



Trash or Treasure? Considerations for Future Ecological Research to Inform Oil and Gas Decommissioning

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Numerous oil and gas (O&G) installations worldwide will need to be decommissioned in the near future. Complete removal of subsea structures is often the default approach although some regions retain structures under rigs-to-reefs programs. Here, we reviewed the published literature to understand the status of global research on decommissioning, and specifically identify gaps in ecological knowledge. We estimated the frequency of different research categories (i.e., themes, and spatial/temporal scales), and tested the assumption that the number of papers across the categories of each research aspect was even in distribution. However, the frequency of studies focusing on biodiversity at a local (≤ 100 km²) scale (relative to regional and oceanic and pan-oceanic scales) were significantly higher; while other theme categories (e.g., ecotoxicology, connectivity, structural-integrity, restoration and other) were significantly lower than expected. Temporally, ≤ 1 -year studies were more frequent than multi-year studies, but these frequencies did not significantly deviate from the assumed distribution of equal frequencies. We propose that further research be carried out to evaluate the benefits of both retention and removal of structures. Ecological research on decommissioning should extend its focus beyond biodiversity, to include eco-toxicology, structural-integrity, connectivity at larger spatial and temporal scales. This would provide a more holistic assessment of ecological impacts to inform sustainable and equitable development choices in multiple Blue Economy sectors, as we transition from offshore O&G to marine renewables.

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DECOMMISSIONING OF OIL AND GAS SUBSEA STRUCTURES: A GROWING ISSUE

Worldwide, oil and gas (O&G) companies are facing the challenge of managing unproductive subsea infrastructure that cannot be re-purposed (Cullinane and Gourvenec, 2017). Retiring infrastructure and returning a title to regulators is known as decommissioning. This process can encompass anything from complete removal to leaving subsea structures in place (*in situ* decommissioning), with numerous options in between (Techera and Chandler, 2015; Fam et al., 2018; Sommer et al., 2019). Full removal is the default regulatory position in the United Kingdom and in Australia. In the North Sea, the OSPAR convention specifies that a derogation could be

obtained for steel foundations weighing over 10,000 t (OSPAR, 1998). Australia has a mechanism to assess decommissioning on a case-by-case basis, where the risk needs to be “as low as reasonably possible” (ALARP) (NOPSEMA, 2020). In the United States, policies vary from full removal to decommissioning *in situ* (Kaiser and Pulsipher, 2005). The Gulf of Mexico’s is often cited for its rigs-to-reef program (Fam et al., 2018). However, policies are set to evolve based on experience in given countries, and shared knowledge worldwide.

There are several presumed drivers for leaving retired subsea structures *in situ*. These include cost savings, logistics, including avoiding potentially unsafe operations at sea, and creating artificial reefs. In addition to ecological considerations, the social (including public perception) and economic dimensions are an important part of multi-criteria assessments and approaches, that consider these varied criteria (e.g., Fowler et al., 2014). Net environmental benefits analysis offers a way to compare and rank net environmental benefits associated with management alternatives and can be used in assessing decommissioning options but research on its merit for *in situ* decommissioning is needed. Stakeholders have concerns regarding the social, economic, and environmental aspects of decommissioning and a comprehensive list of questions on the risks and benefits are given in Shaw et al., 2018. In this article, we focus solely on research questions and research pertaining to the potential ecological value of biological assemblages on and around O&G infrastructure. This is generating considerable interest among regulators, industry, and scientific communities, who seek to understand the environmental implications of *in situ* decommissioning.

As decommissioning is of increasing international relevance (International Energy Agency, 2019), it is important to review existing research and identify gaps in knowledge, to direct future research and facilitate evidence-based decisions by policy makers. To this effect, we evaluated the peer-reviewed ecological research on *in situ* decommissioning and assessed research questions formulated by experts (Fowler et al., 2019) and stakeholders (Shaw et al., 2018). While we recognize that decisions regarding decommissioning will necessarily be multi-faceted and include engineering, social, economic considerations, as well as environmental ones, we focus here specifically on environmental inputs to decommissioning decisions. This review highlights where future research efforts can be targeted to gain a more holistic view of *in situ* decommissioning of subsea O&G infrastructure, and thus better inform government policy and industry decisions worldwide.

ANALYZING GLOBAL ECOLOGICAL RESEARCH ON DECOMMISSIONING THROUGH PUBLISHED RESEARCH AND RESEARCH QUESTIONS

We found global research articles on *in situ* decommissioning through an electronic search using Web of Science and Google Scholar. We used several combinations of the following

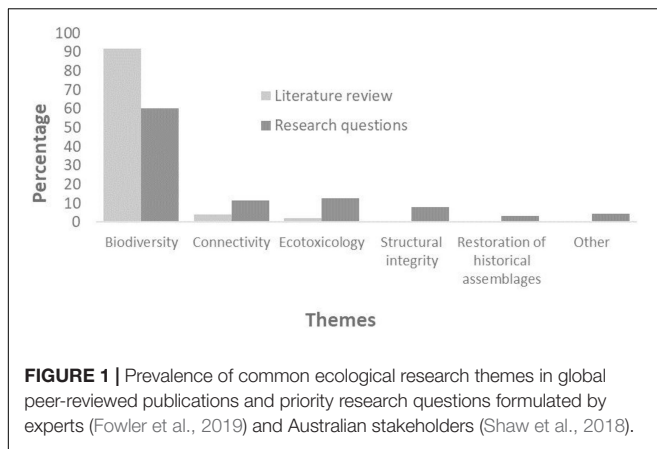
keywords to search both databases: “decommissioning,” “offshore,” “infrastructure,” “platform,” “pipeline,” “oil,” “gas,” “rigs-to-reefs,” “subsea,” “marine,” “environment,” “ecosystem,” “future,” and “impact.”

The literature search was limited to terms that related directly to decommissioning. This gave results that regulators are likely to find when carrying out a similar search. In total, the literature searches yielded 182 records pertaining to ecological aspects of decommissioning (**Supplementary Material**). Those records came predominantly from North America (35.2%), Europe (26.4%), and Australia (9.9%), and 61.5% were published in the last 5 years. Few contributions came from the Middle East (0.5%), Africa (1.1%), South America (3.3%) and Asia (3.8%). Peer-reviewed publications accounted for 59.3% (108) of the search results and the rest was “gray literature,” composed of conference contributions, seminars, workshops (11%), reports (8.8%), theses (3.8%), and other (17%) (**Supplementary Material**). In the peer-reviewed literature, 44.4% were studies with primary data obtained through biological/ecological field work, experiments and/or modeling; while the remaining were papers on methods (4.6%), frameworks (5.6%), concepts (29.6%), and other (15.7%).

Ecological research on decommissioning of O&G infrastructure was analyzed by identifying the (1) main theme, (2) temporal scale, and (3) spatial scale specific to each paper. This was carried out via content analysis (Krippendorff, 2004) and chi-squared goodness-of-fit tests. Content analysis was used to identify the frequency of research themes as well as the spatial and temporal scale of studies. Each paper was classified into one of five common research themes, stemming from the research questions developed by experts (Fowler et al., 2019) and stakeholders (Shaw et al., 2018). Publications were assigned to one theme only, as their focus fell clearly in one category. The research themes were: biodiversity, connectivity, ecotoxicology, structural integrity (i.e., how a collapsing or crumbling structure affects the biological assemblages on and around it), restoration (of historical assemblages at the site that were present prior to the structure being commissioned) and “other.” The literature was classified into two temporal scales of data collection – i.e., ≤ 1 year or multi-year – and four spatial scales of data collection – i.e., local (≤ 100 km²), regional (1,000 km²), ocean and pan-ocean.

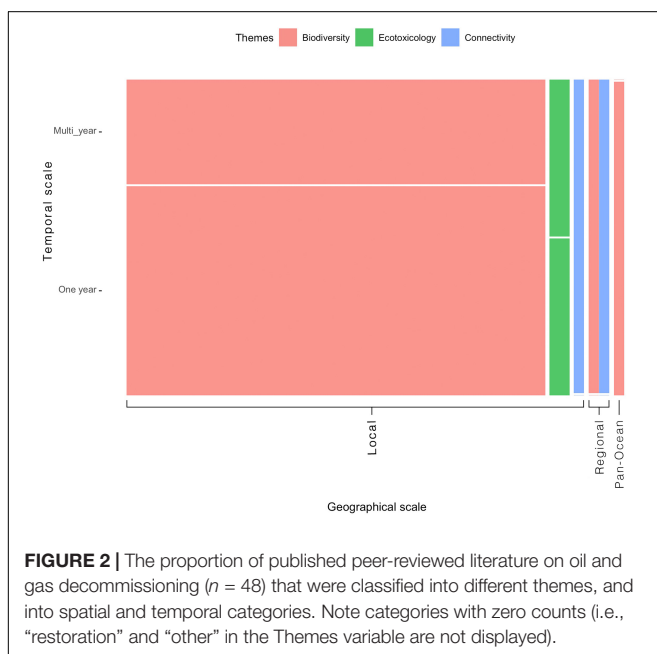
We tested the assumption that studies in research themes, spatial and temporal scales categories would occur with an equal probability using chi-squared goodness-of-fit tests. Statistical analyses were conducted in the R language for statistical computing (R Core Team, 2021). The observed frequencies of each of these research categories were tested independently, but we represented the frequency of interactions between theme, spatial and temporal scale categories using a mosaic plot with the “ggplot2” package in R (Wickham, 2016).

Biodiversity was the focus of 91.7% of all peer-reviewed studies with primary data and the main research question (60.3%) (**Figure 1**). Thirteen of the 44 biodiversity studies used video footage derived from routine engineering inspections with remotely operated vehicles (ROVs), rather than footage from specially designed scientific field campaigns. Of the biodiversity studies, 43.2% were on fish and other species of commercial interest. The presence of such species on structures was typically



used to demonstrate the ecological value of the infrastructure as a habitat, in that it increases local biodiversity. Another cited value of infrastructure was its presumed protective role against trawling and a negative value was its possible role in spreading marine invasive species (Fowler et al., 2018, 2019). Only 9.1% of biodiversity studies were focused on non-native or invasive species, the presence of which was typically used to support removal of subsea infrastructure. Published research was most frequently conducted at a local scale (i.e., $\leq 100 \text{ km}^2$; 98%), and over short periods of time (≤ 1 year) (Figure 2).

We found that developed nations that have started the decommissioning process (United States, United Kingdom, Australia) produce more peer-reviewed publications than other regions of the world, such as Asia, where decommissioning has also begun. We also found that the literature is dominated by studies on biodiversity (mostly fish species of commercial value) rather than being spread across themes selected by stakeholders



(derived from Shaw et al., 2018). The most frequent spatial scale was local ($\leq 100 \text{ km}^2$) and studies were often carried out once (i.e., ≤ 1 year). Chi-square goodness-of-fit tests showed that the themes, and geographical spread were significantly different to an even distribution across categories (Themes: $p = 1.13\text{E-}39$, Geographical scale: $p = 2.24\text{E-}17$, $\alpha = 0.05$). Modeling studies were classified as multi-year, and this resulted in the observed frequencies between single and multi-year studies being not significantly different from each other ($p = 0.249794$, $\alpha = 0.05$) (Supplementary Material).

We recognize that there are challenges involved with acquiring information about biological communities on/around O&G structures. Carrying out field work at these locations is challenging (depth, safety training requirements, company buy-in etc.). Analyzing ROV footage acquired for industry purposes is a first step but does not always guarantee the quality necessary for scientific studies (lack of replication), especially when quantifying marine sessile invertebrates [e.g., 6 months of viewing 5746.2 GB of industrial video at 7.5 h a day took 6 months and yielded only 428 usable photos (Schläppy pers. com)]. Archival footage is better suited to quantify fish biodiversity (Bond et al., 2018a; McLean et al., 2021). Although, research questions formulated by experts (Fowler et al., 2019) and other stakeholders (Shaw et al., 2018) encompass many themes that are important to make informed decisions (Figure 1), those themes, do not get reflected in the research that has been carried out to date, aside from biodiversity assessments.

When regulators need to make decisions and cannot wait for additional information, they have two options: (1) make decisions that are based on the available literature or (2) take into account other themes that have not been researched extensively and apply the precautionary principle. However, unlike in situations where it is clear what precautionary (in)action would be, it is more difficult to ascertain in the case of decommissioning because we do not know yet whether removing or retaining those structures is the more benign option for the environment. This is the reason why there is a pressing need for a wider variety of studies to be carried out. In a context of paucity of studies on alternative perspectives of value and risk of *in situ* decommissioning, it is understandable that nations with a “removal base-case” (e.g., United Kingdom, Australia, parts of the United States) are not yet prepared to consider *in situ* decommissioning as a valid option. Improving temporal and spatial scales of sampling could help, by generally increasing the gradients of environmental conditions and ecological responses observed (Hewitt et al., 2007). Collecting data at larger scales would increase the robustness of models predicting future ecological impacts in changing climate and environmental conditions. Of course, some degree of extrapolation will always be required, as novel climate and ecological responses will emerge in time (Williams et al., 2007; Moritz and Agudo, 2013).

To support decision-making that considers both the advantages of retaining and removing O&G subsea infrastructure in the context of a global increase in ocean sprawl (Firth et al., 2016), future efforts should address ecological questions beyond just biodiversity. This includes connectivity, ecotoxicology, restoration of historical assemblages and finding out whether

collapsing or altered structures will harbor similar biodiversity. This would enhance the transparency, accountability and legitimacy of current decommissioning policies and regulations. Below, we highlight ecological knowledge gaps that should be addressed and considerations for assessing the advantages/disadvantages of *in situ* decommissioning, to reduce uncertainty in decision-making.

CONSIDERATIONS FOR INTERPRETATION OF RESEARCH RESULTS AND KNOWLEDGE GAPS IN DECOMMISSIONING RESEARCH

Themes

Biodiversity

This review revealed that most studies focused on biodiversity and more specifically on fish, with an emphasis on those of commercial value. Much less attention to date has been given to sessile invertebrates or how marine megafauna use and inhabit subsea structures (but see Robinson et al., 2013 and Russell et al., 2014). Although fish studies offer a valuable first step in our knowledge of assemblages on and around subsea structures, it would be highly valuable to broaden the scope and include other organisms, and thus be able to assess diverse trophic levels present on a given structure. The attraction of focusing on fish reflects the perceived social benefits that structures could bring to recreational and commercial fishers. In future, when discussing the value of subsea structures as a habitat for marine organisms, we suggest paying attention to the following points:

The section of a subsea structure that remains in the water does matter

We know that biodiversity on vertical subsea structures is largely dependent on depth (McLean et al., 2018; Thomson et al., 2018). On pipelines, biodiversity is higher at spans, and where structural complexity is enhanced due to sessile invertebrates (McLean et al., 2017). Therefore, not all parts of a subsea structure will have the same habitat value depending on where it is located. The value of biological assemblages on subsea structures should be formulated according to different scenarios: (a) retaining the whole structure; (b) retaining most of the structure except for the portion closest to the sea surface (e.g., platform jacket cut 50 m below the surface, or a pipeline cut 1–10 km from the shore); (c) removing most of the structure (cut 1–10 m above sediment). Thought should also be given to how the structural integrity of the structure will affect biodiversity in the future.

The presence of pelagic fish around a subsea structure is not automatically positive

Subsea structures may not be nurturing habitats for pelagic fish species even if these are attracted to them. Although artificial structures can attract pelagic fish, they could also become ecological traps (Schlaepfer et al., 2002) rather than ecological havens for two reasons: (1) fish at these locations will be easier to catch by fishers, and (2) pelagic fish species attracted to subsea structures may be physiologically disadvantaged

by residing there. For instance, pelagic fish like Skipjack tuna *Katsuwonus pelamis*, and yellowfin tuna *Thunnus albacares* that are attracted to artificial structures i.e., fish aggregation devices (Fonteneau et al., 2000) for long periods of time have been shown to have emptier stomachs and be in poorer condition than conspecifics caught away from the structure (Hallier and Gaertner, 2008; Jaquemet et al., 2011). Future studies on the condition of organisms on and around subsea structures will enable us to test whether the structures offer an optimal habitat for pelagic and/or migratory species or whether their presence may only benefit fishers.

Connectivity

Research on the effect of offshore infrastructure on the metapopulations of different marine organisms already exists (Thorpe, 2012; Simons et al., 2016; van der Molen et al., 2018); however, with the increase of artificial offshore structures (e.g., offshore wind, tidal and wave energy devices), assessing the (cumulative) effect of those structures on marine communities is critical (Bailey et al., 2014; Goodale and Milman, 2016).

The value of biological assemblages on subsea structures is likely to be related to whether they are a source of larvae that spreads to natural communities and therefore will be a function of the extent of their connection with other structures and analogous natural assemblages. Sources and sinks of larvae could be modeled by including the main oceanic currents in a region, coupled with population genetic research. Even if a subsea O&G structure produces larvae of “desirable” species, it might still not be of high ecological interest if the propagules are dispersed by ocean currents to unsuitable locations for their survival. Genetic information about connectivity could be obtained well before decommissioning is necessary, by comparing the genetic structure of organisms on structures to those in analogous natural habitats in the region. If the connectedness of the structures translates into the facilitated spread of invasive species, then connectivity is not conservation-enhancing. When considering the potential for any subsea structures to harbor and spread invasive species by functioning as stepping-stones (Rivas et al., 2010; De Mesel et al., 2015), larger spatial scales than those researched to date are also important. O&G infrastructure has already initiated several species range extensions. Some of these species have gained pest status at their new location (Page et al., 2006; Sammarco et al., 2014; Tanasovici et al., 2020). Noting that current research on invasive species represents only 9% of biodiversity studies for *in situ* decommissioning research, a priority would be to investigate the propensity of invasive species to colonize subsea O&G structures.

Ecotoxicology

Only two studies on decommissioning relate to the theme of ecotoxicology (i.e., Henry et al., 2017 and Lourenço et al., 2015). Ecotoxicology studies are necessary to uncover whether local pollution poses a health risk to organisms on and around subsea structures. This may have repercussions on whether polluted subsea structures constitute a nurturing environment that is conducive to them acting as a source or sink of larvae. We know that bioaccumulation occurs in some organisms such as

mussels (Lourenço et al., 2015) but further ecotoxicological tests of contaminants, and organisms' tolerance are necessary. This is especially true for naturally occurring radioactive materials (NORMs) and plastics, to determine with increased certainty their effect on the growth, reproduction and survival of those organisms and the impact on humans through ingestion of fish caught at these locations. Knowledge gaps exist around species' tolerance to contaminants and which level of pollution exposure in water or sediment is deleterious. Laboratory experiments of sediment resuspension and the effect of NORMs would help to ascertain the rate of uptake by organisms and help predict their level across the food chain.

One of the arguments put forward in favor of *in situ* decommissioning of O&G infrastructures is that the sediment plume and pollution associated with their removal will be deleterious to the biological assemblages on and around the subsea structures. There are three scenarios under which the sediment plume due to decommissioning could be more deleterious than the plume created while installing the infrastructure if: (1) the sediment suspension created by the decommissioning activity is higher than levels deemed acceptable during the development of the O&G field (noting environmental standards may have changed in the intervening period); (2) new scientific evidence shows that lower sediment loads (than previously thought) are deleterious to nearby organisms; (3) the concentrations of pollutants released during the removal operations are above those currently leaching out from the sediments (Gray et al., 1990) and drill cuttings (Henry et al., 2017). Ecotoxicological studies are needed to fill those knowledge gaps and ascertain with more confidence the benefits of retaining or removing O&G structures.

Structural Integrity

No study addressed the theme of structural integrity, but stakeholders are concerned with this issue and have formulated questions on this subject (Shaw et al., 2018 and **Figure 1**). During operations, O&G companies fight to retain the structural integrity of infrastructure by carrying out maintenance and treatments, such a cathodic protection (to prevent oxidation of metals). Therefore, there is a poor understanding about how, when left in the water without care, these structures will lose their current structural integrity. Although this could be viewed as an engineering matter only, it is likely to have an effect on biodiversity and on the ecological significance of the assemblages present on and around the structure, especially if degradation of products are toxic or result in the loss of habitat. The current value given to those biological assemblages may differ in the future as a structure degrades.

Restoration of Historical Assemblages

On land, industries that create environmental disturbances, such as mining, are usually required to remediate the disturbed site when exploitation is finished. To our knowledge, this is not common practice for offshore O&G operations. It is unclear whether restoration is possible, or whether these sites are in fact novel ecosystems whose value lies in a state, different to the historical and current state (van Elden et al., 2019). No

studies were found on restoration of historical assemblages and stakeholders asked whether this is even possible, and with what success (Shaw et al., 2018). The first step to investigate this would be to carry out surveys at sites where subsea structures were removed. Access to those places is likely to be unrestricted, unlike access to active subsea structures. The biodiversity on subsea structures often appears to be much higher than adjacent communities (Bond et al., 2018b). However, many subsea structures with a hard surface cannot be meaningfully compared to the flat areas surrounding the structure that are often dominated by mobile sediments. Before *in situ* decommissioning can be considered a better environmental option than removal, the role of natural or restored historical assemblages should also be studied. For example, vast expanses of sediment with a mix of filter-feeders provide valuable ecosystem services, such as carbon sequestration.

Spatial Scale

The biodiversity of species found at a local scale was the focus of most published studies. How well the subsea structure is connected to analogous natural habitats (i.e., hard substratum, at the same depth) and the role of populations on structures in the context of the metapopulation are two aspects that will drive the value of biological assemblages on a subsea structure. Although local ($\leq 100 \text{ km}^2$) studies constitute a good start that makes the most of available industrial ROV footage, regional ($\leq 1000 \text{ km}^2$) studies are necessary when investigating connectivity.

Status of an Organism's Metapopulation

Subsea structures can influence larval recruitment, and therefore species conservation, by intercepting larvae that would normally recruit to natural habitats, thus depleting larval supply to natural habitats (no conservation gain). If the metapopulation is of a species that requires conservation, subsea structures could provide a habitat for recruitment and contribute recruits to natural habitats (conservation gain). If the metapopulation is healthy elsewhere, no additional gain is obtained from a species present on/around artificial structures especially if those function as ecological traps (see above). Considering these complexities, a precautionary approach would be to consider each species present on the subsea structures as ecologically neutral, until it is shown to be either deleterious or beneficial to its corresponding metapopulation, rather than implying that their presence is beneficial.

Temporal Scale

Biological Assemblages Are Likely to Change Over Time

Our review showed that 30 out of the 48 past studies collected data at one point in time (≤ 1 year), and that multi-year studies were less frequent (18/48, due to several multi-year modeling studies). Characterizing the biological assemblages found on and around O&G subsea structures over less than 1 year is a good preliminary step. However, whether those assemblages are stable through time is uncertain. Studies should ideally consider temporal trends, using appropriate

experimental designs to ensure multi-year comparisons that enhance the predictive power of the ecological value of those assemblages.

Assemblages may change seasonally, before/after natural events (e.g., heatwaves and storms). They may also change as a result of sloughing, may be influenced by the sewage and macerated food that is routinely discarded from crewed platforms (at levels allowed in permits) or by the heat produced during operations, which may favor or disfavor the settlement and survival of certain organisms. Given the difficulty of predicting future assemblages, their future ecological value is equally uncertain. To understand temporal dynamics of organisms on/around O&G infrastructure, surveys should be repeated over several years, well before *in situ* decommissioning becomes considered, using consistent methods to ensure that comparable data can be used for future predictions.

CONCLUSION: A WAY FORWARD

Ultimately, deciding on whether *in situ* decommissioning yields positive, negative, or neutral environmental outcomes requires a body of research on a range of themes. To achieve evidence-based management, science that spans multiple facets of ecology, and across larger spatial and temporal scales than the studies to date, will be required. The questions elicited from stakeholders and experts (Shaw et al., 2018; Fowler et al., 2019) and the studies published to date (**Supplementary Material**) mostly focus on the presence of biodiversity, especially of commercially important fish species. This is not surprising as this is one of the simplest question to address with existing industrial ROV footage, but this perspective unduly emphasizes the advantage of retaining subsea structures. So, while studies conducted to date constitute a valuable start, they partially reflect the availability of archival data, rather than what is required for a holistic approach to research on this topic.

Our identification of knowledge gaps suggests future research projects should also investigate the environmental effects of removing subsea infrastructures and cover ecologically meaningful spatial and temporal scales¹. As decommissioning is becoming an increasingly global societal issue, partnerships between industry, government and philanthropists are necessary to effectively address the full suite of research questions. There is no doubt that considerable investment is required to adequately answer the full range of questions needed to inform a complete environmental assessment of *in situ* decommissioning. Prioritization of research questions could occur through a triage framework (Bottrill et al., 2008) or consultative processes (Wallace et al., 2016).

Ultimately, subsea O&G structures are not the only artificial structures in the marine environment, and their ecological

¹For example, projects funded by programmes such as the INfluence of man-made Structures In The Ecosystem (INSITE) in Europe and the National Decommissioning Research Initiative (NDRI) in Australia.

role needs to be considered in synergy with other types of structures (e.g., shipwrecks, offshore wind turbines, wave and tide renewable energy infrastructure). How regulators decide to approach decommissioning of subsea O&G structures is likely to pave the way for how the decommissioning of future marine renewable installations will be handled. Therefore, best practices must be adopted now, using evidence at the appropriate spatial and temporal scales, as this will contribute to equitable decision-making procedures, which is an investment towards present and future ocean health.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

M-LS designed the study. M-LS, LR, and VC-A acquired and analyzed the data. M-LS, LR, VC-A, and KM interpreted the data, drafted the work, and revised it critically for important intellectual content, approved the final version to be published and agreed to be held accountable for all aspect of the work. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2021.642539/full#supplementary-material>

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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