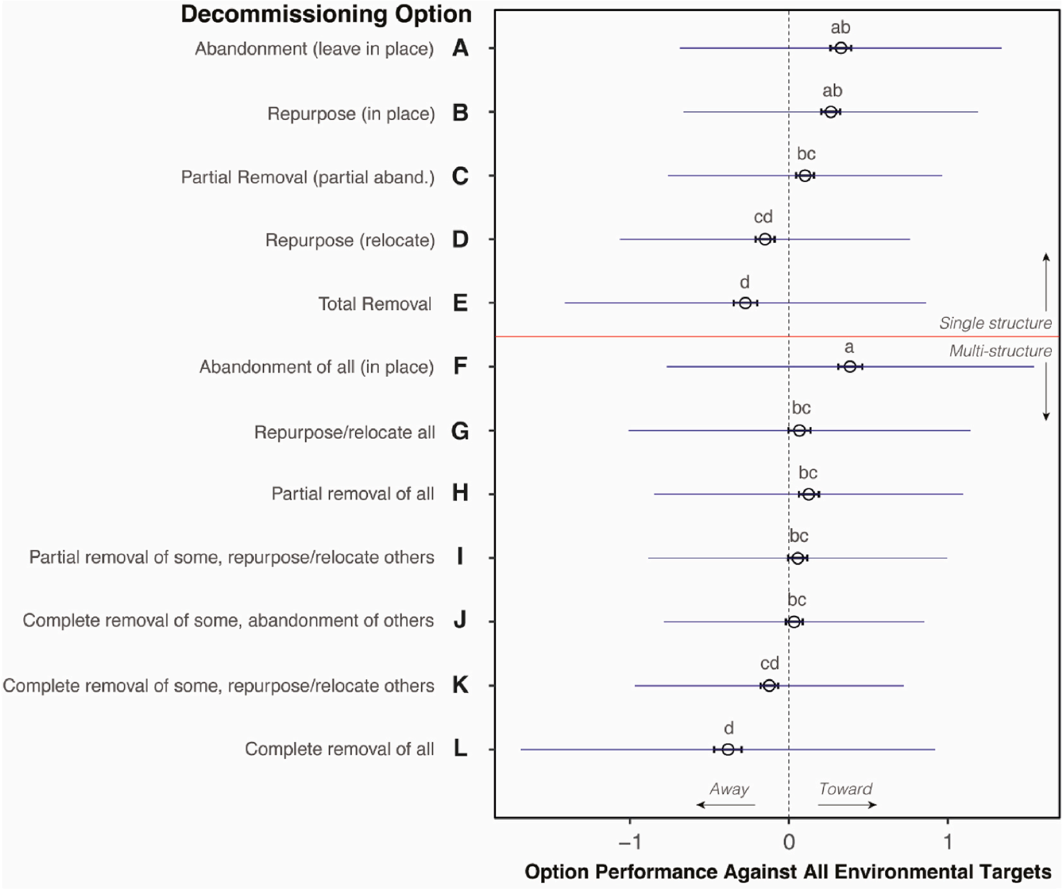

Fig. 3. Performance of all single and regional decommissioning options with respect to all environmental targets. Data are mean values (circle), standard error (capped error bars), and standard deviation (blue lines). Mean values indicate consensus view of to what extent decommissioning options will move us toward (+ve values) or away (-ve values) from environmental targets. NB Targets here are integrated thereby not prioritising one target over another. Letters indicate outcomes of pairwise *posthoc* comparison tests following one-way analysis of variance. Shared letters indicate no significant difference between groups ($p > 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

pressures. On face value, expert opinion supports a change in current decommissioning policy to allow alternative options.

The current position of several international and multi-national regional policies relevant to the decommissioning debate (1958 Geneva Convention, United Nations Convention on the Law of the Sea (1982), guidelines of the International Maritime Organisation (1989) and OSPAR 98/3) is total removal of marine artificial structures at end-of-life. At national level, laws often also require total removal. While some derogations exist under these various policies that allow alternatives to total removal, these instances have typically been constrained to when structures cannot be removed due to technological constraints, structure size, and/or difficulty of safe removal (FLTC, 2018; Jones et al., 2019). Furthermore, derogation cases (at least for OSPAR) require frequent evaluation (every 5 years) with a need for infrastructure to be surveyed and monitored for environmental and structural conditions for their entire lifespan, which could be hundreds of years (Sandberg, 1996; Quigel and Thornton, 1989).

Nevertheless, some nations are now actively considering alternatives to total removal, for instance, by converting Rigs-to-Reefs (Bull and Love, 2019; da Fonseca et al., 2020; Trevisanut, 2020) and which account for local considerations, such as key stakeholders, waste management and disposal facilities, available technologies and the application and interpretation of decommissioning guidelines (Jagerroos and Hughes, 2019). There is an increasing body of evidence and opinion as here suggesting that total removal may not be the optimal option for the environment (Ekins et al., 2006; Sommer et al., 2019, but see Knights et al. submitted), for which dual arguments are presented: (1) MAS can act as artificial reefs providing habitat for species, including fish, with a view to underpin sustainable fisheries (Reggio, 1987; Friedlander et al., 2014), and (2) counteract biodiversity loss by exclusion of other 'harmful' activities (such as exploitative or destructive fishing) through the creation of *de facto* marine protected areas (Schroeder and Love, 2002, 2004; Elliott and Birchenough, 2022); and/or (3) alternative options avoid additional greenhouse gas emissions attributed to decommissioning and recycling (Davies and Hastings, 2022).

Some of the desirable environmental effects associated with leaving structures in place in some form (Jagerroos and Krause, 2016; Sommer et al., 2019) may, however, be location-specific and should be viewed in the wider context of costs and benefits to the environment and society. A recent analysis of scientific opinion drawn from a group of international scientists revealed a complex network of desirable and undesirable effects associated with MAS that led to consensus opinion of limited support for policy change from the *status quo* (i.e. total removal vs. a derogation, see Knights et al. submitted). This essentially amounted to a scientific recommendation of continued case-by-case 'local' assessment and decision-making of whether to remove structures in their entirety or to implement an alternative option, such as implementing RtRs (Knights et al. submitted). This reinforces the recent opinion that a "one-size--fits-all" approach (i.e. a generic, non-site-specific approach based on policy rather than individual circumstances) may be unwise albeit with limited empirical evidence for one or other option (Lemasson et al., 2023).

All decommissioning options, whether implemented for single or multiple structures, will reduce the majority of pressures (except those from other human activities) from structures on the marine environment to a greater or lesser extent. A reduction in some pressures may not be desirable. For instance, maintenance of connectivity as a result of introducing hard bottom species/habitats into sedimentary environments (van der Molen et al., 2018; Tidbury et al., 2020), can underpin stability in ecological networks (Melià et al., 2016; Clubley et al., 2023), structure biodiversity across geographic space (Cristiani et al., 2021), and ensure genetic diversity, population development and growth across multiple spatial scales (Baguette et al., 2013; Hogan et al., 2012; Ross et al., 2017). Given global rates of habitat loss and fragmentation and degradation of habitats (Reddin et al., 2022), either the maintenance or addition of 'novel' habitat as a result of MAS could support biodiversity conservation efforts (Ben-Hamadou et al., 2023; van Elden et al., 2022). Indeed, developers are asked to not only consider mitigation measures but also compensation measures, such as recreating habitat to accommodate lost ecological structure and functions. Conversely, these structures can act as stepping-stones that facilitate biological invasion and impacting biodiversity (Adams et al., 2014; Bulleri et al., 2006), introduce pollution (Breuer et al., 2008) and interfere with sonar (Todd et al., 2009) with potential for significant cost to particular environments (Byrnes et al., 2007). Consequently, there will likely be a loss of some pressure(s) that are considered desirable and others that are undesirable in terms of their associated ecological effects (Knights et al. submitted) and with respect to environmental strategic targets with decision-making needing to be cognisant of the trade-off that will undoubtedly need be acknowledged under any option (Knights et al., 2014).

5. Conclusions

To summarise, we gathered expert opinion to predict the performance of different decommissioning options in ameliorating pressures from MAS and contribution toward 37 environmental targets. Our approach to capture international expert opinion through a structured workshop was necessitated by an absence of empirical data on the direct effects of MAS using appropriate 'before-after' experiments (Lemasson et al. 2022a, 2022b, 2023); an absence of data can lead to a lack of robust, evidence-based decision-making or inaction (Knights et al., 2014). Results suggest repurposed or abandoned individual structures, or abandoned multiple structures across a region, rather than total removal would most likely contribute most strongly to a range of environmental targets and aspirations identified by the United Nations and OSPAR, but to adopt this practice would be a fundamental shift in approach to current policy which without rigorous management, could lead to inappropriate disposal of 1000s of structures in the sea. Recent consensus on the effects of MAS (Knights et al. submitted), and the effect of different options on pressure amelioration and movement toward environmental targets illustrated by this study, show a diversity of effects on pressures and ecological outcomes that are considered positive (desirable) and negative (undesirable) from both an environmental, ethical and societal standpoint. We suggest that decisions will therefore likely require policy makers and managers to prioritise some targets over others, or if a holistic approach is taken, to accept that some targets will likely not be met. They can use these results to make informed and transparent decisions about decommissioning option based on their own context.

Credit author statement

Writing – original draft (Knights, Lemasson); Writing – review & editing (ALL); Data curation (Knights); Formal analysis (Knights); Funding acquisition (Knights, Somerfield); Methodology (Knights); Visualisation (Knights, Lemasson); Conceptualisation (Knights, Lemasson, Somerfield).

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Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119644.

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