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Research article

Developing expert scientific consensus on the environmental and societal effects of marine artificial structures prior to decommissioning

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ABSTRACT

Thousands of artificial ('human-made') structures are present in the marine environment, many at or approaching end-of-life and requiring urgent decisions regarding their decommissioning. No consensus has been reached on which decommissioning option(s) result in optimal environmental and societal outcomes, in part, owing to a paucity of evidence from real-world decommissioning case studies. To address this significant challenge, we asked a worldwide panel of scientists to provide their expert opinion. They were asked to identify and characterise the ecosystem effects of artificial structures in the sea, their causes and consequences, and to identify which, if any, should be retained following decommissioning. Experts considered that most of the pressures driving ecological and societal effects from marine artificial structures (MAS) were of medium severity, occur frequently, and are dependent on spatial scale with local-scale effects of greater magnitude than regional effects. The duration of many effects following decommissioning were considered to be relatively short, in the order of days. Overall, environmental effects of structures were considered marginally undesirable, while societal effects marginally desirable. Experts therefore indicated that any decision to leave MAS in place at end-of-life to be more beneficial to society than the natural environment. However, some individual environmental effects were considered desirable and worthy of retention, especially in certain geographic locations, where structures can support improved trophic linkages, increases in tourism, habitat provision, and population size, and provide stability in population dynamics. The expert analysis consensus that the effects of MAS are both negative and positive for the environment and society, gives no strong support for policy change whether removal or retention is favoured until further empirical evidence is available to justify change to the *status quo*. The combination of desirable and undesirable effects associated with MAS present a significant challenge for policy- and decision-makers in their justification to implement decommissioning options. Decisions may need to be decided on a case-by-case basis accounting for the trade-off in costs and benefits at a local level.

1. Introduction

There is an accelerating shift away from oil and gas extraction towards more renewable sources of energy. Many thousands of marine artificial structures (MAS; also known as man-made structures, MMS) have been installed to service the offshore hydrocarbon industry and provide necessary energy and materials for society. International efforts to decarbonise and turn towards greener energy sources to replace fossil fuels as part of their energy mix (Sovacool et al., 2022; Camarasa et al., 2022) is leading to an increase in new offshore artificial structures in the form of offshore wind farms (OWFs), wave farms, floating solar and tidal energy devices (Gouvernec et al., 2022).

For those MAS at or approaching the end of their operational life, in particular oil and gas infrastructure, urgent decisions regarding their decommissioning are required. These will also be crucial to support regulatory advice for structures that may need to be decommissioned, such as OWFs (Smyth et al., 2015). There are different requirements globally for decommissioning. Internationally, several instruments exist dictating 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)). Locally, such as within regional seas, requirements may vary and decommissioning options other than full removal may be considered (e.g. Gulf of Mexico, da Fonseca et al., 2020; Trevisanut, 2020). In the north-east Atlantic, the Oslo-Paris Commission (OSPAR, 1998) Decision 98/3 (1998) states that any artificial structures should be entirely removed at end-of-life (except for exceptional derogations); the basis of this decision was taken against a complex background of scientific, social, and political concern over mass 'dumping' of offshore installations (Jørgensen, 2012), following the 'Brent Spar incident' (see Huxham and Sumner (1999) and Jørgensen (2012) for a discussion of this event).

Decommissioning is designed to retire facilities or processes in a way that does not pose a risk to public health or the environment (Jagerroos and Krause, 2016) and several recent studies have called for alternative decommissioning options to complete removal to be considered. A component of this discussion is the balance between energy costs and CO_2 emissions involved in removing structures versus leaving *in situ* steel resource that could be repurposed or recycled (Davies and Hastings, 2023). Options include complete removal, complete abandonment *in situ*, partial removal (topping), partial or complete relocation, and repurposing as 'artificial reefs', dive resorts, or mariculture facilities (Jagerroos and Krause, 2016; Sommer et al., 2019). OSPAR themselves, in juxtaposition to their own 1998 Decision, also advocate for the introduction of artificial reefs to mitigate biodiversity loss (OSPAR, 1999), albeit specifying that waste materials should not be used in their construction. Despite the current endeavour and various contributions to the decommissioning debate, as yet there is no consensus on which option results in optimal environmental outcomes.

Several scientific reviews and overviews have provided information on the range of effects of MAS, placed in the context of decommissioning, at local to global scales (Fortune and Paterson, 2020; Sommer et al., 2019; van Elden et al., 2019; Dannheim et al., 2020; Bull and Love, 2019; Watson et al., 2023). Recent reviews of the available published scientific evidence for the effects of MAS on marine ecosystems, and the potential effects their removal may cause, has revealed a paucity of real-world case studies describing the ecological impacts of different decommissioning options (Lemasson et al., 2022a,b; see Elliott and Birchenough, 2022 for a review of the debate)"). Lemasson et al. (2023) argue that this represents a considerable challenge for evidence-informed decommissioning, which could prevent defensible quantitative predictions of the likely ecological benefits or harms from different decommissioning options and thus hinder decisive action on what to do with end-of-life artificial structures.

Decommissioning is now a globally recognised challenge being discussed with urgency in academic, industrial and regulatory spheres (Watson et al., 2023) and was identified as one of 15 global priority issues for biological conservation in 2021 (Sutherland et al., 2021). Yet, few additional empirical data are being produced to inform decommissioning decisions despite the need for a strong evidence base for the development of robust strategic marine planning and governance (Lonsdale et al., 2022). In light of this significant knowledge gap in the peer-reviewed scientific literature, we considered alternative sources of evidence that could inform decision-making, including grey literature, anecdotal evidence, personal opinions, local knowledge, professional expertise, assessment, and advice (referred to hereafter as 'expert knowledge') (Dick et al., 2014, 2016), as well as data held by industry (Murray et al., 2018). Some have questioned the quality, validity, and reliability of these additional evidence sources, arguing that anecdotes and personal opinions can vary widely, and are less robust, unreliable or biased, and therefore less persuasive (Cvitanovic et al., 2014; Walsh et al., 2019). Despite this, expert knowledge, drawing on scientific and technical judgments of experts can be a valuable form of evidence (Morgan, 2014; Knights et al., 2015). When based on the best available research, expert knowledge and assessment can play an important role in decision-making (Lundin and Öberg, 2014; Knights et al., 2014; Elliott et al., 2018), particularly when the issue or question is time-sensitive but the state of knowledge is insufficient to effectively inform decision-making requiring action to be taken despite uncertainty (McBride and Burgman, 2012; Knights et al., 2014).

Given the urgent need to address the decommissioning challenge, and provide additional avenues of evidence, we gathered expert knowledge and assessment related to MAS and their decommissioning from a global panel of international scientists. These experts were invited to participate in two linked workshops: the first to identify the ecological effects arising from the introduction of MAS in the sea, and the second to assess the impact of MAS on the marine environment using an exposure-effect approach (*sensu* Knights et al., 2015). The exposure-effect approach is recognised for its value in assessing on-going, current environmental pressures (Smith et al., 2007) and several studies have effectively used this concept to assess risk to ecosystems from ongoing human activities (Bax and Williams, 2001; Samhouri and Levin, 2012; Knights et al., 2015; Elliott et al., 2018). Indeed, the complexity of marine systems (Knights et al., 2013) coupled with the broad range of human activities requires a holistic (systems) analysis approach to rigorously determine causes, consequences, and management responses to change (Knights et al., 2014, 2015; Elliott et al., 2020b). Burdon et al. (2018) emphasised the benefits of adopting a mechanistic approach to linking the cause-consequence-response continuum of the various stages of oil and gas decommissioning. The workshops were developed to obtain a global scientific consensus on the ecosystem effects of artificial structures in the sea and their causes (herein, pressures), to identify which effects, if any, should be retained following decommissioning.

2. Methods

We invited scientists to take part in two structured workshops. Invitations were extended to individuals with international reputations in marine biology and ecology, marine policy, ecosystem services and socio-ecological systems. This resulted in 39 participants from 30 academic and government institutions, four continents, and seven countries. All participants of the workshops are authors of this paper and their affiliations provided are on the title page.

2.1. *Workshop 1. Identification of ecosystem effects arising from the presence of marine artificial structures*

The first step asked experts to identify all possible ways in which MAS might affect marine ecosystems and its components. Respondents were asked to consider any artificial structures in the sea and to state the effect(s) of these structures using free text statements. In total, 1,233 potential effects were described; many of these effects were the same in intent but phrased differently by respondents. Consequently, after the workshop, a simplified typology was created using categorical descriptions to summarise each of the narrative effects. This resulted in 20 broad ‘effects’ being identified (see Table 1), and each of the 1,233 effects being subdivided into these categories.

Concurrently, we also created a second typology of ‘pressures’ which characterises the mechanism underpinning an effect based on the narrative provided. One scenario might be ‘introducing habitat’ (the pressure) creates resource for benthic species resulting in population size increase (the effect). These typologies were used to populate a ‘lookup table’ for use in the second workshop but were not used to code each effect at this stage. In total, 11 pressures were identified (Table 1).

Table 1
Typology of effects and pressures.

Assessment Criteria	Categories
Pressure “The mechanism through which an effect is introduced”	Chemical contamination Connectivity EMF Food availability Hydrodynamics Light Noise Nutrients Other Other human activities Physical structure
Effect “The change to the ecosystem and/or its components”	Animal behaviour Biodiversity Collision Connectivity Dispersal (assisted) Disturbance Electromagnetic forces Erosion Habitat loss Habitat provision Hydrodynamics Approach to Management Mortality Noise Nutrient cycling Pollution Population dynamics Population size Tourism Trophic effects

2.2. *Workshop 2. An exposure-effect assessment of effects*

Participants were asked to undertake an exposure-effect assessment of the identified effects (see Knights et al., 2015), which assesses the threat associated with each effect using a pressure-assessment approach (see Robinson et al. (2013) for full details). The pressure assessment methodology is designed with the concept of risk assessment in mind; the assessment criteria can be used to evaluate the pressure (cause of impact) and its consequences (here ‘cost/benefit’) of a single or combination of pressures. The assessment is based on expert judgement (Cooke and Goossens, 2004) with data collected using the World Café methodology (Brown, 2002; Elliot et al., 2005) in which participants qualitatively assess each effect using a categorical assessment. Here, respondents were asked to assess effects using seven criteria designed to capture their view of **Impact** (a risk measure based on the ‘exposure’ of the ecosystem to a potential pressure in terms of severity, temporal frequency and spatial extent) and **Cost/Benefit** (a measure of pressure duration, environmental and societal cost/benefit of an effect). Impact and cost/benefit constitute drivers of decision-making for the decommissioning of artificial structures.

Prior to the workshop, we created a unique workbook for each participant. Each workbook contained 250 effects (20% of 1,233), randomly selected from all identified effects. The workbook contained the original description of the effect and our summary of the effect based on the typology (see above). Nine columns were added to the effects workbook; one column to describe the pressure allowing participants to choose from 11 of the predefined options, seven columns to assess the exposure-effect assessment criteria, and one column to assess retention of effects. Each cell within a column allowed a respondent to select just one answer from a pre-defined list of possible answers specific to each criterion.

Impact risk was described using three impact components: (i) **spatial extent** (local and regional), (ii) **frequency of impact**, which both are used to describe the exposure/likelihood of an ecosystem component to a potential pressure, and (iii) **severity**. An ordinal Likert (categorical) scale of effect sizes was used to describe each pressure-effect combination. For (i) and (iii), each effect could be described as either 'Negligible', 'Small', 'Medium' or 'Large'. For (ii), the frequency of impact could be described as either 'Never', 'Rare', 'Occasional', 'Frequent' or 'Continuous'. Cost/Benefit was determined based on the following three components: (iv) **duration** - the time for an impact to dissipate once a pressure (here, the structure) is removed, (v) **environmental** and (vi) **societal cost/benefit** of effects. Duration was quantified using 7 possible options, ranging from short term (6 = hours; 7 = negligible) to long term (1 = > 1 century). Environmental and human costs/benefits were assessed selecting from three possible options: undesirable (−1), neutral (0), or desirable (1). A final additional criterion was used to ask participants if the effect should be **retained** using a binary yes/no response. Possible answers for each assessment criterion are provided in Table 2.

2.2.1. *Workshop 2 data post-processing*

All workshop files were merged into a single file retaining all data in R (R Core Team, 2022) and all effects were independently assessed by multiple respondents. There was a potential for 220 pressure-effect combinations (11 pressures × 20 effects). Following assessment, 86 pressure-effect combinations (39%) were retained with those 'not applicable/not possible' excluded from the dataset. The categorical assessment of impact risk, cost/benefit and retain criteria were converted to an ordered numerical score for analysis (see Table 2 for values attributed to each categorical criterion; method follows Knights et al., 2015). Data were summarised using the R package dplyr (Wickham et al., 2022) generating mean and standard error values for each pressure-effect combination. Here, the mean indicates the consensus score, and the error bars indicate the level of agreement among respondents, i.e., small error bars indicate a high level of agreement between respondents on the score, and large error bars indicate disagreement among respondents.

Two integrated scores (adapted from Knights et al., 2015) important in decision-making were calculated: (1) impact risk – calculated as the product of severity, frequency, local and regional effect scores; and (2) cost/benefit score – calculated as the product of the inverse duration score and the sum of environmental cost/benefit and societal cost/benefit scores. The duration score was inverted (i.e. Duration score of 7 = $\text{Duration}_{\text{inverted}}$ of 1) to ensure longer duration pressures had a greater effect on the integrated score. These two scores allow the ranking of impact risk and cost/benefit components for decision-makers to prioritise pressures and effects. Higher values indicate greater impact risk (ecosystem damage) and cost/benefit. The value sign indicates whether scientists consider the overall effects (environmental and human combined) to be desirable (i.e. a 'benefit'; values > 0) or undesirable (i.e. a 'cost'; values < 0). Increasingly positive or negative values indicate greater duration of the pressure or effect following pressure removal.

Table 2
Assessment criteria with categorical (and associated scores) for use in analysis.

Assessment Criteria	Categories and Associated Ordinal Scores
Severity	Negligible = 1
Local effect	Small = 2
Regional effect	Medium = 3
	Large = 4
Frequency	Never = 0
	Rare = 1
	Occasional = 2
	Frequent = 3
	Continuous = 4
Duration	None = 1
	Hours = 2
	Days = 3
	Months = 4
	Years = 5
	Decades = 6
	Centuries = 7
Environmental Cost/Benefit	Negative = −1
Societal Cost/Benefit	Neutral = 0
	Positive = 1
Retain Score	No = 0
	Yes = 1

2.2.2. *Statistical analysis*

The difference in impact risk and cost/benefit scores between pressure and effect groups were tested using Kruskal-Wallis analysis. Scores are presented as means ± standard errors. The role of impact and cost/benefit components on a respondent's perception of the primary pressure and effects of artificial structures was also assessed using additive ordinal logistic regression (OLR) models. The models were structured to return the observed information matrix from optimization (Hessian) to generate standard errors (S.E.) for each main effect component. Confidence intervals (CIs) were generated for parameter estimates using the standard errors converted into odds ratios. If CIs span odds ratio values < 1 and >1, then a parameter is considered not significant. OLR models were constructed in R using the *polr* function in the MASS package (Venables and Ripley, 2002) and odds ratios and confidence intervals visualised using forest plots.

3. Results

3.1. *Impact risk criteria assessment*

Overall, the number of pressures underpinning each of the 20 effects ranged from 1 (e.g. for erosion) to 8 (e.g. for ecological changes associated within modified animal behaviour, pollution, or trophic effects) (Fig. 1). Effects associated with different pressures were considered to be of small to large severity, rare to continuous in frequency (Fig. 1), and of negligible to large magnitude depending on the spatial scale of focus (Fig. 2; Fig. A1; Fig. A2).

The mean severity score (2.89 ± 0.63) shows respondents considered pressures to be, on average, of small to medium effect, with relatively little variation among respondents within pressure-effect combinations (Fig. 1A). Pressures of highest severity created disturbance, introduced pollution, impacted biodiversity, prevented ecosystem management, and created trophic effects, such as disturbing predator-prey relationships.

The mean frequency score (3.07 ± 0.82) shows respondents considered the introduction of pressures to be frequent, albeit varying from occasional/frequent to continuous (Fig. 1B). For some pressures, such as 'physical structure', frequency was typically very high (∼4) compared to some other causes, such as chemical contamination, that was less frequent.

Respondents suggested differences in the magnitude of cause-effects relationships from artificial structures depending on the spatial scale considered (Fig. 2). At a local scale, pressure-effect relationships overall were considered to be of medium magnitude (mean = 3.18 ± 0.64), with few being of negligible or small magnitude (e.g. chemical contaminants affecting trophic effects) (Fig. 2A). Regionally, pressure-effect relationships were generally of small magnitude (mean = 2.01 ± 0.66), with few exceptions (e.g. connectivity affecting animal behaviour) (Fig. 2B).

3.2. *Cost/benefit criteria assessment*

Assessment of pressure duration, and environmental and societal cost/benefit was similarly diverse depending on the pressure and its effect(s) (Fig. 3A; Fig. A3). Overall, pressure duration averaged 5.08 ± 1.27, therefore of relatively short duration in the order of days, but varied widely across pressures, ranging from negligible or lasting a few hours (e.g. electromagnetic effects from the physical structure, or effects from the impact of light) to several decades (e.g. pollution and

Fig. 1. Expert judgement scores of degree of impact (severity) and frequency of occurrence grouped by pressure and effect types. **(A)** Severity (Mean ± S.E.). **(B)** Frequency (Mean ± S.E.). Colours indicate if the pressure-effect score is better (green) or worse (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

disturbance effects from chemical contamination). Pressure duration also varied widely between effects within pressure category (e.g. human activity).

The environmental effects of structures were, on average, viewed negatively (mean = −0.16 ± 0.81), although cost/benefit varied greatly within certain pressure types (e.g. human activity/physical structure) (Fig. 3B). Some pressures were viewed as having entirely negative (undesirable) effects (e.g. chemical contamination, electromagnetic fields), but none were viewed as having entirely positive (desirable) effects. Desirable effects of structures included supporting biodiversity, providing habitat, increasing population sizes, improving population dynamics, and enhancing tourism. Undesirable effects included changes in animal behaviour, risk of collision, disturbance events and mortality, assisted dispersal (e.g. invasive species), addition of new forms/modification of habitat, and introducing pollution and noise (Fig. 3B).

Societal effects from structures were assessed more positively than environmental effects but mostly ‘neutrally’ (i.e. a score of 0) rather than positively (mean = 0.03 ± 0.60) (Fig. 3C). Again, desirability of effects varied within pressure types, not dissimilarly to environmental outcomes. Societal benefits from structures were associated with

Fig. 2. Expert judgement scores of spatial extent grouped by pressure and effect types. **(A)** Local (Mean ± S.E.). **(B)** Regional (Mean ± S.E.). Colours indicate if the pressure-effect score is better (green) or worse (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

biodiversity, habitat provision, ecosystem management, tourism, and population size. Undesirable effects (societal costs) were associated with assisted dispersal of non-native species, disturbance events, habitat loss, mortality, pollution, and trophic interactions.

3.3. Aggregate impact risk and cost/benefit scores

Severity, frequency, and local and regional magnitude scores were integrated into a single estimate of impact risk, while duration, environmental and societal cost/benefit scores were integrated into a single estimate of cost/benefit (Fig. 4).

There were significant differences in impact risk scores among effects ($\chi^2 = 36.3$, $p < 0.01$) but not between pressures ($\chi^2 = 13.1$, $p = 0.22$; Fig. 4A&C), although some median impact risk cores for individual pressures were markedly higher than others (e.g. food availability: impact score of 72.0; EMF: impact score of 24.1)(Fig. 4A). Structures had the greatest impact on approach to management and on biodiversity effects, and lowest effect on species mortality, electromagnetic forces, and animal behaviour (Fig. 4C).

Similarly, there were significant differences in cost/benefit scores

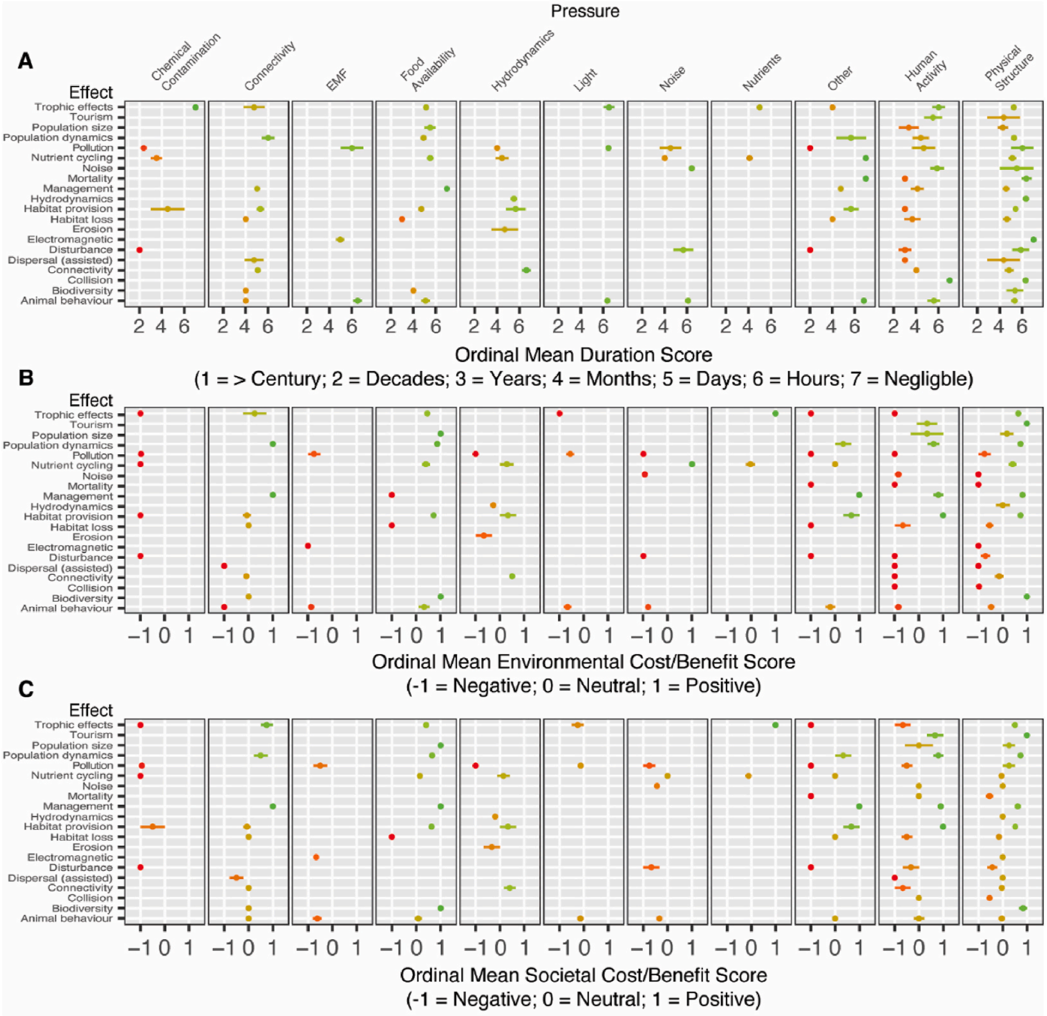

Fig. 3. Expert judgement scores of pressure duration and desirability of environmental and societal effects grouped by pressure and effect types. **(A)** Duration (Mean ± S.E). **(B)** Environmental Cost/Benefit. **(C)** Societal Cost/Benefit (Mean ± S.E.). Colours indicate if the pressure-effect score is longer in duration (red = longest; green = shortest), or more (value > 0; green) or less desirable (values < 0; red) from an environmental and societal perspective. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

among effects ($\chi^2 = 80.6$, $p < 0.001$), but not among pressures ($\chi^2 = 6.68$, $p = 0.75$; Fig. 4B&D). There were clear differences in cost/benefit scores among effects, divided between those considered desirable (e.g. management, population dynamics, habitat provision and biodiversity) and those considered undesirable (pollution, disturbance, habitat loss and assisted dispersal). The overall median score for all pressures was negative (−3.3) and relatively low in variability among categories (S.D. = 4.8)(Fig. 4B) compared to the effects, where the overall score was also negative (−3.4) but considerably more variable (S.D. = 16.9) among categories (Fig. 4D).

3.4. *Reasons for decision-making*

3.4.1. *Impact risk components*

In assessing impact risk components, the odds ratios (OR) describing the relative contribution of assessment criteria to an effect, indicated that frequency of impact and effects at a local scale were more important to respondents than the severity of the pressure, which did not affect decision-making (OR ≅ 0)(Fig. 5A). The regional scale of effect was statistically less likely to affect decision-making (Fig. 5B). Local scale and frequency were 31% and 28% more likely to influence an expert's assessment of a pressure (Figs. 5A), and 43% and 13.5% more likely to affect a respondent's assessment of effects (Fig. 5B).

3.4.2. *Cost/benefit components*

In assessing cost/benefit components (Fig. 5C and D), duration, environmental and societal criteria contributed to the assessment of pressures (Fig. 5C), whereas for effects, environmental cost/benefit was 45.8% more likely to affect assessment, duration time 15% less likely to affect assessment, and societal cost/benefit having no effect on assessment (OR ≅ 0) (Fig. 5D).

3.5. *Retention assessment*

Respondents were also asked to identify which pressures and effects they would like to see retained or removed following decommissioning (Fig. 6). In many cases, a single pressure generated multiple effects, many of which respondents simultaneously wanted to both lose and retain (e.g. those arising from the physical structure, human activities, or food availability). Other pressures (e.g. light, electromagnetic fields, 'other') were considered to generate entirely undesirable effects. No single pressure was considered to create entirely desirable effects (retain scores >0.5).

Regardless of the pressures, effects of artificial structures on tourism and (biological) population size were viewed entirely as desirable (retain scores >0.5), whereas effects on pollution, noise, mortality, hydrodynamics, habitat loss, erosion, electromagnetics, disturbance,

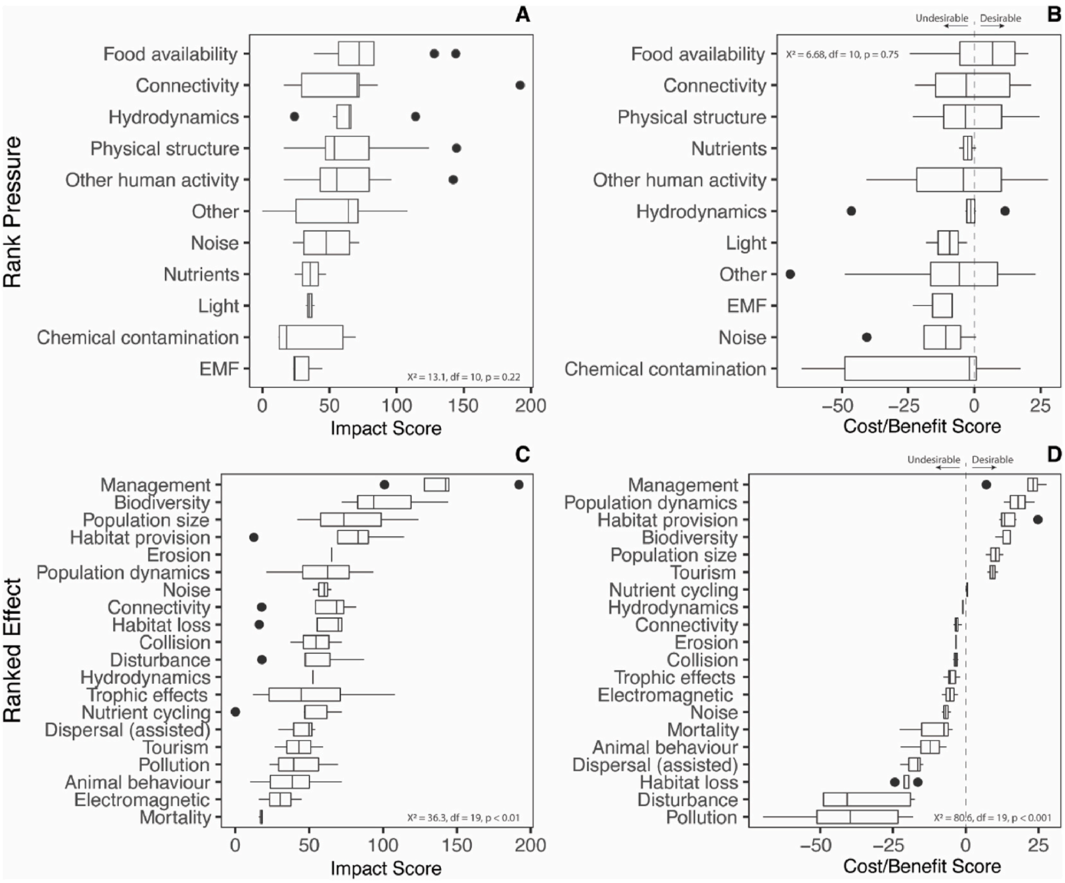

Fig. 4. Ranked Impact and Cost/Benefit Scores. **(A and C)** Aggregate impact risk scores (calculated as the product of severity, frequency, local and regional magnitude scores). **(B and D)** Cost/Benefit scores (calculated as $\sum$(Environmental cost/benefit + Societal cost/benefit) × $\text{Duration}_{\text{inverse}}$). **(A and B)** Scores grouped by ranked pressures, and **(C and D)** by ranked effect. Box hinges indicate the upper and lower interquartile ranges (I.Q.R), box line indicates the median, whiskers = 1 Standard Deviation (SD) beyond the lower/upper I.Q.R, and outliers are values > 1 SD beyond the whisker limits. NB – the duration score was inverted (i.e. duration score of 7 = $\text{Duration}_{\text{inverted}}$ = 1) to make longer duration times have a bigger effect on the integrated score. EMF = electric and magnetic fields.

connectivity, collision, or animal behaviour, were viewed entirely as undesirable (retain scores <0.5).

4. Discussion

Time-sensitive environmental management aims to support sustainable human activity while balancing long-term societal and ecological needs. For the deployment and decommissioning of MAS, scientific consensus on the potential environmental consequences is an urgent and key component in the wider decision-making process (Knights et al., 2014). MAS have potentially significant activity, pressure and effects footprints (Knights et al., 2013, 2015; Elliott et al., 2020a) at all stages of their life cycle (Dafforn et al., 2015). International policy (e.g. 1958 Geneva Convention; IMO, 1989) largely dictates that structures must be fully removed at end-of-life (excluding some derogations such as for structures that are ‘impossible’ to remove), although it has been argued that this could result in the loss of ecosystem functioning and services afforded by a new equilibrium created by those structures over time, and a more nuanced, case-by-case approach could be better for the environment and society (Sommer et al., 2019). Many energy producing MAS are rapidly approaching end-of-life, and consequently, there is urgency with which decommissioning decisions must be taken. However, there is an incomplete and insufficient published scientific evidence base for making informed and holistic decisions about decommissioning options (Lemasson et al. 2022a, 2022, 2023). Hence, to address the gap in decision-making research, we asked a worldwide panel of scientists to provide the needed evidence in the form of expert opinion. Specifically, they were asked to identify and assess the ecosystem effects of artificial structures in the sea and their associated pressures (*sensu* ‘drivers of effect’), and to identify which, if any, should be retained following decommissioning.

Workshop participants comprised a diverse range of experts from the fields of marine biology and ecology, marine policy, ecosystem services and socio-ecological systems, thereby providing both an environmental and socio-economic perspective of MAS (decommissioning). An analysis of which assessment criteria drove ranking of impact and effects indicated that environmental costs/benefits were ~50% more important to these experts when considering the effects of MAS rather than societal costs/benefits, and the duration of those effects 65% less likely to influence their assessment. The prioritisation of environmental over societal (socio-economic) benefits, irrespective of an individual’s background or research interest, is becoming more commonplace as the value of the environment to human health and well-being is increasingly recognised (Soga and Gaston, 2020). Recent studies assessing perceptions of coastal defence structures show that stakeholders prioritise ecological features or benefits over socio-economic or technical aspects of that infrastructure (Evans et al., 2017; Fairchild et al., 2022), despite environmental benefits often being intangible to many (*sensu* Lim et al., 2020).

For the majority of effects arising from the presence of MAS, the severity and frequency of pressures driving them, were generally considered of medium severity and frequent, and with effects at local scales of greater concern than those at regional spatial scales. For the most part, the duration of effects post-removal of the structures (i.e.,

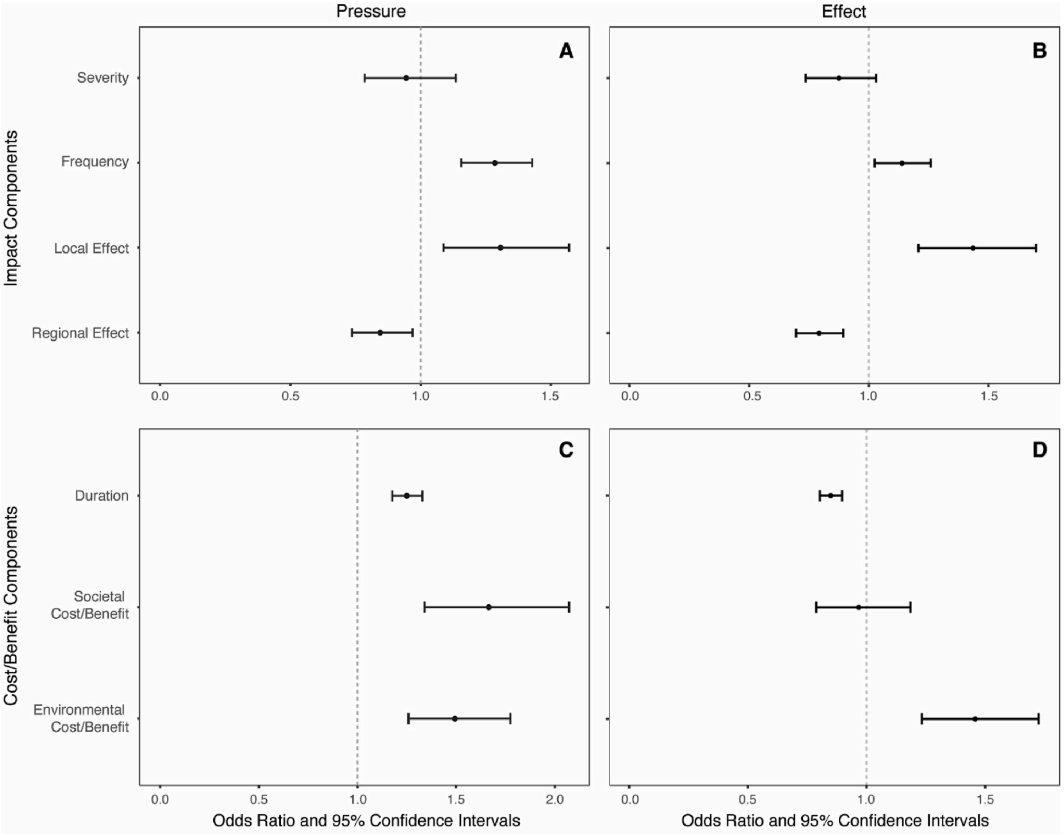

Fig. 5. Odds ratios (OR) and 95% confidence limits generated from ordinal logistic regression models testing the effect of decision-making components on the assessment of (**A and C**) pressures, and (**B and D**) effects. **(A and B)** impact risk components; **(C and D)** cost/benefit components. Error bars that do not span the value of 1.0 indicate greater (values > 1.0) or lesser (values < 1.0) likelihood of driving assessment scoring.

persistence of the effect(s)) was considered to be relatively short, in the order of days rather than years, decades or centuries. Environmental effects of leaving structures in place were scored as marginally undesirable, while societal effects were marginally desirable. The greater concern of pressures and effects at local spatial scales, in particular, is well-placed given the documented trends in biodiversity loss at this scale (Elahi et al., 2015). Although the general consensus of effects of MAS on the environment was negative with the majority of experts suggesting that many effects should be lost (e.g. achieved by the complete removal of MAS), some effects were viewed positively and worthy of retention (e.g. by leaving the MAS in place). It was clear that the costs and benefits of different decommissioning options are highly context-dependent and that decommissioning decisions may well need consideration on a case-by-case basis (Fowler et al., 2018). In some cases, leaving MAS in place was considered undesirable. Examples of negative effects included the assisted dispersal of invasive species (Adams et al., 2014). But in some locations, some pressure-effects have been shown to be desirable, for instance those that support improved trophic linkages, tourism, habitat provision, population size, and providing stability in population dynamics (e.g. Bishop et al., 2017; McLean et al., 2022; Friedlander et al., 2014; Fayram and De Risi, 2007; Meyer-Gutbrod et al., 2020). Given global trends in biodiversity loss, scientists, developers and policy makers alike are seeking mitigation and/or compensation options, such as developing options to reuse/recycle oil rigs, to maintain or enhance connectivity (Olds et al., 2016; McLean et al., 2022) or increase local biomass/biodiversity (Meyer-Gutbrod et al., 2020) alongside or in addition to other interventions like the introduction of artificial reefs (Bartholomew et al., 2022). However, the contribution that structures can make towards biodiversity objectives may be idiosyncratic depending on location (Reis et al., 2021; Lemasson et al., In Review; Firth et al., In Review), such that this approach may not be a panacea. To what extent structures should be decommissioned, either entirely or in part (see Knights et al. (2024) for an overview of the range of decommissioning options), will require further consideration to determine how the diversity of pressures and effects might be modified by choice of option and which might be best for the environment and society determined by local priorities.

The paucity of available data describing the effects of decommissioning meant this assessment needed to be underpinned by expert judgement analysis; an effective method for achieving consensus between groups of individuals (Brown, 2002; Cooke and Goossens, 2004) in data poor systems at low financial cost to the stakeholder (Fletcher et al., 2010). Here, we have calculated the mean, median and variance of responses by experts to estimate the level of consensus, but we recognise that this is not an estimate of uncertainty. Uncertainty is inherent in scientific research and decision-makers and resource managers expect some measure or degree of uncertainty to be included in scientific studies (Maier et al., 2016). However, uncertainty is only estimable when studies exist, and there is a lack of data on the effects of decommissioning MAS. There are generally three types of decisions that require assessment of uncertainty: a signal for action, choosing among fixed options, or creating options for decision-making (Fischhoff and Davis, 2014). The data presented here are expert opinion that transforms an individual's experience into a metric of an effect. This information that can be used by decision-makers to create options for decommissioning MAS in the sea.

This analysis represents a critical first step in screening for impact and costs/benefits of MAS allowing managers, using a mixture of law and policy at international and national level as a basis, to: (a) prioritise which effects they might wish to preserve or be willing to lose at end-of-life (Piet et al., 2015), (b) predict the longevity of those effects, and (c) defend management trade-off decisions using best scientific evidence

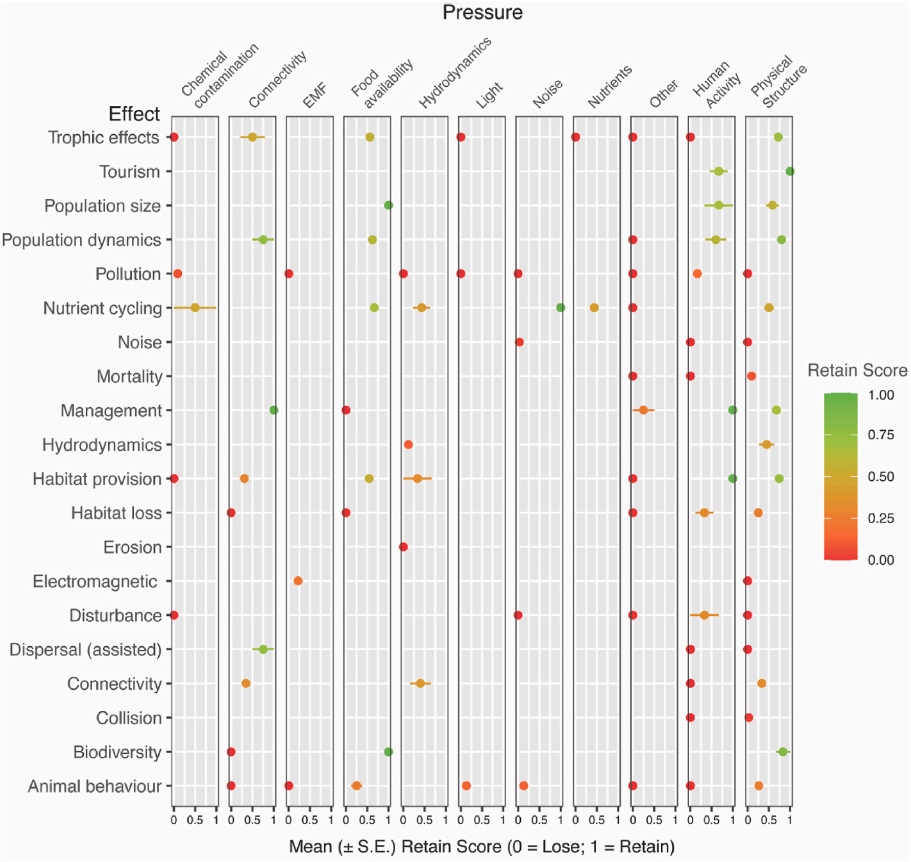

Fig. 6. Retention assessment (mean ± S.E.) of each effect grouped by each pressure. Scores can range from 0 (lose) to 1 (retain), and a value of 0.5 indicates ‘neutral’. Colours indicate if the impact-effect score should be retained (green) or lost (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

that links management measures to environmental objectives and societal costs and benefits of their decisions (Knights et al., 2014). Environmental policy and management are increasingly moving toward a two-stage system of decision-making (within which sits the mitigation hierarchy, Niner et al., 2018) that first considers nature (i.e. biodiversity net gain) followed by socio-economic factors (i.e. environmental net gain). This approach is a mode of regulatory biodiversity trading or “offsetting” (Walker et al., 2009) that is increasingly promoted as a way to achieve conservation objectives and sustainable development (but see Firth et al., 2020).

5. Conclusions

Our results reveal a general consensus in opinion between global scientists on the drivers and ecological costs and benefits of effects from MAS. But it is also clear that any positive and negative effects of MAS are intertwined, presenting a significant challenge for policy- and decision-makers in their justification to implement decommissioning options other than complete removal. Most biodiversity trading has a regulatory or statutory basis that initially prohibits an activity (e.g. habitat modification, dumping of waste) but later permits it conditionally (Salzman and Ruhl, 2000). The consensus was that the effects of MAS are both negative and positive for the environment and society, and thus show no strong support for policy change for removal (OSPAR region) or retention (Gulf of Mexico/California) until further empirical evidence is available to justify change to the *status quo*. At present, the balance may be decided on local “higher impact” effects, depending on local context where this is allowable under regional legislation. Until then, trade-off analyses (multi-criteria decision analysis; examples include Fowler et al., 2014; Martins et al., 2020) across multiple decommissioning options, each with a different suite of positive and negative effects that vary in magnitude, are likely required.

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CRediT authorship contribution statement

Antony M. Knights: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Anaëlle J. Lemasson:** Investigation, Methodology, Project administration, Writing - original draft, Writing - review & editing. **Louise B. Firth:** Investigation, Methodology, Writing - review & editing. **Todd Bond:** Writing - review & editing, Investigation. **Jeremy Claisse:** Writing - review & editing, Investigation. **Joop W.P. Coolen:** Writing - review & editing, Investigation. **Andrea Copping:** Writing - review & editing, Investigation. **Jennifer Dannheim:** Investigation, Writing - review & editing. **Michela De Dominicis:** Investigation, Writing - review & editing. **Steven Degraer:** Investigation, Writing - review & editing. **Michael Elliott:** Investigation, Writing - review & editing. **Paul G. Fernandes:** Investigation, Writing - review & editing. **Ashley M. Fowler:** Investigation, Writing - review & editing. **Matt Frost:** Writing - review & editing, Investigation. **Lea-Anne Henry:** Investigation, Writing - review & editing. **Natalie Hicks:** Investigation, Writing - review & editing. **Kieran Hyder:** Investigation, Writing - review & editing. **Sylvia Jagerroos:** Investigation, Writing - review & editing. **Daniel O.B.**

Jones: Investigation, Writing - review & editing. **Milton Love:** Investigation, Writing - review & editing. **Christopher P. Lynam:** Investigation, Writing - review & editing. **Peter I. Macreadie:** Investigation, Writing - review & editing. **Joseph Marlow:** Investigation, Writing - review & editing. **Ninon Mavraki:** Investigation, Writing - review & editing. **Dianne McLean:** Investigation, Writing - review & editing. **Paul A. Montagna:** Investigation, Writing - review & editing. **David M. Paterson:** Investigation, Writing - review & editing. **Martin Perrow:** Investigation, Writing - review & editing. **Joanne Porter:** Investigation, Writing - review & editing. **Debbie J.F. Russell:** Investigation, Writing - review & editing. **Ann Scarborough Bull:** Investigation, Writing - review & editing. **Michaela Schratzberger:** Investigation, Writing - review & editing. **Brooke Shipley:** Investigation, Writing - review & editing. **Sean van Elden:** Investigation, Writing - review & editing. **Jan Vanaverbeke:** Investigation, Writing - review & editing. **Andrew Want:** Investigation, Writing - review & editing. **Stephen C.L. Watson:** Investigation, Writing - review & editing. **Thomas A. Wilding:** Investigation, Writing - review & editing. **Paul Somerfield:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing - review & editing.

Declaration of competing interest

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Data availability

Data will be made available on request.

Appendix

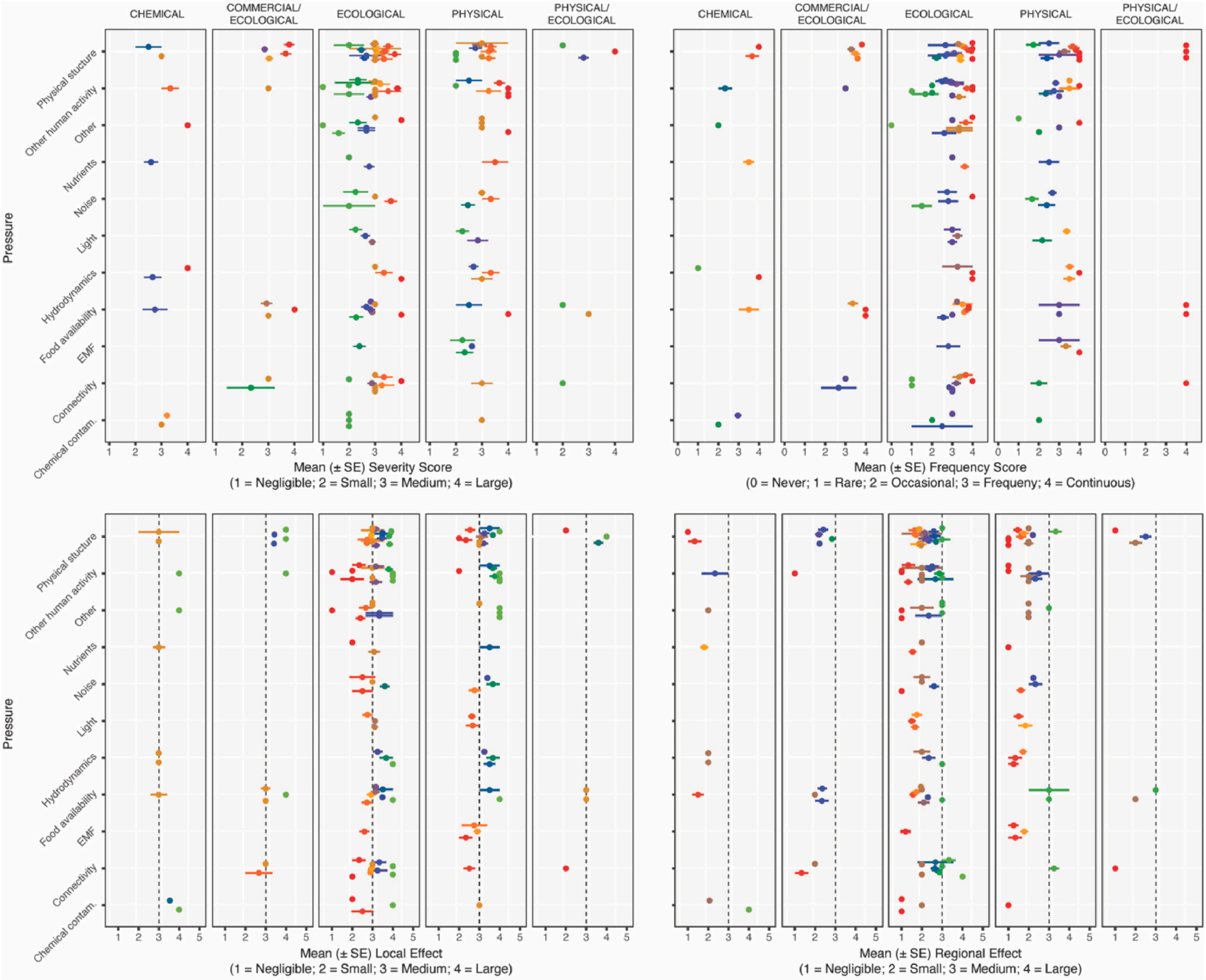

Fig. A1. Mean scores (±SE) for severity, frequency, and magnitude of local- and regional-scale effects of pressures. Individual scores for effects (see Table 1) as a result of each pressure within classification are shown but not differentiated for clarity. Colour ramping reflects the desirability of the scores' categorical value (e.g. for severity, green indicates 'negligible' which can be considered more desirable than red which indicates 'large' severity).

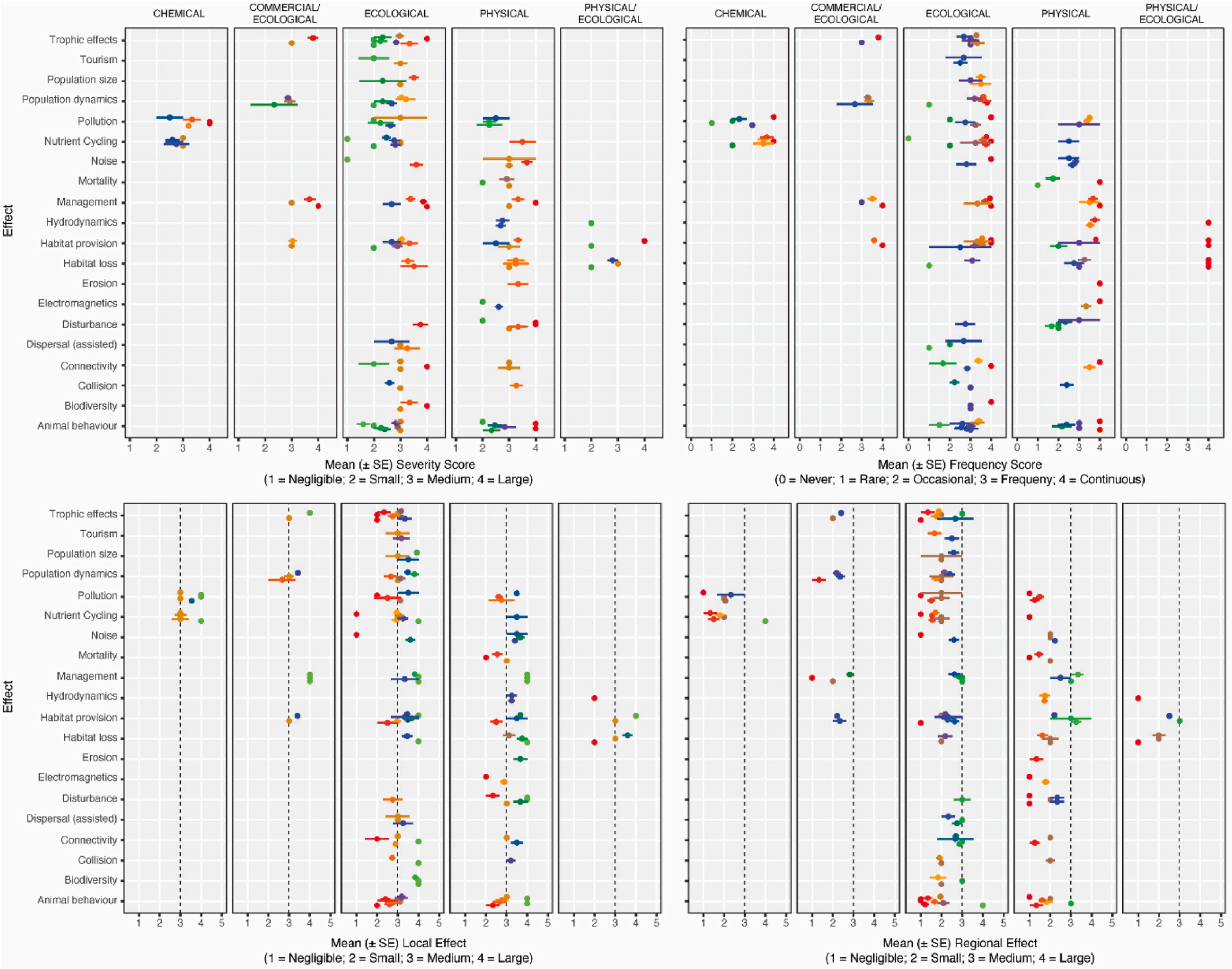

Fig. A2. Mean score (±SE) for severity, frequency, and magnitude of local and regional effect related to ecological effects. Individual scores for pressures (see Table 1) associated with each effect within classification are shown but not differentiated for clarity.

Colour ramping reflects the desirability of the scores' categorical value (e.g. for severity, green indicates 'negligible' which can be considered more desirable than red which indicates 'large' severity).

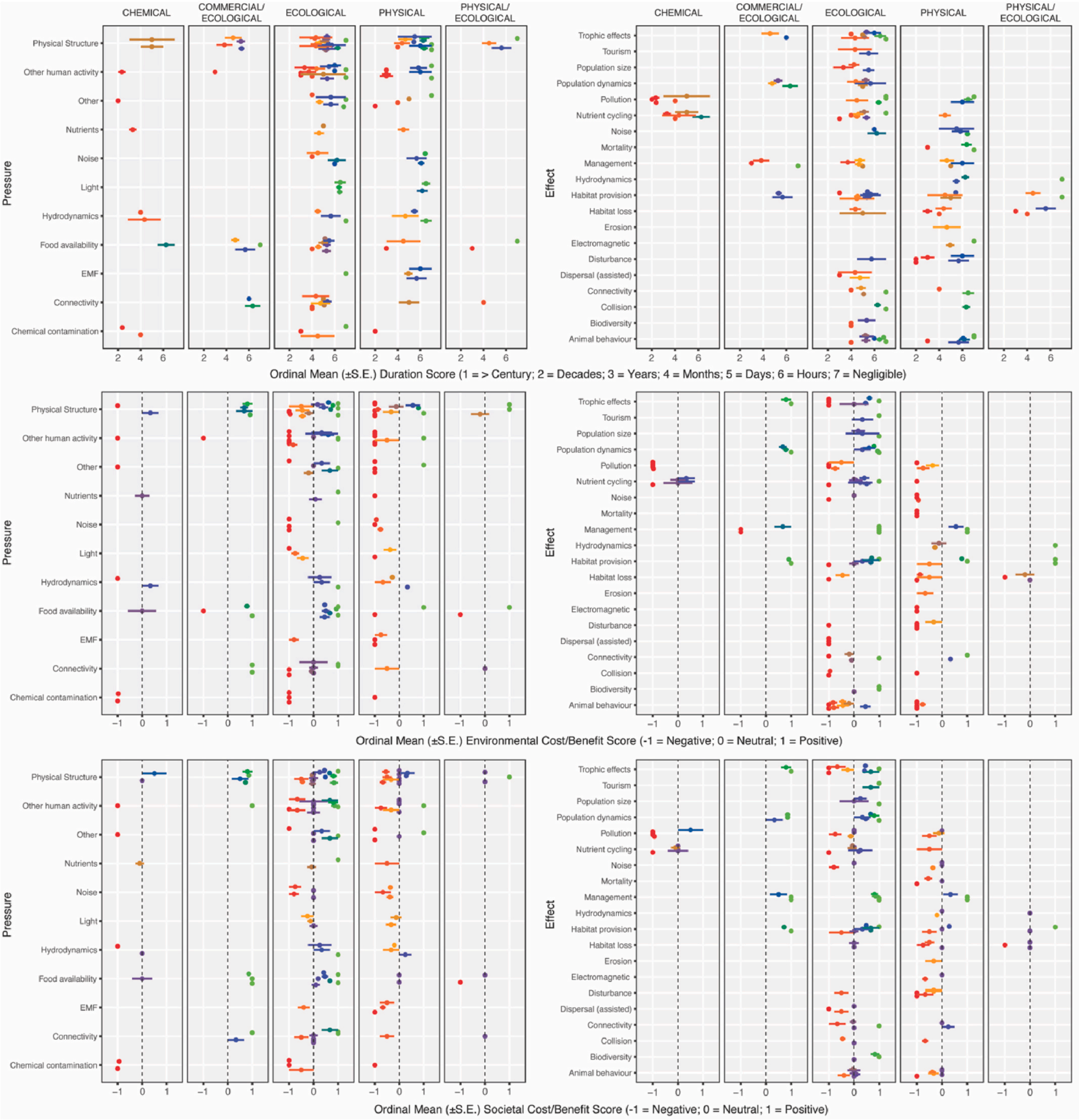

Fig. A3. Mean (top) legacy, (middle) environmental and (bottom) societal cost/benefit scores (±SE) grouped by (left) pressure and (right) effect types. Individual scores for effects (left column) and pressures (right column) are shown for each factor level within classification. Colour ramping reflects the desirability of the scores' categorical value. For legacy, green indicates 'negligible' which can be considered more desirable than red which indicates longer legacy time). For environmental and for societal cost/benefits, green indicates a positive score or 'benefit', while red indicates a negative score or 'cost'.

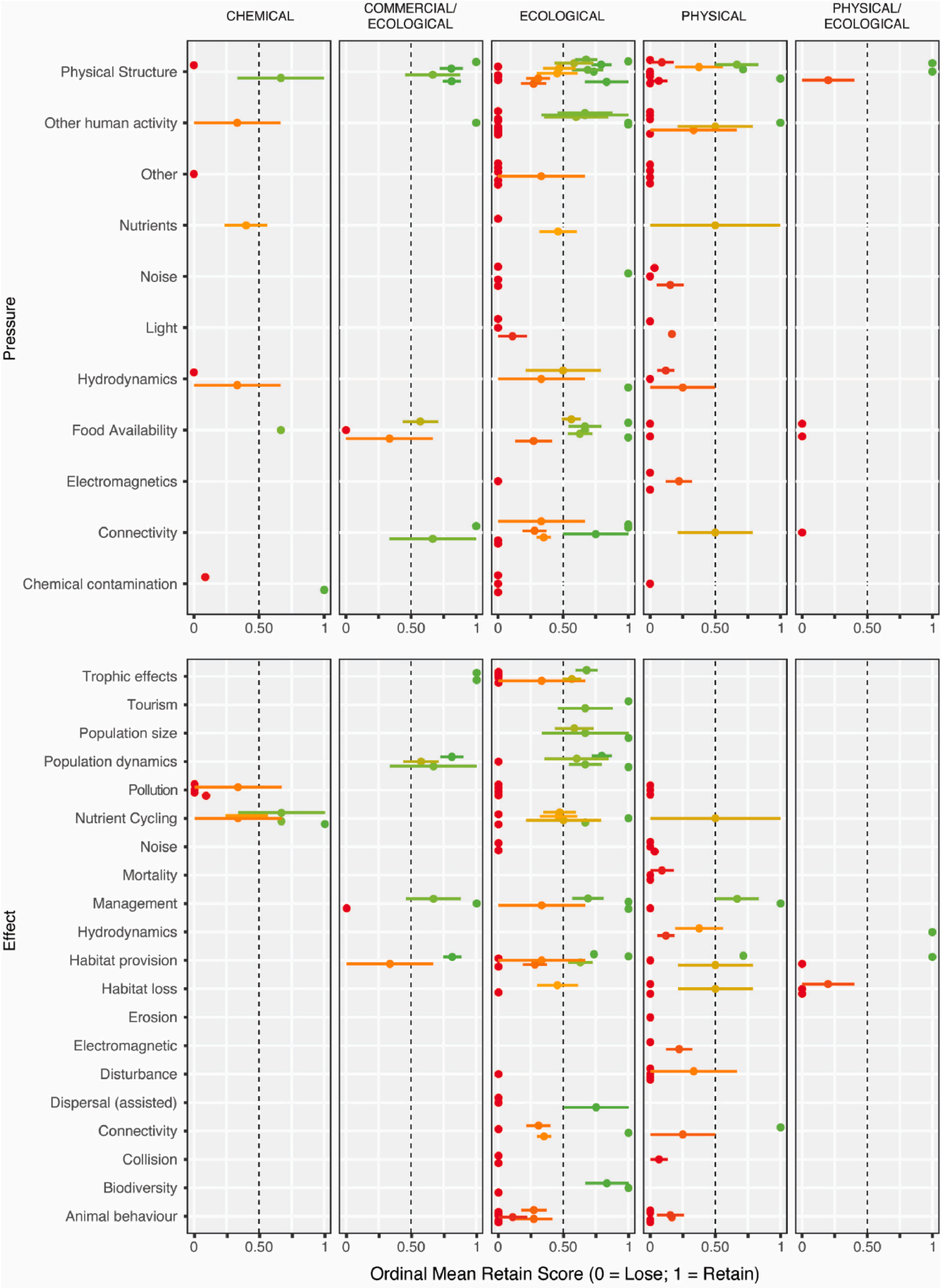

Fig. A4. Assessment of which pressures (top) and effects (bottom) are recommended for retention (values > 0.5) or removal (values < 0.5) following artificial structure decommissioning. Presented as mean retention scores (±SE) grouped by (top) pressure and (bottom) effect types within classification. Colour ramping reflects the retainability of the impact or effect: green indicates 'retain' while red indicates 'lose'.

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