Received: 18 August 2021 | Revised: 17 January 2022 | Accepted: 19 January 2022

DOI: 10.1111/gcb.16134

Global Change Biology WILEY

REVIEW

Influence of offshore oil and gas structures on seascape ecological connectivity

Dianne L. McLean[1,2] | Luciana C. Ferreira[1] | Jessica A. Benthuysen[1] | Karen J. Miller[1] | Marie-Lise Schläppy[1,2,3] | Matthew J. Ajemian[4] | Oliver Berry[5] | Silvana N. R. Birchenough[6] | Todd Bond[2,7] | Fabio Boschetti[8] | Ann S. Bull[9] | Jeremy T. Claisse[10,11] | Scott A. Condie[12,13] | Pierpaolo Consoli[14] | Joop W. P. Coolen[15,16] | Michael Elliott[17,18] | Irene S. Fortune[19] | Ashley M. Fowler[20,21] | Bronwyn M. Gillanders[22] | Hugo B. Harrison[23,24] | Kristen M. Hart[25] | Lea-Anne Henry[26] | Chad L. Hewitt[27] | Natalie Hicks[28] | Karlo Hock[29] | Kieran Hyder[6,30] | Milton Love[9] | Peter I. Macreadie[31,32] | Robert J. Miller[9] | William A. Montevecchi[33] | Mary M. Nishimoto[9] | Henry M. Page[9] | David M. Paterson[18] | Charitha B. Pattiaratchi[34] | Gretta T. Pecl[13,35] | Joanne S. Porter[36,37] | David B. Reeves[38] | Cynthia Riginos[29] | Sally Rouse[39] | Debbie J. F. Russell[40] | Craig D. H. Sherman[41] | Jonas Teilmann[42] | Victoria L. G. Todd[43] | Eric A. Treml[41] | David H. Williamson[44] | Michele Thums[1]

[1]Australian Institute of Marine Science, Indian Ocean Marine Research Centre, University of Western Australia, Perth, Western Australia, Australia

[2]Oceans Institute, The University of Western Australia, Perth, Western Australia, Australia

[3]Oceans Graduate School, The University of Western Australia, Perth, Western Australia, Australia

[4]Harbor Branch Oceanographic Institute, Florida Atlantic University, Fort Pierce, Florida, USA

[5]CSIRO Environomics Future Science Platform, Crawley, Western Australia, Australia

[6]The Centre for Environment, Fisheries and Aquaculture Science (Cefas), Lowestoft, Suffolk, UK

[7]School of Biological Sciences, The University of Western Australia, Perth, Western Australia, Australia

[8]CSIRO Oceans and Atmosphere, Crawley, Western Australia, Australia

[9]University of California Santa Barbara, Marine Science Institute, Santa Barbara, California, USA

[10]Department of Biological Sciences, California State Polytechnic University, Pomona, California, USA

[11]Vantuna Research Group, Occidental College, Los Angeles, California, USA

[12]CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia

[13]Centre for Marine Socioecology, University of Tasmania, Hobart, Tasmania, Australia

[14]Stazione Zoologica Anton Dohrn - SZN, National Institute of Biology, Ecology and Marine Biotechnology, Messina, Italy

[15]Wageningen Marine Research, Den Helder, The Netherlands

[16]Aquatic Ecology and Water Quality Management, Wageningen University, Wageningen, The Netherlands

[17]Department of Biological & Marine Sciences, University of Hull, Hull, UK

[18]International Estuarine & Coastal Specialists (IECS), Leven, UK

[19]Scottish Oceans Institute, School of Biology, University of St Andrews, St Andrews, UK

[20]New South Wales Department of Primary Industries, Sydney Institute of Marine Science, Mosman, New South Wales, Australia

[21]School of Life Sciences, University of Technology Sydney, Sydney, New South Wales, Australia

[22]School of Biological Sciences, and Environment Institute, University of Adelaide, Adelaide, South Australia, Australia

[23]ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland, Australia
[24]Australian Institute of Marine Science, Townsville, Queensland, Australia
[25]United States Geological Survey, Wetland and Aquatic Research Center, Davie, Florida, USA
[26]School of GeoSciences, Grant Institute, University of Edinburgh, Edinburgh, UK
[27]Harry Butler Institute, Murdoch University, Murdoch, Western Australia, Australia
[28]School of Life Sciences, University of Essex, Colchester, UK
[29]School of Biological Sciences, The University of Queensland, St. Lucia, Queensland, Australia
[30]Collaborative Centre for Sustainable Use of the Seas (CCSUS), School of Environmental Sciences, University of East Anglia, Norfolk, UK
[31]School of Life and Environmental Sciences, Centre for Integrative Ecology, Deakin University, Melbourne, Victoria, Australia
[32]Blue Carbon Lab, Centre for Integrative Ecology, Deakin University Burwood Campus, Burwood, Victoria, Australia
[33]Psychology Department, Memorial University, St. John's, Newfoundland, Canada
[34]Oceans Graduate School and the UWA Oceans Institute, The University of Western Australia, Perth, Western Australia, Australia
[35]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia
[36]International Centre for Island Technology, Heriot Watt University Orkney Campus, Orkney, UK
[37]Department of Life Sciences, Natural History Museum London, London, UK
[38]National Fish and Wildlife Foundation, Baton Rouge, Louisina, USA
[39]Marine Scotland Science, Aberdeen, UK
[40]Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews, UK
[41]School of Life and Environmental Sciences, Queenscliff Marine Research Facility, Deakin University, Victoria, Australia
[42]Marine Mammal Research, Department of Ecoscience, Aarhus University, Roskilde, Denmark
[43]Ocean Science Consulting Ltd, Dunbar, UK
[44]Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia

Correspondence
Dianne L. McLean, Australian Institute of Marine Science, Indian Ocean Marine Research Centre, University of Western Australia, Perth, WA 6009, Australia.
Email: d.mclean@aims.gov.au

Funding information
National Decommissioning Research Initiative (NDRI); Scottish Funding Council Open access publishing facilitated by The University of Western Australia, as part of the Wiley - The University of Western Australia agreement via the Council of Australian University Librarians.WOA Institution: The University of Western AustraliaBlended DEAL: CAUL 2022

Abstract

Offshore platforms, subsea pipelines, wells and related fixed structures supporting the oil and gas (O&G) industry are prevalent in oceans across the globe, with many approaching the end of their operational life and requiring decommissioning. Although structures can possess high ecological diversity and productivity, information on how they interact with broader ecological processes remains unclear. Here, we review the current state of knowledge on the role of O&G infrastructure in maintaining, altering or enhancing ecological connectivity with natural marine habitats. There is a paucity of studies on the subject with only 33 papers specifically targeting connectivity and O&G structures, although other studies provide important related information. Evidence for O&G structures facilitating vertical and horizontal seascape connectivity exists for larvae and mobile adult invertebrates, fish and megafauna; including threatened and commercially important species. The degree to which these structures represent a beneficial or detrimental net impact remains unclear, is complex and ultimately needs more research to determine the extent to which natural connectivity networks are conserved, enhanced or disrupted. We discuss the potential impacts of different decommissioning approaches on seascape connectivity and identify, through expert elicitation, critical knowledge gaps that, if addressed, may further inform decision making for the life cycle of O&G infrastructure, with relevance for other industries (e.g. renewables). The most highly ranked critical knowledge gap was a need to understand how O&G structures modify and influence the movement patterns of mobile species and dispersal stages of sessile marine species. Understanding how different decommissioning options affect species survival and movement was also highly ranked, as was understanding the extent to which O&G structures contribute to extending species distributions by providing rest stops, foraging habitat, and stepping stones. These questions could be addressed with further dedicated studies of animal movement in relation to structures using telemetry, molecular techniques and movement models. Our review and these priority questions provide a roadmap for advancing research needed to support evidence-based decision making for decommissioning O&G infrastructure.

KEYWORDS
birds, ecosystem function, fish, hydrodynamics, invasive species, larval dispersal, marine megafauna, particle tracking, subsea infrastructure

1 | BACKGROUND

Worldwide, more than 12,000 offshore platforms and approx. 180,000 km of subsea pipelines support the offshore oil and gas (O&G) industry (Ars & Rios, 2017; CNPC, 2015; Jouffray et al., 2020; Kaiser, 2018). This amount is forecast to increase greatly in the next 20 years driven by offshore marine renewable energy developments (Gourvenec et al., 2022). Platforms range from short monopile structures in shallow depths (<10 m) to enormous steel structures in depths beyond 300 m, although most are situated in 30–150 m (Figure 1). Conventional fixed platforms are typically built on concrete or steel legs (the 'jacket'), anchored directly to the seabed (Oil States Industries Inc., 2008). Pipelines vary from small flowlines (~10 cm diameter) to large trunk lines (>90 cm diameter; Figure 1e) and can be short (tens of metres) to hundreds of kilometres, with the longest (1224 km) carrying gas from Russia to Germany (Offshore Technology, 2014). Importantly, there are other O&G structures often not represented in mapping databases (e.g. umbilicals, wells, manifolds, riser turret moorings, scour protection concrete mattresses, subsea-cable protection, conductor units, etc.; Figure 1) that could exceed the seabed footprint of fixed platforms and pipelines.

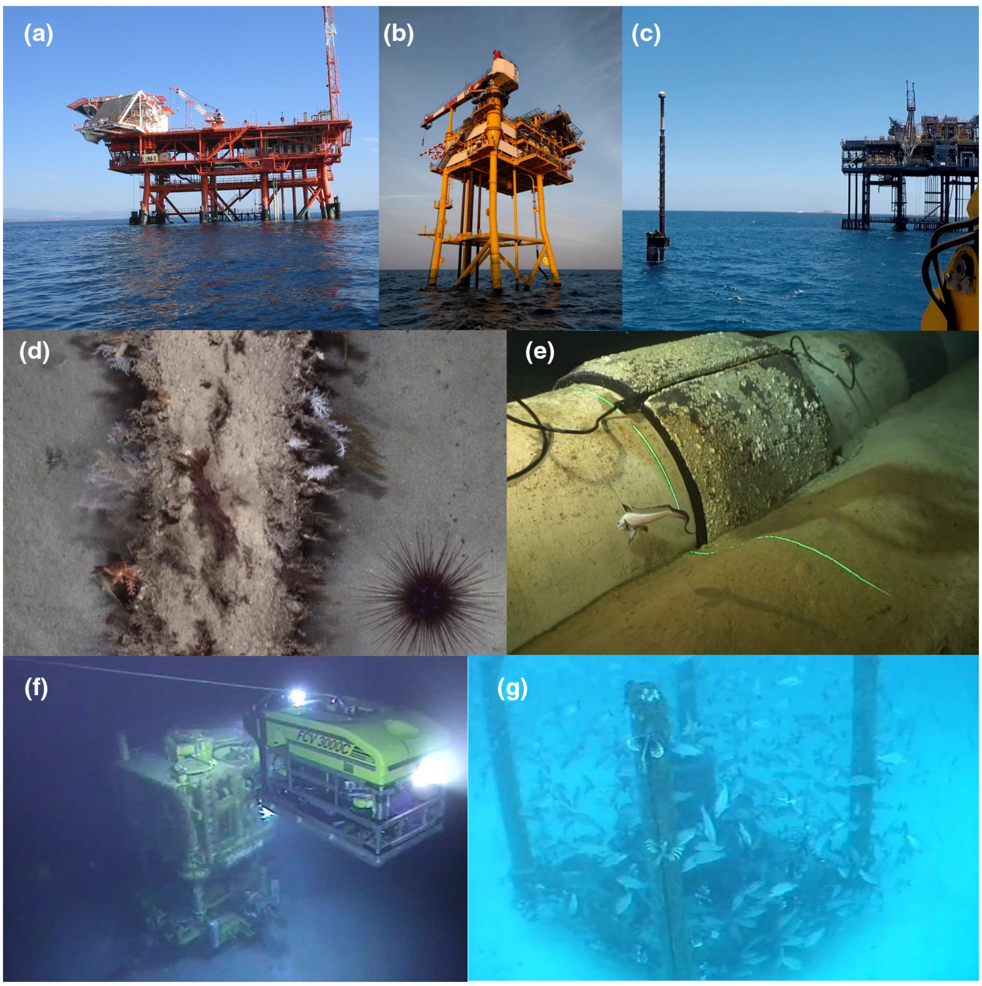

FIGURE 1 Examples of different offshore O&G infrastructure including (a) steel platform for methane extraction located in the Ionian Sea (Central Mediterranean Sea), (b) A18 gas-production platform (North Sea), (c) Harriet Alpha conventional steel platform and flare, (d) and (e) subsea pipelines, (f) and (g) subsea wells. (Photographs from authors)

In recent decades, public concern and scientific interest regarding the impact of O&G infrastructure on the marine environment has increased, due largely to several high-profile oil spills (e.g. Gulf War oil spill; Deepwater Horizon; Montara). A related concern is how best to decommission O&G structures at the end of their operational life (Burdon et al., 2018; Cordes et al., 2016; Fowler et al., 2018, 2020; Macreadie et al., 2011; Melbourne-Thomas et al., 2021). These concerns have led to major research initiatives to improve scientific understanding of the role of such structures in marine environments, such as *SERPENT* (Scientific and Environmental ROV Partnership using Existing iNdustrial Technology), *INSITE North Sea* (Influence of man-made Structures In The Ecosystem) and the *NDRI Australia* (National Decommissioning Research Initiative).

O&G infrastructure and operations have both negative and positive effects on marine ecosystems (Burdon et al., 2018). Negative impacts can include facilitating the establishment and spread of non-native species (Page et al., 2019; Sammarco et al., 2014), disturbing habitats (Järnegren et al., 2017; Jones et al., 2006), introducing artificial lights and noise that alter species behaviour (Barker & Cowan, 2018; Montevecchi, 2006; Todd, Lazar, et al., 2020), introducing contaminants and nutrients (Adewole et al., 2010; Breuer et al., 2008; Henry et al., 2018; MacIntosh et al., 2021), and interfering with hydrodynamic processes and sedimentation patterns (Gray & Elliott, 2009). On the positive side, the presence of O&G infrastructure, particularly in oligotrophic environments or on seabeds where natural hard substrata are scarce, provides a physical structure for marine ecosystems to develop. In such instances, structures can facilitate larval settlement and recruitment (Gass & Roberts, 2006; Love et al., 2006; Nishimoto et al., 2019b), increase the biomass of fish (Claisse et al., 2014; Clausen et al., 2021; Meyer-Gutbrod et al., 2019), and promote biodiversity (Bond, Partridge, Taylor, Cooper, et al., 2018; Bond, Partridge, Taylor, Langlois, et al., 2018; Broadbent et al., 2020; McLean et al., 2017; Todd, Williamson, et al., 2020). The perceived beneficial value of these structures as habitat has led to 'rigs to reefs' (RTR) policies for decommissioned O&G structures in some parts of the globe (Bull & Love, 2019; Smyth et al., 2015). Fishing is limited around most platforms for safety reasons during operation so they can act as *de facto* no-take reserves (e.g. Schroeder & Love, 2004) with resulting potential for wider ecosystem benefits (Love et al., 2006; Lubchenco et al., 2003), including protection of soft sediment and the significant sedimentary carbon stores ('blue carbon', Atwood et al., 2020; Legge et al., 2020). This breadth of effects on marine life shows that decommissioning issues are complex and depend on multiple, and often site-specific, contextual factors (Birchenough & Degraer, 2020; Fowler et al., 2018; Macreadie et al., 2011; Smyth et al., 2015), which may be better understood by considering O&G structures as components of a larger system. For example, a recent review of decommissioning research found a relatively small proportion of studies focussed on biodiversity and connectivity (Schläppy et al., 2021).

The movement of individuals and genes (i.e. connectivity) among 'nodes' (where nodes may represent sources and/or destinations) and the nature of these connected networks (Cecino & Treml, 2021; Roberts et al., 2020; Urban et al., 2009) is a central concept in ecology and is known to influence the ability of a system to resist or recover from disturbance or ecosystem degradation. Connectivity dynamics are determined by the density of node connections, node influence on connections and connection directionality (Gao et al., 2016). O&G structures represent artificial nodes in the ocean, interconnected by pipelines and umbilicals, ocean currents, and the mobile marine organisms that inhabit, invade or visit these structures (Figure 2). Given their high densities in some regions around the world (Figure 3), these structures could play important roles in maintaining, augmenting, altering or disrupting the resilience of marine species, habitats and ecosystems. Yet despite well-established hypotheses regarding the effects of O&G structures on ecological connectivity (Bishop et al., 2017; Fowler et al., 2018, 2020; Macreadie et al., 2011; Schulze et al., 2020), few dedicated scientific studies have been undertaken at O&G sites to ascertain whether O&G infrastructure influences ecological connectivity (e.g. Coolen, Boon, et al., 2020; Henry et al., 2018; Thorpe, 2012; Tidbury et al., 2020). Given the overlap between the global distribution of O&G structures and marine biodiversity (Figure 3), any effects could be long-lasting.

Here, we review the current state of knowledge of the influence of O&G infrastructure on seascape ecological connectivity. Our definition is based on that for landscape connectivity; the degree to which a landscape/seascape facilitates or impedes movement and ecological processes among resource patches (Taylor et al., 1993; Virtanen et al., 2020). As such, we review the relevant literature to understand the degree to which O&G structures are interconnected with natural facets of the seascape to facilitate/impede movements of organisms and other ecological processes. Given the paucity of research on this topic (see also Schläppy et al., 2021), we structured the review around core areas of decommissioning decision making and research focus thus far—fish and megafauna (given many of these are either threatened and/or commercially important), larval and invasive species dispersal, and gene flow. Within these areas, we discuss both functional (movement of individuals) and structural (the physical arrangement of habitat) connectivity in published research. Although we focus mostly on O&G infrastructure, analogous structures are also discussed where appropriate, and many conclusions are pertinent to these structures (e.g. foundations of offshore wind turbines and artificial reefs). We discuss briefly how different decommissioning scenarios may influence seascape connectivity and identify significant knowledge gaps/research priorities that, if addressed, may help to ensure that decisions regarding the fate of marine infrastructure are well informed and evidence based.

2 | REVIEW CRITERIA

We used two methods to assess the global state of knowledge of seascape ecological connectivity among O&G infrastructure, and between infrastructure and surrounding marine ecosystems: (1) a literature review and 2) expert elicitation (see Data S1 and

FIGURE 2 Schematic diagram illustrating (a) how O&G structures could provide connections (weight of line indicative of strength of connection) between natural environments or between other structures and the natural environment, potentially enhancing the connectivity (or connectedness) of a system by adding nodes and (b) relevant processes associated with seascape connectivity influenced by O&G structures. A platform jacket, vessel, subsea wells (yellow), pipeline (grey) and flowlines (black) are indicated. Dashed arrows indicate movements of organisms along pipelines and between structures and surrounding natural ecosystems, either on the seabed, in the water column, or above the surface in the case of seabirds (e.g. storm petrels, sea ducks)

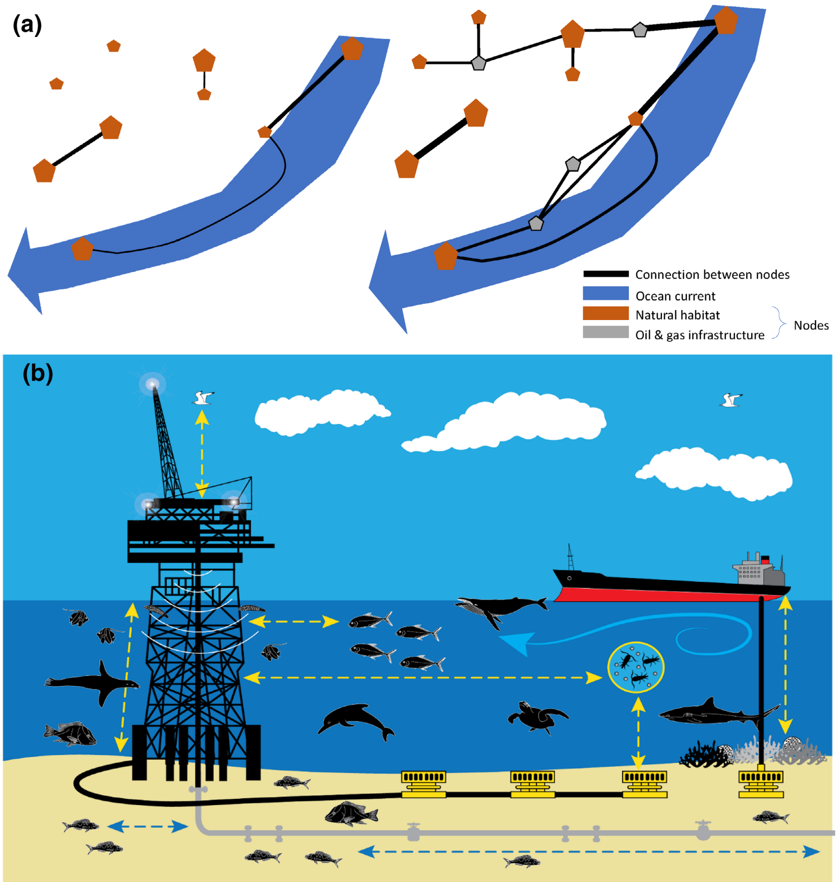

FIGURE 3 Extent of offshore O&G infrastructure and hotspots of marine biodiversity. Spatial layer of O&G infrastructure was obtained from Lujala et al. (2007). Taxa occurrence data from AquaMaps (Kaschner et al., 2019) and GBIF (GIBF 29 March 2021). Infrastructure layer is indicative of the presence of O&G only and does not represent footprint covered. See Methods S1 for details. (a) Indo-Pacific region, (b) Europe, Mediterranean, eastern Atlantic Ocean and northern Indian Ocean, (c) Northern America and Gulf of Mexico, (d) South America

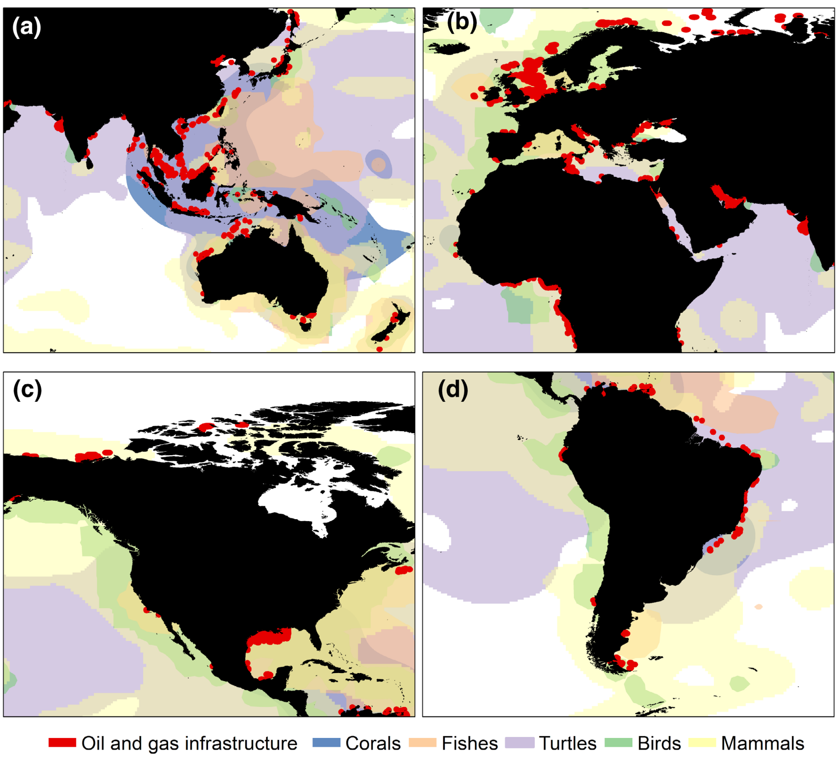

Figure 4a,b). Via SCOPUS, we used a systematic approach to locate relevant literature (Moher et al., 2015; Williamson et al., 2019) and experts. A list of search terms was developed, associated with four broad groupings: (1) O&G industry, (2) Connectivity, (3) Species and (4) Region (see Table S1). The search covered 1990 up to the date the search was performed (24 November 2020) and focussed

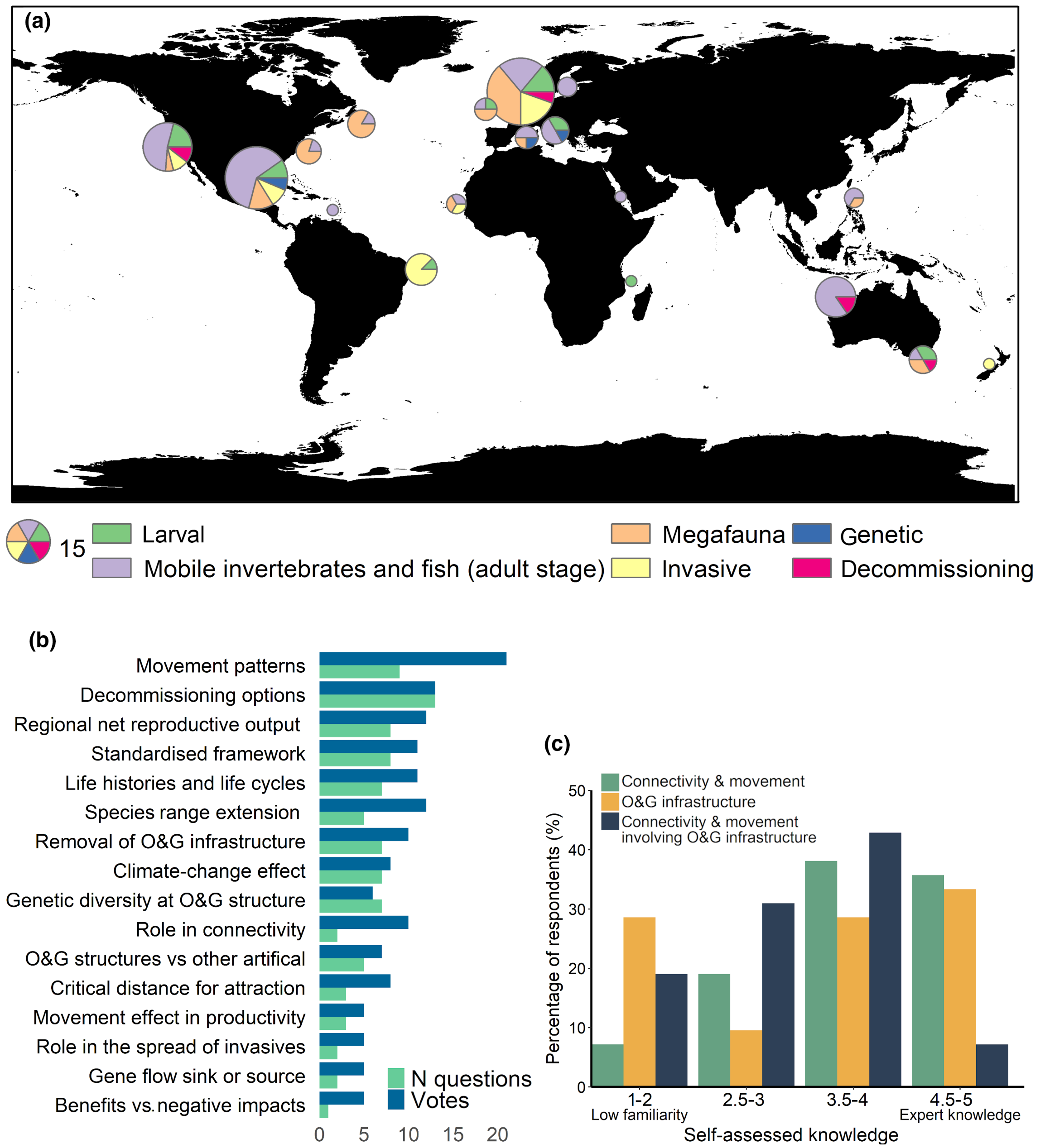

FIGURE 4 Summary of literature and expert opinion that informed this review and identification of priority research questions. (a) Relative contribution of each of the study areas of ecology and connectivity (see Data S1) with respect to O&G infrastructure that were identified during the literature search and via expert contribution. The size of each pie chart is related to the total number of studies in each region, with the legend indicating the reference size for a total (15 studies used as an example). (b) Expert-identified top 16 priority science questions to address knowledge gaps (Section 8—Table 1, Table S2; Figure S1) showing the number of original questions within each overarching science question and number of votes each priority area received (see Data S1); (c) Expert ($n = 46$) self-assessed knowledge of the subject areas of this review from 1 (low familiarity) to 5 (expert knowledge)

on the Title, Abstract and Keywords of articles (see Data S1). Two hundred and eighty nine research articles were found, but only 33 of these directly addressed the influence of O&G infrastructure on seascape ecological connectivity (see Data S1). All 33 and some of the remaining 256 were reviewed here. In addition, we subsequently referenced other papers that came to our attention (e.g. noted by experts, citations within papers), further improving the comprehensiveness of literature included.

We used the 289 research articles to identify experts to be invited as co-authors who were able to list key research questions under the review topic. The top 50 experts were identified by ranking their number of publications. We elicited five key research questions from each of the 42 experts who agreed to be involved, and the answers were consolidated into 38 questions (Table S2). Experts were then asked to review the 38 consolidated research questions (Table S2) and vote on their top five questions.

Subsequently, the top 10 research questions were identified from the most frequently and highly ranked questions (Table 1). We also asked experts to self-assess their knowledge in relation to the subject areas of this review (Figure 4c) based on the method detailed in Pittman et al. (2021). The self-assessment process indicated that most respondents attested to having moderate to high knowledge of connectivity and movement (>75%) and O&G infrastructure (64%; Figure 4c). Only 5% of respondents judged themselves at the highest level of knowledge (4.5–5) on the influence of O&G structures on connectivity and movement (Figure 4c), which mirrors our finding that there is a paucity of studies (33) on this subject (Figure 4a,b; see Data S1).

We focussed the review on fixed O&G structures for which decommissioning decisions must be made, and thus limit discussion of mobile structures (e.g. floating platforms, exploration drilling rigs, supply vessels, etc.) to only those relevant to the introduction of marine non-native species where they are the vectors for initial introduction, from which persistence on fixed structures may occur.

3 | HOW DOES O&G INFRASTRUCTURE INFLUENCE LARVAL DISPERSAL?

Most marine species have a dispersive larval stage. Larval dispersal is largely driven by physical processes (ocean circulation, water mass characteristics, biogeochemical variables) across multiple spatial and temporal scales and by larval sensory and behavioural capabilities to direct their movement (Leis, 2021; Swearer et al., 2019; Thresher & Brothers, 1985). Larval dispersal may be influenced by the presence of O&G infrastructure where larvae may be intercepted or produced. The spatial scale and strength of dispersal and potential connectivity impacted by the presence of O&G structures will vary between species depending on their biological traits, time to metamorphosis and settlement characteristics and their interaction with physical dispersal processes (Pondella et al., 2015).

Particle tracking in hydrodynamic models is a commonly used method to explore how ocean current characteristics (strength, directionality, reach and variability in time and depth) affect the connectivity of marine organisms by simulating passive larval dispersal and may aid in understanding the effect of O&G structures on connectivity. However, many larvae are not passive particles, especially when reaching metamorphosis, and require more realistic models to incorporate biological parameters such as survival and dispersal probabilities (Emery et al., 2006) and whether larvae are lecithotrophic or planktotrophic, which have implication for their survival (McEdward, 2000). Other biological parameters that can be incorporated into models include vertical migration, time to metamorphosis, swimming performance and orientation (van der Molen et al., 2018; Treml et al., 2015), length of the larval competency window, ability to extend planktonic duration and their distribution in the water column (surface, mid-water or near the seafloor). Although inclusion of these parameters can improve estimates of connectivity (e.g. Bode et al., 2019; van der Molen et al., 2018), larvae may also respond to olfactory, light, and audible cues to divert to suitable habitats for settlement (Coon et al., 1990; Leis, 2021; Simpson et al., 2011). Thus, modelled trajectories may not represent actual connectivity, even though such considerations are essential for understanding how O&G structures may support the spread of species with a larval stage.

Where O&G infrastructure has been colonised and occupied by a range of marine organisms, larvae may be attracted to reef sounds emanating from a structure (e.g. fish, crustaceans) as found in natural reef ecosystems (Jeffs et al., 2005; Radford et al., 2007; Vermeij et al., 2010). Other larvae may be triggered to settle via surface chemical cues (e.g. Pacific oyster; *Crassostrea gigas*; Coon et al., 1990), yet no research has examined this behaviour in relation to O&G structures. However, attraction or inducement to settle may be altered by anthropogenic stimuli (lights, sounds, vibrations) that come from infrastructure, for example, drilling, production-related activities (Kent et al. 2016). Where platforms exist in offshore waters far from natural reef features, their influence on larval dispersal and settlement may be comparatively high, relative to platforms in more naturally connected environments. O&G infrastructure may, therefore, influence larval attraction and settlement in various ways and consequently geographical and population connectivity.

As species become established on O&G structures, they can become source populations (e.g. Henry et al., 2018). In the North Sea, interannual variability in the North Atlantic Oscillation results in larvae of the protected cold-water coral species, *Desmophyllum pertusum* (=*Lophelia pertusa*) being dispersed from O&G structures across distances of ~300 km (Fox et al., 2016) and into marine protected areas (MPAs) (Henry et al., 2018). In the Adriatic Sea, offshore platforms can enhance connectivity of moon jellyfish (*Aurelia* spp.) populations, helping to sustain shore-based sub-populations, while also contributing to jellyfish blooms in some areas (Vodopivec et al., 2017). As such, O&G infrastructure can lead to species range extensions (e.g. Coolen et al., 2015; Coolen, Boon, et al., 2020; Guerin, 2009), including the spread of non-native species (see Section 5). Understanding the consequences of these biophysical relationships is a key component to determine how O&G infrastructure acts as stepping-stones for hard substratum species or the ecological consequences of fragmenting habitats for soft sediment communities (Adams et al., 2014; Meyer et al., 2018; Simons et al., 2016).

Ocean currents can transport marine organisms hundreds to thousands of kilometres (Simpson et al., 2014; Williamson et al., 2016) and connect subsea infrastructure downstream (Lugo-Fernández et al., 2001), depending on distance and directionality (Emery et al., 2006; Nishimoto, Simons, et al., 2019; Nishimoto, Washburn, et al., 2019; Treml et al., 2015). At smaller scales, mesoscale eddies, reversing flows and oscillating tidal currents can also connect organisms among neighbouring platforms/structures (Thorpe, 2012) and natural habitats (Elliott et al., 2020; Nishimoto, Simons, et al., 2019; Nishimoto, Washburn, et al., 2019). For example, although circulation patterns in the Gulf of Mexico suggest potential basin-wide larval dispersal over decadal to millennial scales (Lugo-Fernández

TABLE 1 Top 10 priority research questions on the influence of O&G infrastructure on seascape connectivity, derived from expert elicitation (see Section 2 and Data S1 for details)

No.	Priority research questions
1	How do structures modify/influence the movement patterns (migration, dispersal, foraging, spawning/breeding sites) of mobile species (invasives, megafauna, fish, invertebrates) and sessile species?
2	What is the influence of different decommissioning options on the survival, movement and dispersal of organisms?
3	To what extent do O&G structures contribute to extending species distributions by providing rest stops, foraging habitat and stepping stones?
4	What is the contribution that breeding fish and invertebrate species on O&G structures make to regional net reproductive output and populations elsewhere?
5	Which life histories (e.g. traits, strategies, anatomy) and life cycles (age and stage) enable species to capitalise on O&G structures and increase their connectivity?
6	Can we develop a standardised framework for modelling, testing, and validating seascape connectivity between O&G structures and decommissioning scenarios based on current methods (biophysical, genetic, isotopes) from species to assemblages throughout the water column?
7	What influence would the cumulative/large-scale removal of O&G infrastructure have on ecological function?
8	What role does the current array of O&G infrastructure play in ecological and regional connectivity and maintaining a stable state ecosystem, and does it strengthen or degrade the resilience of marine ecosystems?
9	From how far away are mobile species drawn to O&G structures, is biodiversity related to distances between structures, and what is the critical distance that facilitates seascape connectivity?
10	How will climate change affect environmental variables that shape habitat conditions, species movement and dispersal, residency and larval success, and hence seascape connectivity between O&G structures?

et al., 2001), high genetic affinity of *Madracis decatis* corals is limited to platforms in the western Gulf and the Mississippi river outflow acts as a geographical barrier to eastern platforms (Sammarco et al., 2012). Similarly, in the North Sea, 60% of platforms in the shallow, southern section are linked to each other through tidal flows, but are disconnected from the deeper northern section (Thorpe, 2012) by the Flamborough-Helgoland Front. The Front acts as a hydrodynamic barrier (an oceanographic discontinuity) preventing migration of less mobile organisms, such as larvae, across the front, while the dominant anticlockwise gyre in the North Sea as a whole can disperse reproductive stages (Ducrotoy et al., 2000). The influence of oceanographic features in species dispersal and distribution emphasizes the importance in characterising the hydrodynamics underpinning potential connectivity (Boschetti et al., 2020) and in considering time-scales relevant to the lifespan of O&G structures in modelling scenarios.

Potential barriers to settlement, growth, reproduction and survival of larvae on both O&G and offshore energy infrastructure also exist, including cleaning regimes, surface coatings (e.g. antifoulant, corrosion inhibitors and quick-release paints; C. Nall, unpublished data; Want et al., 2017, 2021) and operational discharges (e.g. drill waste, production water, cooling water, sewage, etc.). Production water discharge levels may exceed 10 gigalitres per day globally (Igunnu & Chen, 2014) and form 'contaminant barriers' to potential seascape connectivity with natural habitats, favouring pollution-tolerant species. Discharges have been shown to negatively affect species growth and survival near structures (Bakke et al., 2013; Fan et al., 1992). The specific impacts on populations and the ecosystem more broadly, and thus seascape ecological connectivity, are not known.

4 | HOW DOES O&G INFRASTRUCTURE INFLUENCE THE MOVEMENT OF MOBILE FAUNA?

The design and placement of O&G infrastructure may facilitate vertical and horizontal movements for mobile species (Topolski & Szedlmayer, 2004). For example, platforms form constellations of 'hard habitat' patches, often in seascapes dominated by soft sediments. Subsea structures can influence directional movement of organisms (e.g. seals—Arnould et al., 2015; Russell et al., 2014) or alter ocean currents and therefore dispersal (e.g. Henry et al., 2018; van der Molen et al., 2018; Figure 2) at depths ranging from the seafloor to ocean surface. Pipelines may facilitate movements by providing a continuous habitat, potentially across great distances (Figure 2; Broadbent et al., 2020). This suggests that the presence of structures may increase habitat connectivity and facilitate expansion of organisms along geographical and depth ranges (Gass & Roberts, 2006; McLean et al., 2018; Sammarco et al., 2014). Considerations of the effect of O&G infrastructure in movement connectivity of mobile fauna are important and future research should move beyond examining individual structures and local impacts, to how O&G structures interconnectedness affects broader ecosystem processes (Page et al., 2019) over intergenerational timescales (Adams et al., 2014; Simons et al., 2016).

4.1 | Fish and mobile invertebrates

Offshore platforms provide habitat for primary and secondary producers that support rich and diverse communities through trophic cascades and the movement of resources through trophic connectivity (Reeves et al., 2019; Topolski & Szedlmayer, 2004), altering grazing and predator populations (Friedlander et al., 2014; Robinson et al., 2013) and enriching sediments through bio-deposition from upper layers (Love et al., 1999). Physical and habitat connectivity provided by O&G platforms occurs both vertically and horizontally. For example, vertical connectivity in the water column (Figure 2) facilitates the persistence of benthic communities in the northern Gulf of Mexico hypoxic zone, where demersal fishes that normally occupy deeper waters can move to shallow, oxygen rich waters and find refuge around platform substrata (Reeves et al., 2018; Stanley & Wilson, 2004). Depth zonation is often observed on both shallow and tall platform jackets (Coolen et al., 2020c; McLean et al., 2019), with phototrophic species (e.g. algae) characterising the shallowest areas and filter feeder and heterotrophic species (soft corals and sponges) dominant at depth (Lewbel et al., 1987). This vertical pattern usually reflects light attenuation, but in deep areas, heterotrophic organisms can benefit from feeding on organic material settling through the water column (Love et al., 2019). Platforms can act as islands or stepping stones, particularly in seascapes without other 3-D features, by facilitating the presence of fish and invertebrate species that might not otherwise occur in these areas (Consoli et al., 2013; Friedlander et al., 2014; Nishimoto et al., 2019b). Movement of fish and invertebrates between O&G structures and their surroundings can also influence seascape connectivity through the transfer of nutrients (sinks and sources, Layman et al., 2013; Shantz et al., 2015) or altering benthic-pelagic coupling (Reeves et al., 2019). These changes to nutrient and energy transfers can be facilitated by a variety of movement, including regular movement, such as diel lateral or vertical excursions (Bond, Langlois, et al., 2018), or irregular movement, such as part of a larger migration route (McLean et al., 2019; Todd, Williamson, et al., 2020). The ecological significance of such nutrient transfer is likely to be greater where surrounding ecosystems have limited hard bottom habitat or occur in oligotrophic areas.

Pipelines may function as a corridor of continuous habitat for species and can influence behaviour (e.g. foraging activity; Arnould et al., 2015; Russell et al., 2014) or physical connectivity, for example, connecting shallow nursery grounds with offshore breeding grounds. Many fish and invertebrate species undergo ontogenetic shifts moving from shallow to deep environments as they mature (Huijbers et al., 2015; Love et al., 2019), yet no research has assessed whether pipelines are used during ontogenetic migrations. Pipelines that connect shallow and deep environments or cooler and warmer environments, may also facilitate range extensions. However, large diameter pipelines might present a physical barrier to mobile invertebrate species such as crabs and lobsters (Glaholt, 2008) or even seastars, urchins and sea cucumbers, yet some research suggests this is not the case for many invertebrate species (Todd et al., 2020c). Barriers to movement may decrease or modify physical connectivity in a system, and movement connectivity within species distributions. Although no studies have focused on the effect of pipelines on movement and habitat connectivity for mobile invertebrates, mobile invertebrate species use features of pipelines such as free-spans, field joins, protective mattresses, scour support structures and the benthic sessile communities that colonise pipelines (Glaholt, 2008; Lacey & Hayes, 2020; McLean et al., 2020; Redford et al., 2021; Rouse et al., 2019).

O&G structures appear to provide feeding opportunities (Arnould et al., 2015; Robinson et al., 2013; Russell et al., 2014) and facilitate dispersal of protected species (Henry et al., 2018). They may assist the recovery of exploited fish stocks through site-specific reproductive productivity (Love et al., 2006; Streich et al., 2017) or increased availability of preferred habitats and by increasing connectivity within species distributions. In southern California, critically endangered and economically important young-of-year bocaccio (*Sebastes paucispinis*) are able to settle on offshore O&G structures where otherwise they would be advected to unsuitable offshore waters (Emery et al., 2006). The bocaccio recruit to the upper 100 m of mid-water habitat then progressively move deeper, with mature adults only appearing at jackets that extend beyond 200 m depth (Love et al., 2006, 2019; Pondella et al., 2015); the level of reproductive output from a jacket is dependent on factors such as its depth and any fishing restrictions (Claisse et al., 2019; Love et al., 2019). The reproductive potential of fish and invertebrate communities on O&G structures depends greatly on the level of residency, mortality rates (natural and/or fishing), surface area cover, abundance and biomass (Barneche et al., 2018; Claisse et al., 2019; Rouse et al., 2019; Smith et al., 2016) and water-column productivity (oligotrophic vs. eutrophic waters; Consoli et al., 2013). The relative importance of this contribution to regional reproduction (the production—attraction debate, i.e. to what degree do structures attract marine fauna to them versus increase production and thus overall biomass) requires an understanding of how net reproductive output from O&G structures compares to that originating from natural features (Claisse et al., 2019; Wu et al., 2019) and whether the biomass in the whole region would be significantly lower if the structures were not present.

Comparative studies of red snapper (*Lutjanus campechanus*) growth rates, age, reproductive output and size composition between natural and artificial structures, suggests these habitats can contribute to stock productivity (Downey et al., 2018; Streich et al., 2017); however, some debate remains as to the extent/importance of such contribution (Cowan & Rose, 2016). Net productivity from O&G infrastructure is likely to be higher and easier to assess for regions where there are few natural reefs (e.g. Louisiana waters; Parker et al., 1983) compared to areas where there is an abundance of natural reef ecosystems (e.g. nearshore Australian waters). Perhaps the most productive O&G structures: those contributing biomass into surrounding ecosystems, will therefore, be those that are older, larger (provide a greater area of habitat), taller (span a great depth range), unfished and located in areas where natural hard substrata are limited (e.g. Claisse et al., 2019; Edgar et al., 2014). Furthermore, the concentration of more structures in an area is likely to increase the net contribution. However, this production can only benefit the ecosystem if a certain level of seascape connectivity (physical, trophic and movement) is maintained among structures and natural habitats and if structures are not acting as ecological traps. Understanding net productivity from O&G structures at seascape scales (km to 10s of km) remains a significant knowledge gap.

Understanding the level of residency on O&G structures by specific life history stages of fish and invertebrates is critical for assessing a structure's importance to population connectivity and species persistence throughout surrounding areas. This is because occasional visits by highly mobile species (or frequent visits by few individuals) may not necessarily result in increased seascape connectivity for populations or ecosystems. Species may only be present at O&G structures during specific ontogenetic stages (Dance & Rooker, 2019; Fujii, 2015; Munnelly et al., 2021). Intraspecies segregation among structures suggests that different structures support different ecological niches. Variations in residency reflect habitat preference, feeding strategies and biological traits. For example, cod (*Gadus morhua*), plaice (*Pleuronectes platessa*) and thornback ray (*Raja clavata*) showed seasonal increases in abundance in areas with high densities of artificial structures, including O&G platforms and wrecks (Wright et al., 2020). However, abundance was also associated with natural variables such as temperature, depth and substratum and the authors noted that it was unclear whether fish purposefully associated with structures or whether structures happen to coincide with locations favoured by fish. A non-continuous, acoustic telemetry study on yellowfin tuna (*Thunnus albacares*) around deep-water O&G structures in the Gulf of Mexico found short-term residency linked to feeding at the surface in the light spill from structures at night (Edwards & Sulak, 2006). However, where O&G structures act as fish attraction devices, antagonistic behaviours and heightened intra- and inter-species competition and predation may occur. Platforms and other artificial structures with well-developed sessile communities may reduce these predation and competition effects through provision of shelter to prey, or instead they can increase these by providing shelter to predators and, thus, concentrating them (Burke et al., 2012; Wilson et al., 2019) or by providing sub-optimal shelter. As these processes and inter-species interactions may differ from interactions in natural ecosystems, their effect on trophic and population connectivity remains unknown and constitutes another knowledge gap to assess the impact of subsea structures on fish and mobile invertebrates.

Diel patterns in movement behaviour have been shown to differ between fish species present on O&G structures and natural reefs. Species with a predominantly nocturnal diel pattern on O&G structures (Bond, et al., 2018; Brown et al., 2010) are recorded as having a predominantly diurnal pattern on natural reefs (Koeck et al., 2013), suggesting that O&G structures may modify behaviour patterns. Furthermore, attraction to or deterrence from structures because of stimuli such as lights (Barker & Cowan, 2018), sounds (Benfield et al., 2019) and discharges (e.g. produced water) can modify species behaviour and, consequently, broader ecosystem interactions (see also Section 4.2).

4.2 | Marine megafauna

Marine megafauna (sharks, marine reptiles, seabirds and mammals), many of which are threatened globally, occur commonly around O&G infrastructure (Todd et al., 2020). These species are often highly mobile, with movements ranging from short term (days) over distances of tens to hundreds of kilometres or longer, with some species travelling thousands of kilometres (Block et al., 2011; Sequeira et al., 2018). Their movements link various water masses with different oceanographic regimes, habitats and species compositions; therefore, the additional habitat provided by O&G infrastructure in the marine environment can influence seascape connectivity.

Acoustic telemetry revealed that whale sharks (*Rhincodon typus*) were drawn to O&G platforms off north-west Australia from natural habitat off Ningaloo Reef 340 km away (Thomson et al., 2021). Attraction included infrequent visits over a 6-week period, to high residency, potentially for feeding (Thomson et al., 2021), with feeding observed at offshore platforms in the Arabian Gulf (Robinson et al., 2013). Passive acoustic monitoring detection of harbour porpoise (*Phocoena phocoena*) echolocation around offshore O&G installations may indicate foraging behaviour, particularly at night (Clausen et al., 2021; Todd et al., 2009), and were closer to the installations than at control sites further away (Clausen et al., 2021). Satellite tracking of pinnipeds (harbour *Phoca vitulina* and grey seals *Halichoerus grypus*) shows that some individuals can spend prolonged periods at O&G infrastructure for foraging (Russell et al., 2014). Seals have also been observed attempting to forage on fish underwater around O&G pipelines (Todd et al., 2020). In Australia, 72% (n = 26) of nursing Australian fur seals (*Actocephalus pusillus doriferus* - satellite tagged at a breeding colony) were associated with O&G structures (Arnould et al., 2015). Seals appear to have fidelity to O&G infrastructure locations and subsequently demonstrate learned behaviours that may involve energy efficiency (Arnould et al., 2015). However, the degree to which this represents a beneficial or detrimental impact of O&G structures is unclear (Russell et al., 2014; Thaxter et al., 2015), with underlying mechanisms likely to be complex and dependent on installation type, operational activity, ecosystem/area type and scale. In some cases, these structures could provide sustainable foraging opportunities for predators in environments with limited other opportunities (e.g. oligotrophic environments, those degraded through trawling or overfishing). The fishing exclusion zone usually enforced around platforms may also offer protection from incidental capture in fishing gear, such as bottom-set gillnets, which is especially the case for harbour porpoise (Vinther & Larsen, 2004). The extent to which these structures act as fish-aggregation devices, with high vulnerability to predation, also determines the degree to which they act as ecological traps (Russell et al., 2014). Furthermore, such a concentration of prey could lead to exclusion of less competitive predators (age classes or species), which are limited to the depleted surrounding environment.

Marine megafauna movements to/from O&G infrastructure can also impact natural connectivity in other ways, such as through nutrient transfer when seabirds and seals rest and breed on these structures, via range extension of central place foragers (those that transfer resources back to some fixed point such as a nest or colony) and during non-breeding periods. Use of O&G platforms as temporary seal haul-out sites probably allows some individuals to travel further offshore to feed, with harbour seals found resting on accessible parts of O&G platforms 200 km from shore (Delefosse et al., 2018), when they forage usually in areas <150 km from shore (Figure 5d). California sea lions (*Zalophus californianus*) also haul-out on O&G installations regularly and have also been reported nursing in these locations (Orr et al., 2017). For migrating passerines, platforms in the Gulf of Mexico provide stepping stones facilitating trans-Gulf movements (Russell, 2005), which might enhance migratory survival. In the North Sea, kittiwakes (*Rissa tridactla*) and black guillemots (*Cepphus grille*; Figure 5a) breed on offshore O&G platforms and functionally similar structures (Camphuysen & Leopold, 2007; Christensen-Dalsgaard et al., 2019; Miles & Mellor, 2018). On a few platforms (4), kittiwake productivity was higher than in most colonies on coastal man-made structures over the same period, and much higher than that in natural breeding habitats, suggesting O&G platforms are potentially enhancing the population with these differences possibly related to differences in food availability and exposure to predators (Christensen-Dalsgaard et al., 2019). Finally, marine turtles have also been observed to rest on artificial structures (Broadbent et al., 2020; Figure 5b).

Support-vessel surveys, platform monitoring and tracking of land and sea birds show several negative impacts (lethal and non-lethal) of O&G platforms with the potential to impact connectivity, including increased exposure to oil and other discharges, collisions with platforms and vessels, avoidance of feeding sites, attraction to lights and exposure to predators (Burke et al., 2012; Hedd et al., 2018; Montevecchi et al., 2012; Ronconi et al., 2015; Tasker et al., 1986; Tranquilla et al., 2013; Wiese et al., 2001). Although some positive short-term benefits accrue for birds (e.g. resting sites and foraging opportunities), that attraction is mostly disruptive to seabird nocturnal ecology and increases mortality (Burke et al., 2012; Ronconi et al., 2015). Avoidance of O&G platforms could also potentially affect connectivity, although there is little available information. This could be extensive in areas with high concentrations of structures or where they are located in highly productive sites (Ronconi et al., 2015).

In some areas, such as the North Sea, O&G infrastructure (together with the expansion of offshore wind developments) means that a large proportion of the area available to marine megafauna will be altered either directly or indirectly through changes to shipping

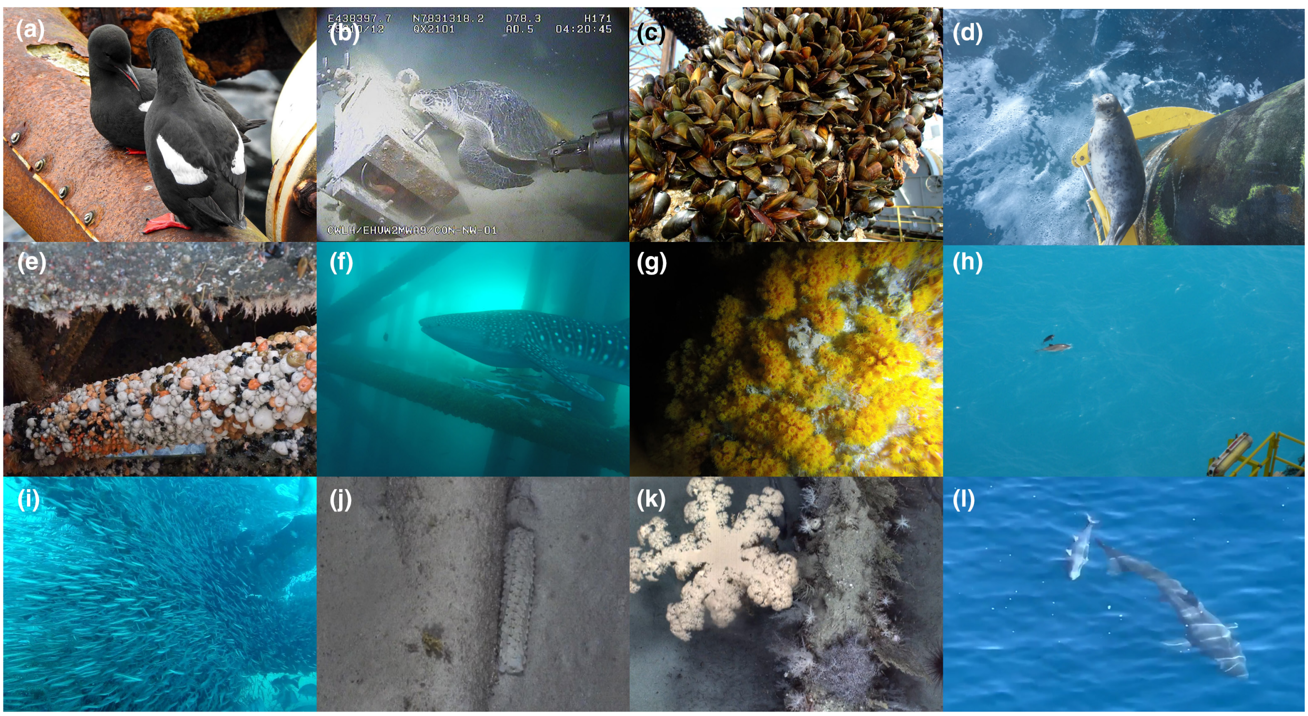

FIGURE 5 Fauna associations with offshore O&G infrastructure; (a) black guillemots on platform, (b) green turtle beside a subsea O&G structure, (c) *Mytilus sp.* mussels on jack-up-rig leg, (d) grey seal resting on North Sea oil platform, (e) Metridium senile anemones on jack-up-rig leg, (f) whale shark beneath platform, north-west Australia, (g) *Tubastraea sp.* on a platform, north-west Australia, (h) harbour porpoise mother and calf by a North Sea oil rig, (i) shoals of bait fish beneath a flare tower, north-west Australia, (j) Australian giant whelk egg casing beside a subsea pipeline, (k) soft coral communities colonising a subsea pipeline and (l) bluefin tuna and feeding basking shark by a North Sea oil rig. (Photographs provided by authors)

routes and fisheries (Ducrotoy et al., 2000; Smyth et al., 2015). Only a handful of studies have investigated overlap between infrastructure and megafauna distribution. For highly migratory tuna, swordfish, billfish and oceanic sharks in the Gulf of Mexico, spatial overlap of their distributions with O&G platforms is relatively low, and offshore installations in the Gulf have been deemed unlikely to have a significant impact on highly migratory stocks, although more localised impacts are possible (Snodgrass et al., 2020). Conversely, for nocturnally active birds such as Leach's storm petrel (*Hydrobates leaucorhous*) that are attracted to offshore light, overlap with O&G platforms in the Northwest Atlantic occurred for five of seven colonies, and O&G platforms intersected the core area of use for four of these colonies, which include the species largest breeding sites and the bulk of the world population (Hedd et al., 2018). Thus, to assess the potential impact of O&G structures, it is necessary to understand the associations at both large and small temporo-spatial scales, also considering the extent and operational lifetime of the infrastructure. Access to the latter information is lacking, as noted in our (and others) attempts to map these structures globally (Figure 3 used a free global data set created by Lujala et al., 2007).

5 | HOW DOES O&G INFRASTRUCTURE INFLUENCE THE SPREAD OF NON-NATIVE SPECIES?

O&G infrastructure provides hard surfaces for organisms to colonise in environments often dominated by soft substrata (sandy, muddy or mixed sediment beds) and opportunities for non-native species (including invasive species) to colonise and establish beyond their usual range (e.g. Almeida & Coolen, 2020; Sammarco et al., 2012). However, deposits in among the biofouling will also provide a habitat for non-sessile species, including non-native ones, for example, the Japanese skeleton shrimp, *Caprella mutica* on artificial structures in Scotland (C. Nall, [unpublished data]).

Although temporary in nature and beyond the scope of this review, it is important to note that movable structures (e.g. exploration jack-up rigs, semi-submersible drilling rigs, floating, production, storage and offloading, FPSOs and shipping/vessel activities) can be the vectors for non-native and invasive species introductions into new areas, including onto fixed infrastructure in these locations (Hicks & Tunnell, 1993; Pajuelo et al., 2016). For example, in the Canary Islands, non-native fish species occurred on semi-submersible drilling rigs that had performed a transoceanic crossing, with their departure location coinciding with the native distribution range of the non-native fish species (Pajuelo et al., 2016). A similar 'rafting' of damselfish (*Chromis limbate*) to towed rigs in Africa saw the species introduced to Brazilian coastal habitats (Anderson et al., 2017). The 2006 stranding of a towed rig, lost at sea, on Tristan de Cunha (British territory, South-Atlantic Ocean), led to the introduction of 62 non-native species (Wanless et al., 2010). Despite significant ecological differences between tropical Brazil and sub-temperate Tristan de Cunha, at least two fish species, *Diplodus argenteus argenteus* and *Parablennius pilicornis*, a crab, *Pachycheles laevidactylus*, and a barnacle, *Megabalanus tintinnabulum*, have become established and show signs of becoming invasive (Wanless et al., 2010). Similarly, the arrival of six Japanese barnacle species were recorded in New Zealand on the 'Maui' oil platform (Foster & Willan, 1979). These species are often observed in high abundances on O&G infrastructure, indicating that these habitats can harbour non-native species (Adelir-Alves et al., 2018; Robertson et al., 2016).

Once colonised by non-native species, platforms can act as a source for non-native larvae, often to colonise wide geographical areas, depending on the species larval duration (Page et al., 2019; Simons et al., 2016). For example, corals from the genus *Tubastraea* are non-native species that are now widely distributed throughout the western Atlantic Ocean (Sammarco et al., 2012, 2014) and are also present in the eastern Atlantic Ocean (Mantelatto et al., 2020). This genus does not compete well in its natural habitat, but the presence of O&G platforms allows successful settlement of their non-native larvae in new areas and expansion of their distribution range (Sammarco et al., 2012, 2014). O&G infrastructure and associated ship traffic have contributed to their spread, and they have now reached Brazil, where they are considered a nuisance (de Paula & Creed, 2004; Silva et al., 2014).

Compared with movable structures and large fixed O&G platforms, the role of subsea pipelines in facilitating the spread of invasive and non-native species has received little attention, despite the vast distances these structures occupy along the seafloor. Subsea pipelines are long corridors of hard substrata that could facilitate the movement of mobile pest species across great distances, potentially resulting in range expansions.

6 | GENETIC IMPLICATIONS OF ENHANCED SEASCAPE CONNECTIVITY FACILITATED BY O&G INFRASTRUCTURE

Genetic consequences of O&G structures are likely to be complex, with little consensus at present on how these hard substrata will affect evolutionary trajectories. For small and potentially isolated populations, increased gene flow may improve population resilience to inbreeding effects or boost adaptive capacity through the creation of connected systems of artificial and natural habitats (Bishop et al., 2017; Henry et al., 2018). Conversely, gene flow facilitated through O&G infrastructure may lead to the loss of genetic novelty and localised adaptation through homogenisation of the gene pool (Atchison et al., 2008). The genetic consequences of connectivity facilitated by O&G infrastructure will differ with geographic location, distance, oceanographic setting (e.g. Sammarco et al., 2012; Shanks, 2009), evolutionary history and species life history (Shanks, 2009).

Limited information exists on genetic connectivity associated with O&G infrastructure (Schläppy et al., 2021; Data S1). The few published studies highlight the value of genetic data for characterising the nature and frequency of dispersal between natural and artificial habitats. For example, genetic data led to inferring that corals on platforms in the Gulf of Mexico most likely recruited from the natural reefs of the Flower Garden Banks, although local hydrodynamic influences still had a major effect on dispersal and connectivity even among platforms (Atchison et al., 2008; Sammarco et al., 2012). Populations of blue mussels on artificial structures in the North Sea (Figure 5c) were found to be genetically isolated, and in combination with particle-tracking models, genetic data suggested that colonisation of structures most likely occurred via anthropogenic activities such as vessel visitation and the movement of structures, rather than natural dispersal pathways (Coolen, Boon, et al., 2020). Similarly, strong genetic differentiation among populations of the tube-building amphipod *Jassa herdmani* in the North Sea on O&G platform jackets suggests that these structures do not enhance genetic connectivity for this species due to the absence of a pelagic larval stage (Luttikhuizen et al., 2019).

Genetic diversity in populations on O&G infrastructure can represent just a subset of the diversity found in natural populations. For example, low genetic diversity in corals on platforms in the Gulf of Mexico has been attributed to the founder effect (Atchison et al., 2008; Sammarco et al., 2012; the loss of genetic variation that results when a new population is established by a limited number of individuals from a larger population), and lower genetic diversity of annelid worms on O&G structures compared with natural rocky habitats in the Adriatic Sea suggests that these artificial habitats cannot be considered analogues of natural habitats (Fauvelot et al., 2009, 2012). Through the founder-effect, structures are colonised by a few individuals of a species that then build populations through asexual reproduction or local recruitment of sexual propagules, with the result being low population genetic diversity. Conversely, artificial structures may provide novel selective environments that promote adaptive divergence. Given that only very low rates of dispersal may be required to spread this genetic variation (Rieseberg & Burke, 2001) in a rapidly changing environment, this new variation could be important for the persistence or recovery of natural marine systems.

7 | IMPLICATIONS OF DIFFERENT DECOMMISSIONING OPTIONS

Laws regarding the specific requirements for decommissioning of O&G infrastructure differ across jurisdictions and across different structures and range from full removal to enabling reefing (Hamzah, 2003; Techera & Chandler, 2015). Presently, a great deal of uncertainty exists as to whether removing or retaining O&G subsea structures would give the best environmental outcome (Burdon et al., 2018; Fowler et al., 2020; Techera & Chandler, 2015). Significant knowledge gaps exist (Figure 4a), and current regulations cannot consider the ecological context until questions such as connectivity are addressed and resolved (Elliott et al., 2020; Fortune & Paterson, 2018; Melbourne-Thomas et al., 2021).

For platform jackets, alternative options to full removal (where regulation and derogation permits) can include removing the top 20 to ~50 m (safety for shipping) and retaining the rest as it stands or toppling it. These options allow for retention of habitat and the species utilising it, protection from the impacts of bottom trawling (Burdon et al., 2018; Coolen, Bittner, et al., 2020; Fowler et al., 2018) and potentially connecting isolated populations of species, whether they be native or non-native species (Adams et al., 2014; Henry et al., 2018). Persistence of connectivity associated with structures retained will depend on the maintenance of structural integrity, with this timespan potentially hundreds of years based on the corrosion and degradation rates of >100-year-old shipwrecks (De Baere et al., 2020).

Modelling suggests partial removal of platforms may have minimal impacts on rates of production by deep water species (Claisse et al., 2015; Meyer-Gutbrod et al., 2020). However, the loss of shallow sections may reduce recruitment of some deep dwelling species through the loss of larval settlement cues (Rilov & Benayahu, 2002). Additionally, removal of shallow platform habitat will affect deposition of falling mussels and other settled sessile and epibenthic organisms that regularly fall to the seafloor and in some areas (e.g. southern California) create extensive biogenic habitats (e.g. 'shell mounds') covering hectares of seafloor surrounding a platform (Bomkamp et al., 2004; Meyer-Gutbrod et al., 2019). In the Gulf of Mexico, fish communities on intact platforms are functionally similar to those on platforms where shallow sections have been removed, although toppling a platform has been suggested to considerably alter community structure on the platforms via removal of vertical complexity (Ajemian et al., 2015). Many mobile organisms will remain within the structure as it is removed (e.g. site attached coral reef fish *Pseudanthias rubrizonatus*, Fowler et al., 2015; decapods, Cummings et al., 2011), while others may disperse either to nearby suitable habitat or be predated if no other suitable shelter is available. Partial removal or toppling of a platform will, therefore, alter trophic connectivity with flow on effects to the surrounding ecosystem. While losing organisms residing on platforms may have minor consequences at small spatial and temporal scales, long-term (decadal) implications at the ecosystem scale are unknown, notwithstanding the eventual erosion and collapse of these structures and thus eventual loss of these organisms.

Relocation of infrastructure to 'reefiing' sites must consider the environmental implications associated with the location of the new reef site (in addition to the removal site), the need to guard against translocating non-native species (Pajuelo et al., 2016), the structural configuration of the new reef and any potential for contaminants (e.g. mercury, naturally occurring radioactive materials—NORMs) to spread into the environment. Placement of infrastructure into habitat-limited or habitat-degraded areas (e.g. dredge material disposal sites) may concentrate fisheries at the new site (Florisson et al., 2020) and alter trophic connectivity in these areas (Macreadie et al., 2011). Placement and augmentation to incorporate structural designs that promote biodiversity, abundance and connectivity with surrounding habitats are additional considerations when disposing of structures at a reefing site.

Decommissioning decisions for pipelines typically occur on a case-by-case basis (Rouse et al., 2019) but can involve complete or partial removal, as well as leaving sections *in situ* with requirements for demonstrating long-term stabilisation or burial. The potential for contaminant release during decommissioning, particularly where NORMs and other chemicals may have built up in scale within these structures (MacIntosh et al., 2021) is a consideration in decommissioning decisions. Furthermore, although large diameter pipelines are typically constructed of steel with concrete or polymer coatings, small diameter flexible flowlines and umbilicals can comprise significant amounts of thermoplastic with little currently known on the degradation (and subsequent dispersal) pathways and timeframes for these materials. Pipeline removal could reduce seascape connectivity via the removal of this linear hard substratum that can act as a corridor facilitating movements and foraging (Arnould et al., 2015; Rouse et al., 2019). Furthermore, their removal can significantly impact soft sediment communities around pipelines, for example, via burial from disturbed sediment, increased turbidity, physical disturbance, disruption of carbon sequestration within the sediments, disturbance and displacement of animals within the sediment and scouring due to changed current patterns.

The scale of decommissioning differs across ocean basins with some regions (e.g. North Sea; Thailand) facing decisions on many O&G structures while other regions (e.g. Japan, New Zealand) have fewer. Direct impacts on the local environment caused by removing a single structure may be easily assessed, although consideration of potential cumulative impacts on marine ecosystems and seascape connectivity associated with the removal of many O&G structures over time is much more complex (Tidbury et al., 2020). Network analysis has been used to assess the impact of hypothetical decommissioning scenarios on ecological connectivity between hard substrate communities in the North Sea and showed the potential for nearly 60% reduction with the most extreme scenarios (Tidbury et al., 2020). The cumulative impact of O&G infrastructure removal on marine ecosystems is likely to be more significant where they provide hard substratum in areas dominated by mobile sediments. Recent approaches for determining cumulative impacts (e.g. Lonsdale et al., 2020) are required for both determining the effects of removal of several structures and for the removal of structures in the presence of many other marine activities (Bishop et al., 2017; Bugnot et al., 2021).

An historical focus on single structures when evaluating decommissioning impacts has greatly limited our understanding of broader seascape effects (Schläppy et al., 2021). Such combined effects are essential for understanding the impact of decommissioning on ecological connectivity along with simultaneous consideration of climate change driven alterations to species distributions (Brito-Morales et al., 2020; Gormley et al., 2013).

8 | KNOWLEDGE GAPS AND OPPORTUNITIES TO INVESTIGATE O&G INFRASTRUCTURE'S INFLUENCE ON SEASCAPE CONNECTIVITY

Despite the large number of studies on community composition at O&G structures that infer the influences of these structures on seascape connectivity, our review shows that there is a paucity of studies that explicitly demonstrate this. Many insights into connectivity have come about opportunistically (e.g. Arnould et al., 2015) rather than resulting from dedicated research (e.g. Mireles et al., 2019; Thomson et al., 2021). Nonetheless, there is direct evidence of connectivity between O&G structures (Henry et al., 2018; Thorpe, 2012) and between structures and the surrounding environment (Arnould et al., 2015; Delefosse et al., 2018; Edwards & Sulak, 2006; Henry et al., 2018; Nishimoto, Simons, et al., 2019; Orr et al., 2017; Russell et al., 2014; Thomson et al., 2021). This includes connections through the water column facilitated by platforms (Reeves et al., 2018; Stanley & Wilson, 2004), structures being used as corridors or stepping stones (Russell, 2005) and facilitating range extensions (Coolen, Boon, et al., 2020; Delefosse et al., 2018). Some platforms may even disrupt or cease natural migration patterns for some species of fish. For example, in the North Sea, lumpsuckers, *Cyclopterus lumpus* migrate considerable distances in an annual cycle between deeper offshore waters in winter and shallower coastal waters in summer; however, a breeding male was found on an offshore gas production platform in the central North Sea (Todd et al., 2018). Although fish production on platforms can be high (Claisse et al., 2014), its contribution to regional production and populations elsewhere remains a critical knowledge gap. Although numerous papers have documented mobile species on O&G structures, we do not have a good understanding of levels of residency which is critical for assessing production versus attraction and a structure's importance to population connectivity and species persistence throughout surrounding ecosystems. This is evidenced by this subject area being ranked number 1 in the top 10 most frequently identified questions (Figure 4b) across experts (Table 1), representing views on current critical knowledge gaps regarding O&G infrastructure impacts on seascape connectivity (see the top 16 areas in Figure 4b). Addressing these areas of research can enhance our understanding of the influence of O&G structures on seascape connectivity and could easily be applied to aspects of natural connectivity among habitats and also other artificial structures. Such knowledge is also required to predict the potential influence of different decommissioning options (question 2) most accurately on different aspects of seascape connectivity.

Research to address these questions primarily involves an element of field research, including telemetry/tagging studies, modelling (e.g. oceanographic particle tracking, connectivity), molecular approaches and biological sampling (e.g. fecundity assessments).

However, many priority research questions could be addressed concurrently with similar data requirements (e.g. telemetry/tagging data would inform a number of questions). Moreover, current tracking data repositories, such as Seatrack (https://seapop.no/en/seatrack/about-seatrack/) and Movebank (https://www.movebank.org/cms/movebank-main) can be used to interrogate the temporo-spatial associations of seabirds and other taxa with O&G infrastructure.

O&G infrastructure influences on seascape connectivity have previously been suggested but rarely demonstrated. This situation has arisen largely from challenges involved with *in situ* investigations of operating infrastructure in a dynamic offshore environment. Additional knowledge gaps have resulted from a historical focus on community composition, faunal biomass and productivity of ecosystems associated with marine infrastructure (Schläppy et al., 2021), that is, on structural rather than functional aspects of marine ecology. The current study highlights the substantial nature and broad scale of connectivity impacts potentially arising during installation and decommissioning of O&G structures. This review and the priority research questions we articulate provide much needed direction for research in this area and will facilitate evidence-based decision making related to connectivity and the subsequent resilience of marine populations.

ACKNOWLEDGEMENTS

The views and conclusions contained in this document are those of the authors and do not necessarily represent the opinions, views or policies of their organisations but do represent the view of the U.S. Geological Survey. Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government or other organisations. This research was supported by the National Decommissioning Research Initiative (NDRI Australia). We acknowledge the time contribution of all co-authors and additionally via research undertaken through the UKRI INSITE Programme including projects ANChor, CHASANS (NE/T010886/1), EcoConnect, EcoSTAR (NE/T010614/1), FuECoMMS (NE/T010800/1), MAPS, NSERC. DMP was supported through The Marine Alliance for Science and Technology for Scotland (MASTS) funded by the Scottish Funding Council and contributing institutions. SNRB and KH (Cefas) were funded by Cefas and the UK INSITE North Sea programme https://insitenorthsea.org/. Open access publishing facilitated by The University of Western Australia, as part of the Wiley - The University of Western Australia agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST

This paper is the result of a study funded by National Decommissioning Research Initiative (NDRI) with the NDRI having received funding from the Oil and Gas industry sector and Australian Government. Funding from the NDRI supported the core project team (authors DM, LC, MT, JB, KM, M-LS). This funding source has not influenced any of the authors objectivity. We have no further potential conflicts of interest to disclose.

AUTHORS CONTRIBUTIONS

DM and MT conceived the idea; LF conducted the literature search and analysis of results; DM and LF prepared figures with input from VT, PC, JWPC, DBR, DMP, DM, LF, JB, MLS, MT and ME. DM, LF, MT, JB, MLS reviewed the literature and led the first draft of manuscript; all experts (42) invited during expert elicitation contributed to completion of writing of manuscript; all authors reviewed and approved the submitted and revised manuscript.

DATA AVAILABILITY STATEMENT

Data sharing not applicable—no new data generated.

ORCID

Luciana C. Ferreira https://orcid.org/0000-0001-6755-2799
Marie-Lise Schläppy https://orcid.org/0000-0002-2131-8515
Matthew J. Ajemian https://orcid.org/0000-0002-2725-4030
Silvana N. R. Birchenough https://orcid.org/0000-0001-5321-8108
Joop W. P. Coolen https://orcid.org/0000-0002-8127-6097
Ashley M. Fowler https://orcid.org/0000-0003-3075-7066
Hugo B. Harrison https://orcid.org/0000-0001-8831-0086
Jonas Teilmann https://orcid.org/0000-0002-4376-4700

REFERENCES

Adams, T. P., Miller, R. G., Aleynik, D., & Burrows, M. T. (2014). Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. *Journal of Applied Ecology*, *51*, 330–338. https://doi.org/10.1111/1365-2664.12207

Adelir-Alves, J., Soeth, M., Braga, R. R., & Spach, H. L. (2018). Non-native reef fishes in the Southwest Atlantic Ocean: A recent record of *Heniochus acuminatus* (Linnaeus, 1758) (Perciformes, Chaetodontidae) and biological aspects of *Chromis limbata* (Valenciennes, 1833) (Perciformes, Pomacentridae). *Check List*, *14*, 379–385. https://doi.org/10.15560/14.2.379

Adewole, G. M., Adewale, T. M., & Ufuoma, E. (2010). Environmental aspect of oil and water-based drilling muds and cuttings from Dibi and Ewan off-shore wells in the Niger Delta, Nigeria. *African Journal of Environmental Science and Technology*, *4*, 284–292.

Ajemian, M. J., Wetz, J. J., Shipley-Lozano, B., Shively, J. D., & Stunz, G. W. (2015). An analysis of artificial reef fish community structure along the northwestern Gulf of Mexico shelf: Potential impacts of "Rigs-to-Reefs" programs. *PLoS One*, *10*, e0126354. https://doi.org/10.1371/journal.pone.0126354

Almeida, L. P., & Coolen, J. W. P. (2020). Modelling thickness variations of macrofouling communities on offshore platforms in the Dutch North Sea. *Journal of Sea Research*, *156*, 101836. https://doi.org/10.1016/j.seares.2019.101836

Anderson, A. B., Salas, E. M., Rocha, L. A., & Floeter, S. R. (2017). The recent colonization of south Brazil by the Azores chromis *Chromis limbata*. *Journal of Fish Biology*, *91*, 558–573.

Arnould, J. P. Y., Monk, J., Ierodiaconou, D., Hindell, M. A., Semmens, J., Hoskins, A. J., Costa, D. P., Abernathy, K., & Marshall, G. J. (2015). Use of anthropogenic sea floor structures by Australian fur seals: Potential positive ecological impacts of marine industrial development? *PLoS One*, *10*, e0130581. https://doi.org/10.1371/journal.pone.0130581

Ars, F., & Rios, R. (2017). Decommissioning: A call for a new approach. Offshore Technology Conference, Houston, Texas, USA.

Atchison, A. D., Sammarco, P. W., & Brazeau, D. A. (2008). Genetic connectivity in corals on the Flower Garden Banks and surrounding oil/gas platforms, Gulf of Mexico. *Journal of Experimental Marine Biology and Ecology*, *365*, 1–12. https://doi.org/10.1016/j.jembe.2008.07.002

Atwood, T. B., Witt, A., Mayorga, J., Hammill, E., & Sala, E. (2020). Global patterns in marine sediment carbon stocks. *Frontiers in Marine Science*, *7*, 165. https://doi.org/10.3389/fmars.2020.00165

Bakke, T., Klungsøyr, J., & Sanni, S. (2013). Environmental impacts of produced water and drilling waste discharges from the Norwegian offshore petroleum industry. *Marine Environmental Research*, *92*, 154–169. https://doi.org/10.1016/j.marenvres.2013.09.012

Barker, V. A., & Cowan, J. H. (2018). The effect of artificial light on the community structure of reef-associated fishes at oil and gas platforms in the northern Gulf of Mexico. *Environmental Biology of Fishes*, *101*, 153–166. https://doi.org/10.1007/s10641-017-0688-9

Barneche, D. R., Robertson, D. R., White, C. R., & Marshall, D. J. (2018). Fish reproductive-energy output increases disproportionately with body size. *Science*, *360*, 642. https://doi.org/10.1126/science.aao6868

Benfield, M. C., Kupchik, M. J., Palandro, D. A., Dupont, J. M., Blake, J. A., & Winchell, P. (2019). Documenting deepwater habitat utilization by fishes and invertebrates associated with *Lophelia pertusa* on a petroleum platform on the outer continental shelf of the Gulf of Mexico using a remotely operated vehicle. *Deep Sea Research Part I: Oceanographic Research Papers*, *149*, 103045. https://doi.org/10.1016/j.dsr.2019.05.005

Birchenough, S. N. R., & Degraer, S. (2020). Science in support of ecologically sound decommissioning strategies for offshore man-made structures: Taking stock of current knowledge and considering future challenges. *ICES Journal of Marine Science*, *77*, 1075–1078. https://doi.org/10.1093/icesjms/fsaa039

Bishop, M. J., Mayer-Pinto, M., Airoldi, L., Firth, L. B., Morris, R. L., Loke, L. H. L., Hawkins, S. J., Naylor, L. A., Coleman, R. A., Chee, S. Y., & Dafforn, K. A. (2017). Effects of ocean sprawl on ecological connectivity: Impacts and solutions. *Journal of Experimental Marine Biology and Ecology*, *492*, 7–30. https://doi.org/10.1016/j.jembe.2017.01.021

Block, B. A., Jonsen, I. D., Jorgensen, S. J., Winship, A. J., Shaffer, S. A., Bograd, S. J., Hazen, E. L., Foley, D. G., Breed, G. A., Harrison, A.-L., Ganong, J. E., Swithenbank, A., Castleton, M., Dewar, H., Mate, B. R., Shillinger, G. L., Schaefer, K. M., Benson, S. R., Weise, M. J., … Costa, D. P. (2011). Tracking apex marine predator movements in a dynamic ocean. *Nature*, *475*, 86–90. https://doi.org/10.1038/nature10082

Bode, M., Leis, J. M., Mason, L. B., Williamson, D. H., Harrison, H. B., Choukroun, S., & Jones, G. P. (2019). Successful validation of a larval dispersal model using genetic parentage data. *PLoS Biology*, *17*, e3000380. https://doi.org/10.1371/journal.pbio.3000380

Bomkamp, R. E., Page, H. M., & Dugan, J. E. (2004). Role of food subsidies and habitat structure in influencing benthic communities of shell mounds at sites of existing and former offshore oil platforms. *Marine Biology*, *146*, 201–211. https://doi.org/10.1007/s00227-004-1413-8

Bond, T., Langlois, T. J., Partridge, J. C., Birt, M. J., Malseed, B. E., Smith, L., & McLean, D. L. (2018). Diel shifts and habitat associations of fish assemblages on a subsea pipeline. *Fisheries Research*, *206*, 220–234. https://doi.org/10.1016/j.fishres.2018.05.011

Bond, T., Partridge, J. C., Taylor, M. D., Cooper, T. F., & McLean, D. L. (2018). The influence of depth and a subsea pipeline on fish assemblages and commercially fished species. *PLoS One*, *13*, e0207703. https://doi.org/10.1371/journal.pone.0207703

Bond, T., Partridge, J. C., Taylor, M. D., Langlois, T. J., Malseed, B. E., Smith, L. D., & McLean, D. L. (2018). Fish associated with a subsea pipeline and adjacent seafloor of the North West Shelf of Western Australia. *Marine Environmental Research*, *141*, 53–65. https://doi.org/10.1016/j.marenvres.2018.08.003

Boschetti, F., Babcock, R. C., Doropoulos, C., Thomson, D. P., Feng, M., Slawinski, D., Berry, O., & Vanderklift, M. A. (2020). Setting priorities for conservation at the interface between ocean circulation, connectivity, and population dynamics. *Ecological Applications*, *30*, e02011.

Breuer, E., Shimmield, G., & Peppe, O. (2008). Assessment of metal concentrations found within a North Sea drill cuttings pile. *Marine Pollution Bulletin*, *56*, 1310–1322. https://doi.org/10.1016/j.marpolbul.2008.04.010

Brito-Morales, I., Schoeman, D. S., Molinos, J. G., Burrows, M. T., Klein, C. J., Arafeh-Dalmau, N., Kaschner, K., Garilao, C., Kesner-Reyes, K., & Richardson, A. J. (2020). Climate velocity reveals increasing exposure of deep-ocean biodiversity to future warming. *Nature Climate Change*, *10*, 576–581. https://doi.org/10.1038/s41558-020-0773-5

Broadbent, H. A., Grasty, S. E., Hardy, R. F., Lamont, M. M., Hart, K. M., Lembke, C., Brizzolara, J. L., & Murawski, S. (2020). West Florida Shelf pipeline serves as sea turtle benthic habitat based on in situ towed camera observations. *Aquatic Biology*, *29*, 17–31. https://doi.org/10.3354/ab00722

Brown, H., Benfield, M. C., Keenan, S. F., & Powers, S. P. (2010). Movement patterns and home ranges of a pelagic carangid fish, *Caranx crysos*, around a petroleum platform complex. *Marine Ecology Progress Series*, *403*, 205–218. https://doi.org/10.3354/meps08465

Bugnot, A. B., Mayer-Pinto, M., Airoldi, L., Heery, E. C., Johnston, E. L., Critchley, L. P., Strain, E. M. A., Morris, R. L., Loke, L. H. L., Bishop, M. J., Sheehan, E. V., Coleman, R. A., & Dafforn, K. A. (2021). Current and projected global extent of marine built structures. *Nature Sustainability*, *4*, 33–41. https://doi.org/10.1038/s41893-020-00595-1

Bull, A. S., & Love, M. S. (2019). Worldwide oil and gas platform decommissioning: A review of practices and reefing options. *Ocean & Coastal Management*, *168*, 274–306. https://doi.org/10.1016/j.ocecoaman.2018.10.024

Burdon, D., Barnard, S., Boyes, S. J., & Elliott, M. (2018). Oil and gas infrastructure decommissioning in marine protected areas: System complexity, analysis and challenges. *Marine Pollution Bulletin*, *135*, 739–758. https://doi.org/10.1016/j.marpolbul.2018.07.077

Burke, C. M., Montevecchi, W. A., & Wiese, F. K. (2012). Inadequate environmental monitoring around offshore oil and gas platforms on the Grand Bank of Eastern Canada: Are risks to marine birds known? *Journal of Environmental Management*, *104*, 121–126. https://doi.org/10.1016/j.jenvman.2012.02.012

Camphuysen, C. J., & Leopold, M. F. (2007). Drieteenmeeuw vestigt zich op meerdere platforms in Nederlandse wateren. *Limosa*, *80*, 153–156.

Cecino, G., & Treml, E. A. (2021). Local connections and the larval competency strongly influence marine metapopulation persistence. *Ecological Applications*, *3131*(4), e02302. https://doi.org/10.1002/eap.2302

Christensen-Dalsgaard, S., Dehnhard, N., Moe, B., Systad, G. H. R. & Follestad, A. (2019). Unmanned installations and birds. A desktop study on how to minimize area of conflict. NINA Report 1731. Norwegian Institute for Nature Research, Trondheim.

Claisse, J. T., Love, M. S., Meyer-Gutbrod, E. L., Williams, C. M., & Pondella, D. J. II (2019). Fishes with high reproductive output potential on California offshore oil and gas platforms. *Bulletin of Marine Science*, *95*, 515–534. https://doi.org/10.5343/bms.2019.0016

Claisse, J. T., Pondella, D. J. II, Love, M., Zahn, L. A., Williams, C. M., & Bull, A. S. (2015). Impacts from partial removal of decommissioned oil and gas platforms on fish biomass and production on the remaining platform structure and surrounding shell mounds. *PLoS One*, *10*, e0135812. https://doi.org/10.1371/journal.pone.0135812

Claisse, J. T., Pondella, D. J., Love, M., Zahn, L. A., Williams, C. M., Williams, J. P., & Bull, A. S. (2014). Oil platforms off California are among the most productive marine fish habitats globally. *Proceedings of the National Academy of Sciences*, *111*, 15462–15467. https://doi.org/10.1073/pnas.1411477111

Clausen, K. T., Teilmann, J., Wisniewska, D. M., Balle, J. D., Delefosse, M., & van Beest, F. M. (2021). Echolocation activity of harbour porpoises, *Phocoena*, shows seasonal artificial reef attraction despite elevated noise levels close to oil and gas platforms. *Ecological Solutions and Evidence*, *2*, e12055.

CNPC. (2015). *Submarine oil and gas pipeline technology*. Science and Technology Management Department, China National Petroleum Corporation. https://www.cnpc.com.cn/cnpc/gcdx/201507/1a6f5193e5514a218fa7ffc4064c7f90/files/d3946f4cc5964a1099f7125a4778b73e.pdf

Consoli, P., Romeo, T., Ferraro, M., Sarà, G., & Andaloro, F. (2013). Factors affecting fish assemblages associated with gas platforms in the Mediterranean Sea. *Journal of Sea Research*, *77*, 45–52. https://doi.org/10.1016/j.seares.2012.10.001

Coolen, J. W. P., Bittner, O., Driessen, F. M. F., Van Dongen, U., Siahaya, M. S., De Groot, W., Mavraki, N., Bolam, S. G., & Van Der Weide, B. (2020). Ecological implications of removing a concrete gas platform in the North Sea. *Journal of Sea Research*, *166*, 101968. https://doi.org/10.1016/j.seares.2020.101968

Coolen, J. W. P., Boon, A. R., Crooijmans, R., van Pelt, H., Kleissen, F., Gerla, D., Beermann, J., Birchenough, S. N. R., Becking, L. E., & Luttikhuizen, P. C. (2020). Marine stepping-stones: Connectivity of *Mytilus edulis* populations between offshore energy installations. *Molecular Ecology*, *29*, 686–703.

Coolen, J. W., Lengkeek, W., Lewis, G., Bos, O. G., Van Walraven, L., & Van Dongen, U. (2015). First record of *Caryophyllia smithii* in the central southern North Sea: Artificial reefs affect range extensions of sessile benthic species. *Marine Biodiversity Records*, *8*. https://doi.org/10.1017/S1755267215001165

Coolen, J. W. P., van der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G. W. N. M., Faasse, M. A., Bos, O. G., Degraer, S., & Lindeboom, H. J. (2020c). Benthic biodiversity on old platforms, young wind farms, and rocky reefs. *ICES Journal of Marine Science*, *77*, 1250–1265.

Coon, S. L., Walch, M., Fitt, W. K., Weiner, R. M., & Bonar, D. B. (1990). Ammonia induces settlement behavior in oyster larvae. *The Biological Bulletin*, *179*, 297–303. https://doi.org/10.2307/1542321

Cordes, E. E., Jones, D. O. B., Schlacher, T. A., Amon, D. J., Bernardino, A. F., Brooke, S., Carney, R., DeLeo, D. M., Dunlop, K. M., Escobar-Briones, E. G., Gates, A. R., Génio, L., Gobin, J., Henry, L.-A., Herrera, S., Hoyt, S., Joye, M., Kark, S., Mestre, N. C., … Witte, U. (2016). Environmental impacts of the deep-water oil and gas industry: A review to guide management strategies. *Frontiers in Environmental Science*, *4*. https://doi.org/10.3389/fenvs.2016.00058

Cowan, J. H., & Rose, K. A. (2016). Oil and gas platforms in the Gulf of Mexico: Their relationship to fish and fisheries. In H. Mikkola (Ed.), *Fisheries and aquaculture in the modern world* (pp. 95–122). InTech.

Cummings, D. O., Lee, R. W., Simpson, S. J., Booth, D. J., Pile, A. J., & Holmes, S. P. (2011). Resource partitioning amongst co-occurring decapods on wellheads from Australia's North-West shelf. An analysis of carbon and nitrogen stable isotopes. *Journal of Experimental Marine Biology and Ecology*, *409*, 186–193.

Dance, M. A., & Rooker, J. R. (2019). Cross-shelf habitat shifts by red snapper (*Lutjanus campechanus*) in the Gulf of Mexico. *PLoS One*, *14*, e0213506. https://doi.org/10.1371/journal.pone.0213506

De Baere, K., Van Haelst, S., Chaves, I., Luyckx, D., Van Den Bergh, K., Verbeken, K., De Meyer, E., Verhasselt, K., Meskens, R., & Potters, G. (2020). The influence of concretion on the long-term corrosion rate of steel shipwrecks in the Belgian North Sea. *Corrosion Engineering, Science and Technology* *56*, 71–80.

de Paula, A. F., & Creed, J. C. (2004). Two species of the coral Tubastraea (Cnidaria, Scleractinia) in Brazil: A case of accidental introduction. *Bulletin of Marine Science*, *74*, 175–183.

Delefosse, M., Rahbek, M. L., Roesen, L., & Clausen, K. T. (2018). Marine mammal sightings around oil and gas installations in the central North Sea. *Journal of the Marine Biological Association of the United Kingdom*, *98*, 993–1001. https://doi.org/10.1017/S0025315417000406

Downey, C. H., Streich, M. K., Brewton, R. A., Ajemian, M. J., Wetz, J. J., & Stunz, G. W. (2018). Habitat-specific reproductive potential of red snapper: A comparison of artificial and natural reefs in the western Gulf of Mexico. *Transactions of the American Fisheries Society*, *147*, 1030–1041. https://doi.org/10.1002/tafs.10104

Ducrotoy, J.-P., Elliott, M., & de Jonge, V. N. (2000). The North Sea. *Marine Pollution Bulletin*, *41*, 5–23. https://doi.org/10.1016/S0025-326X(00)00099-0

Edgar, G. J., Stuart-Smith, R. D., Willis, T. J., Kininmonth, S., Baker, S. C., Banks, S., Barrett, N. S., Becerro, M. A., Bernard, A. T. F., Berkhout, J., Buxton, C. D., Campbell, S. J., Cooper, A. T., Davey, M., Edgar, S. C., Försterra, G., Galván, D. E., Irigoyen, A. J., Kushner, D. J., … Thomson, R. J. (2014). Global conservation outcomes depend on marine protected areas with five key features. *Nature*, *506*, 216–220. https://doi.org/10.1038/nature13022

Edwards, R. E., & Sulak, K. J. (2006). New paradigms for yellowfin tuna movements an distributions–implications for the Gulf and Caribbean region. *Proceedings of the Gulf and Caribbean Fisheries Institute*, *57*, 283–296.

Elliott, M., Borja, A., & Cormier, R. (2020). Activity-footprints, pressures-footprints and effects-footprints–Walking the pathway to determining and managing human impacts in the sea. *Marine Pollution Bulletin*, *155*, 111201.

Emery, B. M., Washburn, L., Love, M. S., Nishimoto, M. M., & Ohlmann, J. C. (2006). Do oil and gas platforms off California reduce recruitment of bocaccio (*Sebastes paucispinis*) to natural habitat? An analysis based on trajectories derived from high-frequency radar. *Fishery Bulletin*, *104*, 391–400.

Fan, T. W. M., Higashi, R. M., Cherr, G. N., & Pillai, M. C. (1992). Use of noninvasive NMR spectroscopy and imaging for assessing produced water effects on mussel reproduction. In J. P. Ray & F. R. Engelhardt (Eds.), *Produced water: Technological/environmental issues and solutions* (pp. 403–414). Springer.

Fauvelot, C., Bertozzi, F., Costantini, F., Airoldi, L., & Abbiati, M. (2009). Lower genetic diversity in the limpet *Patella caerulea* on urban coastal structures compared to natural rocky habitats. *Marine Biology*, *156*, 2313–2323. https://doi.org/10.1007/s00227-009-1259-1

Fauvelot, C., Costantini, F., Virgilio, M., & Abbiati, M. (2012). Do artificial structures alter marine invertebrate genetic makeup? *Marine Biology*, *159*, 2797–2807. https://doi.org/10.1007/s00227-012-2040-4

Florisson, J. H., Rowland, A. J., Harvey, E. S., Allen, M. B., Watts, S. L., & Saunders, B. J. (2020). King Reef: An Australian first in repurposing oil and gas infrastructure to benefit regional communities. *The APPEA Journal*, *60*, 435–439. https://doi.org/10.1071/AJ19134

Fortune, I. S., & Paterson, D. M. (2018). Ecological best practice in decommissioning: A review of scientific research. *ICES Journal of Marine Science*, *77*, 1079–1091. https://doi.org/10.1093/icesjms/fsy130

Foster, B. A., & Willan, R. C. (1979). Foreign barnacles transported to New Zealand on an oil platform. *New Zealand Journal of Marine and Freshwater Research*, *13*, 143–149. https://doi.org/10.1080/00288330.1979.9515788

Fowler, A. M., Jørgensen, A. M., Coolen, J. W. P., Jones, D. O. B., Svendsen, J. C., Brabant, R., Rumes, B., & Degraer, S. (2020). The ecology of infrastructure decommissioning in the North Sea: What we need to know and how to achieve it. *ICES Journal of Marine Science*, *77*, 1109–1126. https://doi.org/10.1093/icesjms/fsz143

Fowler, A. M., Jørgensen, A.-M., Svendsen, J. C., Macreadie, P. I., Jones, D. O., Boon, A. R., Booth, D. J., Brabant, R., Callahan, E., Claisse, J. T., Dahlgren, T. G., Degraer, S., Dokken, Q. R., Gill, A. B., Johns, D. G., Leewis, R. J., Lindeboom, H. J., Linden, O., May, R., … Coolen, J. W. (2018). Environmental benefits of leaving offshore infrastructure in the ocean. *Frontiers in Ecology and the Environment*, *16*, 571–578. https://doi.org/10.1002/fee.1827

Fowler, A. M., Macreadie, P. I., Bishop, D. P., & Booth, D. J. (2015). Using otolith microchemistry and shape to assess the habitat value of oil structures for reef fish. *Marine Environmental Research*, *106*, 103–113. https://doi.org/10.1016/j.marenvres.2015.03.007

Fox, A. D., Henry, L.-A., Corne, D. W., & Roberts, J. M. (2016). Sensitivity of marine protected area network connectivity to atmospheric variability. *Royal Society Open Science*, *3*, 160494. https://doi.org/10.1098/rsos.160494

Friedlander, A. M., Ballesteros, E., Fay, M., & Sala, E. (2014). Marine communities on oil platforms in Gabon, West Africa: High biodiversity oases in a low biodiversity environment. *PLoS One*, *9*, e103709.

Fujii, T. (2015). Temporal variation in environmental conditions and the structure of fish assemblages around an offshore oil platform in the North Sea. *Marine Environmental Research*, *108*, 69–82. https://doi.org/10.1016/j.marenvres.2015.03.013

Gao, J., Barzel, B., & Barabási, A.-L. (2016). Universal resilience patterns in complex networks. *Nature*, *530*, 307–312. https://doi.org/10.1038/nature16948

Gass, S. E., & Roberts, J. M. (2006). The occurrence of the cold-water coral *Lophelia pertusa* (Scleractinia) on oil and gas platforms in the North Sea: Colony growth, recruitment and environmental controls on distribution. *Marine Pollution Bulletin*, *52*, 549–559. https://doi.org/10.1016/j.marpolbul.2005.10.002

Glaholt, R. D. (2008). Investigation of the potential effects of marine pipelines on Dungeness crab movement and benthic ecology. 679-692. https://doi.org/10.1016/B978-044453223-7.50076-9

Gormley, K. S. G., Porter, J. S., Bell, M. C., Hull, A. D., & Sanderson, W. G. (2013). Predictive habitat modelling as a tool to assess the change in distribution and extent of an OSPAR priority habitat under an increased ocean temperature scenario: Consequences for marine protected area networks and management. *PLoS One*, *8*, e68263. https://doi.org/10.1371/journal.pone.0068263

Gourvenec, S., Sturt, F., Reid, E., & Trigos, F. (2022). Global assessment of historical, current and forecast ocean energy infrastructure: Implications for marine space planning, sustainable design and end-of-engineered-life management. *Renewable and Sustainable Energy Reviews*, *154*, 111794.

Gray, J. S., & Elliott, M. (2009). *Ecology of marine sediments: From science to management*. Oxford University Press.

Guerin, A. (2009). *Marine communities of North Sea offshore platforms, and the use of stable Isotopes to explore artificial reef food webs*. University of Southampton.

Hamzah, B. A. (2003). International rules on decommissioning of offshore installations: Some observations. *Marine Policy*, *27*, 339–348. https://doi.org/10.1016/S0308-597X(03)00040-X

Hedd, A., Pollet, I. L., Mauck, R. A., Burke, C. M., Mallory, M. L., McFarlane Tranquilla, L. A., Montevecchi, W. A., Robertson, G. J., Ronconi, R. A., Shutler, D., Wilhelm, S. I., & Burgess, N. M. (2018). Foraging areas, offshore habitat use, and colony overlap by incubating Leach's storm-petrels *Oceanodroma leucorhoa* in the Northwest Atlantic. *PLoS One*, *13*, e0194389.

Henry, L.-A., Mayorga-Adame, C. G., Fox, A. D., Polton, J. A., Ferris, J. S., McLellan, F., McCabe, C., Kutti, T., & Roberts, J. M. (2018). Ocean sprawl facilitates dispersal and connectivity of protected species. *Scientific Reports*, *8*, 11346. https://doi.org/10.1038/s41598-018-29575-4

Hicks, D., & Tunnell, J. (1993). Invasion of the south Texas coast by the edible brown mussel *Perna perpa* (Linnaeus, 1758). *Veliger*, *36*, 92–94.

Huijbers, C. M., Nagelkerken, I., & Layman, C. A. (2015). Fish movement from nursery bays to coral reefs: A matter of size? *Hydrobiologia*, *750*, 89–101. https://doi.org/10.1007/s10750-014-2162-4

Igunnu, E. T., & Chen, G. Z. (2014). Produced water treatment technologies. *International Journal of Low-Carbon Technologies*, *9*, 157–177. https://doi.org/10.1093/ijlct/cts049

Järnegren, J., Brooke, S., & Jensen, H. (2017). Effects of drill cuttings on larvae of the cold-water coral *Lophelia pertusa*. *Deep Sea Research Part II: Topical Studies in Oceanography*, *137*, 454–462. https://doi.org/10.1016/j.dsr2.2016.06.014

Jeffs, A. G., Montgomery, J. C., & Tindle, C. T. (2005). How do spiny lobster post-larvae find the coast? *New Zealand Journal of Marine and Freshwater Research*, *39*, 605–617. https://doi.org/10.1080/00288330.2005.9517339

Jones, D. O. B., Hudson, I. R., & Bett, B. J. (2006). Effects of physical disturbance on the cold-water megafaunal communities of the Faroe-Shetland Channel. *Marine Ecology Progress Series*, *319*, 43–54. https://doi.org/10.3354/meps319043

Jouffray, J.-B., Blasiak, R., Norström, A. V., Österblom, H., & Nyström, M. (2020). The Blue Acceleration: The trajectory of human expansion into the ocean. *One Earth*, *2*, 43–54. https://doi.org/10.1016/j.oneear.2019.12.016

Kaiser, M. J. (2018). The global offshore pipeline construction service market 2017 – Part I. *Ships and Offshore Structures*, *13*, 65–95. https://doi.org/10.1080/17445302.2017.1342923

Kaschner, K., Kesner-Reyes, K., Garilao, C., Segschneider, J., Rius-Barile, J., Rees, T., & Froese, R. (2019). AquaMaps: Predicted range maps for aquatic species. https://www.aquamaps.org

Kent, C. S., McCauley, R. D., Duncan, A., Erbe, C., Gavrilov, A., Lucke, K., & Parnum, I. (2016). Underwater sound and vibration from offshore petroleum activities and their potential effects on marine fauna: An Australian perspective. Report 2015-13 for APPEA, 184 pp. https://appea.com.au/wp-content/uploads/2017/08/CMST-Underwater-Sound-and-Vibration-from-Offshore-Activities.pdf

Koeck, B., Alós, J., Caro, A., Neveu, R., Crec'hriou, R., Saragoni, G., & Lenfant, P. (2013). Contrasting fish behavior in artificial seascapes with implications for resources conservation. *PLoS One*, *8*, e69303. https://doi.org/10.1371/journal.pone.0069303

Lacey, N. C., & Hayes, P. (2020). Epifauna associated with subsea pipelines in the North Sea. *ICES Journal of Marine Science*, *77*, 1137–1147. https://doi.org/10.1093/icesjms/fsy196

Layman, C. A., Allgeier, J. E., Yeager, L. A., & Stoner, E. W. (2013). Thresholds of ecosystem response to nutrient enrichment from fish aggregations. *Ecology*, *94*, 530–536. https://doi.org/10.1890/12-0705.1

Legge, O., Johnson, M., Hicks, N., Jickells, T., Diesing, M., Aldridge, J., Andrews, J., Artioli, Y., Bakker, D. C. E., Burrows, M. T., Carr, N., Cripps, G., Felgate, S. L., Fernand, L., Greenwood, N., Hartman, S., Kröger, S., Lessin, G., Mahaffey, C., … Williamson, P. (2020). Carbon on the northwest European shelf: Contemporary budget and future influences. *Frontiers in Marine Science*, *7*, 143. https://doi.org/10.3389/fmars.2020.00143

Leis, J. M. (2021). Perspectives on larval behaviour in biophysical modelling of larval dispersal in marine, demersal fishes. *Oceans*, *2*(1), 1–25.

Lewbel, G. S., Howard, R. L., & Gallaway, B. J. (1987). Zonation of dominant fouling organisms on northern Gulf of Mexico petroleum platforms. *Marine Environmental Research*, *21*, 199–224. https://doi.org/10.1016/0141-1136(87)90066-3

Lonsdale, J.-A., Nicholson, R., Judd, A., Elliott, M., & Clarke, C. (2020). A novel approach for cumulative impacts assessment for marine spatial planning. *Environmental Science & Policy*, *106*, 125–135. https://doi.org/10.1016/j.envsci.2020.01.011

Love, M. S., Caselle, J., & Snook, L. (1999). Fish assemblages on mussel mounds surrounding seven oil platforms in the Santa Barbara Channel and Santa Maria Basin. *Bulletin of Marine Science*, *65*, 497–513.

Love, M. S., Claisse, J. T., & Roeper, A. (2019). An analysis of the fish assemblages around 23 oil and gas platforms off California with comparisons with natural habitats. *Bulletin of Marine Science*, *95*, 477–514. https://doi.org/10.5343/bms.2018.0061

Love, M. S., Schroeder, D. M., Lenarz, W., MacCall, A., Bull, A. S., & Thorsteinson, L. (2006). Potential use of offshore marine structures in rebuilding an overfished rockfish species, bocaccio (*Sebastes paucispinis*). *Fishery Bulletin*, *104*, 383–390.

Lubchenco, J., Palumbi, S. R., Gaines, S. D., & Andelman, S. (2003). Plugging a hole in the ocean: The emerging science of marine reserves. *Ecological Applications*, *13*, 3–7.

Lugo-Fernández, A., Deslarzes, K. J. P., Price, J. M., Boland, G. S., & Morin, M. V. (2001). Inferring probable dispersal of Flower Garden Banks coral larvae (Gulf of Mexico) using observed and simulated drifter trajectories. *Continental Shelf Research*, *21*, 47–67. https://doi.org/10.1016/S0278-4343(00)00072-8

Lujala, P., Ketil Rod, J., & Thieme, N. (2007). Fighting over oil: Introducing a new dataset. *Conflict Management and Peace Science*, *24*, 239–256. https://doi.org/10.1080/07388940701468526

Luttikhuizen, P. C., Beermann, J., Crooijmans, R., Jak, R. G., & Coolen, J. W. P. (2019). Low genetic connectivity in a fouling amphipod among man-made structures in the southern North Sea. *Marine Ecology Progress Series*, *615*, 133–142. https://doi.org/10.3354/meps12929

MacIntosh, A., Dafforn, K., Penrose, B., Chariton, A., & Cresswell, T. (2021). Ecotoxicological effects of decommissioning offshore petroleum infrastructure: A systematic review. *Critical Reviews in Environmental Science and Technology*, 1–39. https://doi.org/10.1080/10643389.2021.1917949

Macreadie, P. I., Fowler, A. M., & Booth, D. J. (2011). Rigs-to-reefs: Will the deep sea benefit from artificial habitat? *Frontiers in Ecology and the Environment*, *9*, 455–461. https://doi.org/10.1890/100112

Mantelatto, M. C., Póvoa, A. A., Skinner, L. F., de Araujo, F. V., & Creed, J. C. (2020). Marine litter and wood debris as habitat and vector for the range expansion of invasive corals (*Tubastraea* spp.). *Marine Pollution Bulletin*, *160*, 111659. https://doi.org/10.1016/j.marpolbul.2020.111659

McEdward, L. R. (2000). Adaptive evolution of larvae and life cycles. *Seminars in Cell & Developmental Biology*, *11*, 403–409. https://doi.org/10.1006/scdb.2000.0193

McLean, D. L., Partridge, J. C., Bond, T., Birt, M. J., Bornt, K. R., & Langlois, T. J. (2017). Using industry ROV videos to assess fish associations with subsea pipelines. *Continental Shelf Research*, *141*, 76–97. https://doi.org/10.1016/j.csr.2017.05.006

McLean, D. L., Taylor, M. D., Giraldo Ospina, A., & Partridge, J. C. (2019). An assessment of fish and marine growth associated with an oil and gas platform jacket using an augmented remotely operated vehicle. *Continental Shelf Research*, *179*, 66–84. https://doi.org/10.1016/j.csr.2019.04.006

McLean, D. L., Taylor, M. D., Partridge, J. C., Gibbons, B., Langlois, T. J., Malseed, B. E., Smith, L. D., & Bond, T. (2018). Fish and habitats on wellhead infrastructure on the north west shelf of Western Australia. *Continental Shelf Research*, *164*, 10–27. https://doi.org/10.1016/j.csr.2018.05.007

McLean, D. L., Vaughan, B. I., Malseed, B. E., & Taylor, M. D. (2020). Fish-habitat associations on a subsea pipeline within an Australian Marine Park. *Marine Environmental Research*, *153*, 104813. https://doi.org/10.1016/j.marenvres.2019.104813

Melbourne-Thomas, J., Hayes, K. R., Hobday, A. J., Little, L. R., Strzelecki, J., Thomson, D. P., van Putten, I., & Hook, S. E. (2021). Decommissioning research needs for offshore oil and gas infrastructure in Australia. *Frontiers in Marine Science*, *8*, 1007. https://doi.org/10.3389/fmars.2021.711151

Meyer, K. S., Li, Y., & Young, C. M. (2018). Oceanographic and biological influences on recruitment of benthic invertebrates to hard substrata on the Oregon shelf. *Estuarine, Coastal and Shelf Science*, *208*, 1–8. https://doi.org/10.1016/j.ecss.2018.04.037

Meyer-Gutbrod, E. L., Kui, L., Nishimoto, M. M., Love, M. S., Schroeder, D. M., & Miller, R. J. (2019). Fish densities associated with structural elements of oil and gas platforms in southern California. *Bulletin of Marine Science*, *95*, 639–656. https://doi.org/10.5343/bms.2018.0078

Meyer-Gutbrod, E. L., Love, M. S., Claisse, J. T., Page, H. M., Schroeder, D. M., & Miller, R. J. (2020). Decommissioning impacts on biotic assemblages associated with shell mounds beneath southern California offshore oil and gas platforms. *Bulletin of Marine Science*, *95*, 683–702. https://doi.org/10.5343/bms.2018.0077

Miles, W., & Mellor, M. (2018). *Ornithological monitoring programme in Shetland. A report to the Shetland Oil terminal Environmental Advisory Group*. SOTEAG.

Mireles, C., Martin, C. J. B., & Lowe, C. G. (2019). Site fidelity, vertical movement, and habitat use of nearshore reef fishes on offshore petroleum platforms in southern California. *Bulletin of Marine Science*, *95*, 657–682. https://doi.org/10.5343/bms.2018.0009

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L. A. & P.-P. Group. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic Reviews*, *4*, 1. https://doi.org/10.1186/2046-4053-4-1

Montevecchi, W. A. (2006). Influences of artificial light on marine birds. In C. Rich, & T. Longcore (Eds.), *Ecological consequences of artificial night lighting*. Island Press.

Munnelly, R. T., Reeves, D. B., Chesney, E. J., & Baltz, D. M. (2021). Spatial and temporal influences of nearshore hydrography on fish assemblages associated with energy platforms in the northern Gulf of Mexico. *Estuaries and Coasts*, *44*, 269–285.

Nishimoto, M. M., Simons, R. D., & Love, M. S. (2019). Offshore oil production platforms as potential sources of larvae to coastal shelf regions off southern California. *Bulletin of Marine Science*, *95*, 535–558. https://doi.org/10.5343/bms.2019.0033

Nishimoto, M. M., Washburn, L., Love, M. S., Schroeder, D. M., Emery, B. M., & Kui, L. (2019). Timing of juvenile fish settlement at offshore oil platforms coincides with water mass advection into the Santa Barbara Channel, California. *Bulletin of Marine Science*, *95*, 559–582. https://doi.org/10.5343/bms.2018.0068

Offshore Technology. (2014). Underwater arteries – The world's longest offshore pipelines. https://www.offshore-technology.com/features/featureunderwater-arteries-the-worlds-longestoffshore-pipelines-4365616/

Oil States Industries Inc. (2008). Types of offshore oil and gas structures. *Courtesy of Oil States Industries with license to NOAA Ocean Explorer: Expedition to the deep llope*. National Oceanic and Atmospheric Administration. https://oceanexplorer.noaa.gov/explorations/06mexico/background/oil/media/types_600.html

Orr, A. J., Harris, J. D., Hirschberger, K. A., DeLong, R. L., Sanders, G. A. & Laake, J. L. (2017). Qualitative and quantitative assessment of use of offshore oil and gas platforms by the California sea lion (*Zalophus californianus*). U.S. Department of Commerce, NOAA Technical Memorandum. NMFS-AFSC-362, 72 p. http://doi.org/10.7289/V5/TM-AFSC-362

Page, H., Simons, R. D., Zaleski, S., Miller, R., Dugan, J. E., Schroeder, D. M., Doheny, B., & Goddard, J. H. (2019). Distribution and potential larval connectivity of the non-native Watersipora (Bryozoa) among harbors, offshore oil platforms, and natural reefs. *Aquatic Invasions*, *14*, 615–637. https://doi.org/10.3391/ai.2019.14.4.04

Pajuelo, J. G., González, J. A., Triay-Portella, R., Martín, J. A., Ruiz-Díaz, R., Lorenzo, J. M., & Luque, Á. (2016). Introduction of non-native marine fish species to the Canary Islands waters through oil platforms as vectors. *Journal of Marine Systems*, *163*, 23–30. https://doi.org/10.1016/j.jmarsys.2016.06.008

Parker, R. O., Colby, D. R., & Willis, T. D. (1983). Estimated amount of reef habitat on a portion of the US South Atlantic and Gulf of Mexico continental shelf. *Bulletin of Marine Science*, *33*, 935–940.

Pittman, S. J., Yates, K. L., Bouchet, P. J., Alvarez-Berastegui, D., Andréfouët, S., Bell, S. S., Berkström, C., Boström, C., Brown, C. J., Connolly, R. M., Devillers, R., Eggleston, D., Gilby, B. L., Gullström, M., Halpern, B. S., Hidalgo, M., Holstein, D., Hovel, K., Huettmann, F., … Young, M. (2021). Seascape ecology: Identifying research priorities for an emerging ocean sustainability science. *Marine Ecology Progress Series*, *663*, 1–29. https://doi.org/10.3354/meps13661

Pondella, D. J., Zahn, L. A., Love, M. S., Siegel, D., & Bernstein, B. B. (2015). Modeling fish production for southern California's petroleum platforms. *Integrated Environmental Assessment and Management*, *11*, 584–593. https://doi.org/10.1002/ieam.1689

Radford, C. A., Jeffs, A. G., & Montgomery, J. C. (2007). Directional swimming behavior by five species of crab postlarvae in response to reef sound. *Bulletin of Marine Science*, *80*, 369–378.

Redford, M., Rouse, S., Hayes, P., & Wilding, T. A. (2021). Benthic and fish interactions with pipeline protective structures in the North Sea. *Frontiers in Marine Science*, *8*, 417. https://doi.org/10.3389/fmars.2021.652630

Reeves, D. B., Chesney, E. J., Munnelly, R. T., Baltz, D. M., & Maiti, K. (2019). Trophic ecology of sheepshead and stone crabs at oil and gas platforms in the northern Gulf of Mexico's hypoxic zone. *Transactions of the American Fisheries Society*, *148*, 324–338. https://doi.org/10.1002/tafs.10135

Reeves, D. B., Chesney, E. J., Munnelly, R. T., Baltz, D. M., & Marx, B. D. (2018). Abundance and distribution of reef-associated fishes around small oil and gas platforms in the northern Gulf of Mexico's hypoxic zone. *Estuaries and Coasts*, *41*, 1835–1847. https://doi.org/10.1007/s12237-017-0349-4

Rieseberg, L. H., & Burke, J. M. (2001). The biological reality of species: Gene flow, selection, and collective evolution. *Taxon*, *50*, 47–67. https://doi.org/10.2307/1224511

Rilov, G., & Benayahu, Y. (2002). Rehabilitation of coral reef-fish communities: The importance of artificial-reef relief to recruitment rates. *Bulletin of Marine Science*, *70*, 185–197.

Roberts, C. M., O'Leary, B. C., & Hawkins, J. P. (2020). Climate change mitigation and nature conservation both require higher protected area targets. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*, 20190121. https://doi.org/10.1098/rstb.2019.0121

Robertson, D. R., Simoes, N., Gutierrez Rodriguez, C., Pineros, V. J., & Perez-Espana, H. (2016). An Indo-Pacific damselfish well established in the southern Gulf of Mexico: Prospects for a wider, adverse invasion. *Journal of the Ocean Science Foundation*. https://doi.org/10.5281/zenodo.44898

Robinson, D. P., Jaidah, M. Y., Jabado, R. W., Lee-Brooks, K., Nour El-Din, N. M., Malki, A. A. A., Elmeer, K., McCormick, P. A., Henderson, A. C., Pierce, S. J., & Ormond, R. F. G. (2013). Whale sharks, *Rhincodon typus*, aggregate around offshore platforms in Qatari waters of the Arabian Gulf to feed on fish spawn. *PLoS One*, *8*, e58255.

Ronconi, R. A., Allard, K. A., & Taylor, P. D. (2015). Bird interactions with offshore oil and gas platforms: Review of impacts and monitoring techniques. *Journal of Environmental Management*, *147*, 34–45.

Rouse, S., Lacey, N. C., Hayes, P., & Wilding, T. A. (2019). Benthic conservation features and species associated with subsea pipelines: Considerations for decommissioning. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00200

Russell, D. J. F., Brasseur, S. M. J. M., Thompson, D., Hastie, G. D., Janik, V. M., Aarts, G., McClintock, B. T., Matthiopoulos, J., Moss, S. E. W., & McConnell, B. (2014). Marine mammals trace anthropogenic structures at sea. *Current Biology*, *24*, R638–R639. https://doi.org/10.1016/j.cub.2014.06.033

Russell, R. W. (2005). Interactions between migrating birds and offshore oil and gas platforms in the northern Gulf of Mexico: Final Report. *OCS Study MMS*, *9*, 327.

Sammarco, P. W., Brazeau, D. A., & Sinclair, J. (2012). Genetic connectivity in Scleractinian corals across the northern Gulf of Mexico: Oil/gas platforms, and relationship to the Flower Garden Banks. *PLoS One*, *7*, e30144.

Sammarco, P. W., Porter, S. A., Sinclair, J., & Genazzio, M. (2014). Population expansion of a new invasive coral species, *Tubastraea micranthus*, in the northern Gulf of Mexico. *Marine Ecology Progress Series*, *495*, 161–173. https://doi.org/10.3354/meps10576

Schläppy, M., Robinson, L., Camilieri-Asch, V., & Miller, K. (2021). Trash or treasure? Considerations for future research on oil and gas decommissioning research. *Frontiers in Marine Science*. https://doi.org/10.3389/fmars.2021.642539

Schroeder, D. M., & Love, M. S. (2004). Ecological and political issues surrounding decommissioning of offshore oil facilities in the Southern California Bight. *Ocean & Coastal Management*, *47*, 21–48. https://doi.org/10.1016/j.ocecoaman.2004.03.002

Schulze, A., Erdner, D. L., Grimes, C. J., Holstein, D. M., & Miglietta, M. P. (2020). Artificial reefs in the Northern Gulf of Mexico: Community ecology amid the "Ocean Sprawl". *Frontiers in Marine Science*, *7*, 447. https://doi.org/10.3389/fmars.2020.00447

Sequeira, A. M. M., Rodríguez, J. P., Eguíluz, V. M., Harcourt, R., Hindell, M., Sims, D. W., Duarte, C. M., Costa, D. P., Fernández-Gracia, J., Ferreira, L. C., Hays, G. C., Heupel, M. R., Meekan, M. G., Aven, A., Bailleul, F., Baylis, A. M. M., Berumen, M. L., Braun, C. D., Burns, J., … Thums, M. (2018). Convergence of marine megafauna movement patterns in coastal and open oceans. *Proceedings of the National Academy of Sciences, USA*, *115*, 3072–3077. https://doi.org/10.1073/pnas.1716137115

Shanks, A. L. (2009). Pelagic larval duration and dispersal distance revisited. *The Biological Bulletin*, *216*, 373–385. https://doi.org/10.1086/BBLv216n3p373

Shantz, A. A., Ladd, M. C., Schrack, E., & Burkepile, D. E. (2015). Fish-derived nutrient hotspots shape coral reef benthic communities. *Ecological Applications*, *25*, 2142–2152. https://doi.org/10.1890/14-2209.1

Silva, A. G. D., Paula, A. F. D., Fleury, B. G., & Creed, J. C. (2014). Eleven years of range expansion of two invasive corals (*Tubastraea coccinea* and *Tubastraea tagusensis*) through the southwest Atlantic (Brazil). *Estuarine, Coastal and Shelf Science*, *141*, 9–16. https://doi.org/10.1016/j.ecss.2014.01.013

Simons, R. D., Page, H. M., Zaleski, S., Miller, R., Dugan, J. E., Schroeder, D. M., & Doheny, B. (2016). The effects of anthropogenic structures on habitat connectivity and the potential spread of non-native invertebrate species in the offshore environment. *PLoS One*, *11*, e0152261. https://doi.org/10.1371/journal.pone.0152261

Simpson, S. D., Harrison, H. B., Claereboudt, M. R., & Planes, S. (2014). Long-distance dispersal via ocean currents connects Omani clownfish populations throughout entire species range. *PLoS One*, *9*, e107610. https://doi.org/10.1371/journal.pone.0107610

Simpson, S. D., Radford, A. N., Tickle, E. J., Meekan, M. G., & Jeffs, A. G. (2011). Adaptive avoidance of reef noise. *PLoS One*, *6*, e16625. https://doi.org/10.1371/journal.pone.0016625

Smith, J. A., Lowry, M. B., Champion, C., & Suthers, I. M. (2016). A designed artificial reef is among the most productive marine fish habitats: New metrics to address 'production versus attraction'. *Marine Biology*, *163*, 188. https://doi.org/10.1007/s00227-016-2967-y

Smyth, K., Christie, N., Burdon, D., Atkins, J. P., Barnes, R., & Elliott, M. (2015). Renewables-to-reefs? Decommissioning options for the offshore wind power industry. *Marine Pollution Bulletin*, *90*, 247–258. https://doi.org/10.1016/j.marpolbul.2014.10.045

Snodgrass, D. J. G., Orbesen, E. S., Walter, J. F., Hoolihan, J. P., & Brown, C. A. (2020). Potential impacts of oil production platforms and their function as fish aggregating devices on the biology of highly migratory fish species. *Reviews in Fish Biology and Fisheries*, *30*, 405–422. https://doi.org/10.1007/s11160-020-09605-z

Stanley, D. R., & Wilson, C. A. (2004). Effect of hypoxia on the distribution of fishes associated with a petroleum platform off coastal Louisiana. *North American Journal of Fisheries Management*, *24*, 662–671. https://doi.org/10.1577/M02-194.1

Streich, M. K., Ajemian, M. J., Wetz, J. J., & Stunz, G. W. (2017). A comparison of fish community structure at mesophotic artificial reefs and natural banks in the western Gulf of Mexico. *Marine and Coastal Fisheries*, *9*, 170–189. https://doi.org/10.1080/19425120.2017.1282897

Swearer, S. E., Treml, E. A., & Shima, J. S. (2019). *A review of biophysical models of marine larval dispersal*. CRC Press.

Tasker, M. L., Jones, P. H., Blake, B. F., Dixon, T. J., & Wallis, A. W. (1986). Seabirds associated with oil production platforms in the North Sea. *Ringing & Migration*, *7*, 7–14. https://doi.org/10.1080/03078698.1986.9673873

Taylor, P. D., Fahrig, L., Henein, K., & Merriam, G. (1993). Connectivity is a vital element of landscape structure. *Oikos*, *68*(3), 571–573. https://doi.org/10.2307/3544927

Techera, E. J., & Chandler, J. (2015). Offshore installations, decommissioning and artificial reefs: Do current legal frameworks best serve the marine environment? *Marine Policy*, *59*, 53–60.

Thaxter, C. B., Ross-Smith, V. H., Bouten, W., Clark, N. A., Conway, G. J., Rehfisch, M. M., & Burton, N. H. K. (2015). Seabird–wind farm interactions during the breeding season vary within and between years: A case study of lesser black-backed gull *Larus fuscus* in the UK. *Biological Conservation*, *186*, 347–358. https://doi.org/10.1016/j.biocon.2015.03.027

Thomson, P., Pillans, R., Jaine, F., Harcourt, R., Taylor, M., Pattiaratchi, C., & McLean, D. L. (2021). Acoustic telemetry around Western Australia's oil and gas infrastructure helps monitor an elusive and endangered migratory giant. *Frontiers in Marine Science*, *8*, 631449.

Thorpe, S. A. (2012). On the biological connectivity of oil and gas platforms in the North Sea. *Marine Pollution Bulletin*, *64*, 2770–2781. https://doi.org/10.1016/j.marpolbul.2012.09.011

Thresher, R. E., & Brothers, E. B. (1985). Reproductive ecology and biogeography of Indo-West Pacific angelfishes (Pisces: Pomacanthidae). *Evolution*, *39*, 878–887. https://doi.org/10.1111/j.1558-5646.1985.tb00429.x

Tidbury, H., Taylor, N., van der Molen, J., Garcia, L., Posen, P., Gill, A., Lincoln, S., Judd, A., & Hyder, K. (2020). Social network analysis as a tool for marine spatial planning: Impacts of decommissioning on connectivity in the North Sea. *Journal of Applied Ecology*, *57*, 566–577. https://doi.org/10.1111/1365-2664.13551

Todd, V., Lavallin, E., & Macreadie, P. (2018). Quantitative analysis of fish and invertebrate assemblage dynamics in association with a North Sea oil and gas installation complex. *Marine Environmental Research*, *142*, 69–79. https://doi.org/10.1016/j.marenvres.2018.09.018

Todd, V. L. G., Lazar, L., Williamson, L. D., Peters, I. T., Hoover, A. L., Cox, S. E., Todd, I. B., Macreadie, P. I., & McLean, D. L. (2020). Underwater visual records of marine megafauna around offshore anthropogenic structures. *Frontiers in Marine Science*, *7*, 230. https://doi.org/10.3389/fmars.2020.00230

Todd, V. L. G., Pearse, W. D., Tregenza, N. C., Lepper, P. A., & Todd, I. B. (2009). Diel echolocation activity of harbour porpoises (*Phocoena phocoena*) around North Sea offshore gas installations. *ICES Journal of Marine Science*, *66*, 734–745. https://doi.org/10.1093/icesjms/fsp035

Todd, V. L. G., Williamson, L. D., Cox, S. E., Todd, I. B., & Macreadie, P. I. (2020c). Characterising the first wave of fish and invertebrate colonisation on a new offshore petroleum platform. *ICES Journal of Marine Science*, *77*, 1127–1136.

Todd, V. L. G., Williamson, L. D., Jiang, J., Cox, S. E., Todd, I. B., & Ruffert, M. (2020). Proximate underwater soundscape of a North Sea offshore petroleum exploration jack-up drilling rig in the Dogger Bank. *The Journal of the Acoustical Society of America*, *148*, 3971–3979. https://doi.org/10.1121/10.0002958

Topolski, M. F., & Szedlmayer, S. T. (2004). Vertical distribution, size structure, and habitat associations of four Blenniidae species on gas platforms in the northcentral Gulf of Mexico. *Environmental Biology of Fishes*, *70*, 193–201. https://doi.org/10.1023/B:EBFI.0000029364.23532.94

Tranquilla, L. A. M., Montevecchi, W. A., Hedd, A., Fifield, D. A., Burke, C. M., Smith, P. A., Regular, P. M., Robertson, G. J., Gaston, A. J., & Phillips, R. A. (2013). Multiple-colony winter habitat use by murres *Uria* spp. in the Northwest Atlantic Ocean: implications for marine risk assessment. *Marine Ecology Progress Series*, *472*, 287–303.

Treml, E. A., Ford, J. R., Black, K. P., & Swearer, S. E. (2015). Identifying the key biophysical drivers, connectivity outcomes, and metapopulation consequences of larval dispersal in the sea. *Movement Ecology*, *3*, 1–16. https://doi.org/10.1186/s40462-015-0045-6

Urban, D. L., Minor, E. S., Treml, E. A., & Schick, R. S. (2009). Graph models of habitat mosaics. *Ecology Letters*, *12*, 260–273. https://doi.org/10.1111/j.1461-0248.2008.01271.x

van der Molen, J., García-García, L. M., Whomersley, P., Callaway, A., Posen, P. E., & Hyder, K. (2018). Connectivity of larval stages of sedentary marine communities between hard substrates and offshore structures in the North Sea. *Scientific Reports*, *8*, 14772. https://doi.org/10.1038/s41598-018-32912-2

Vermeij, M. J. A., Marhaver, K. L., Huijbers, C. M., Nagelkerken, I., & Simpson, S. D. (2010). Coral larvae move toward reef sounds. *PLoS One*, *5*, e10660. https://doi.org/10.1371/journal.pone.0010660

Vinther, M., & Larsen, F. (2004). Updated estimates of harbour porpoise by-catch in the Danish North Sea bottom set gillnet fishery. *Journal of Cetacean Research and Management*, *6*, 19–24.

Virtanen, E. A., Moilanen, A., & Viitasalo, M. (2020). Marine connectivity in spatial conservation planning: Analogues from the terrestrial realm. *Landscape Ecology*, *35*, 1021–1034. https://doi.org/10.1007/s10980-020-00997-8

Vodopivec, M., Peliz, Á. J., & Malej, A. (2017). Offshore marine constructions as propagators of moon jellyfish dispersal. *Environmental Research Letters*, *12*, 084003. https://doi.org/10.1088/1748-9326/aa75d9

Wanless, R. M., Scott, S., Sauer, W. H. H., Andrew, T. G., Glass, J. P., Godfrey, B., Griffiths, C., & Yeld, E. (2010). Semi-submersible rigs: A vector transporting entire marine communities around the world. *Biological Invasions*, *12*, 2573–2583. https://doi.org/10.1007/s10530-009-9666-2

Want, A., Bell, M. C., Harris, R. E., Hull, M. Q., Long, C. R., & Porter, J. S. (2021). Sea-trial verification of a novel system for monitoring biofouling and testing anti-fouling coatings in highly energetic environments targeted by the marine renewable energy industry. *Biofouling*, *37*(4), 433–451. https://doi.org/10.1080/08927014.2021.1928091

Want, A., Crawford, R., Kakkonen, J., Kiddie, G., Miller, S., Harris, R. E., & Porter, J. S. (2017). Biodiversity characterisation and hydrodynamic consequences of marine fouling communities on marine renewable energy infrastructure in the Orkney Islands Archipelago, Scotland, UK. *Biofouling*, *33*(7), 567–579. https://doi.org/10.1080/08927014.2017.1336229

Wiese, F. K., Montevecchi, W. A., Davoren, G. K., Huettmann, F., Diamond, A. W., & Linke, J. (2001). Seabirds at risk around offshore oil platforms in the North-west Atlantic. *Marine Pollution Bulletin*, *42*, 1285–1290. https://doi.org/10.1016/S0025-326X(01)00096-0

Williamson, D. H., Harrison, H. B., Almany, G. R., Berumen, M. L., Bode, M., Bonin, M. C., Choukroun, S., Doherty, P. J., Frisch, A. J., Saenz-Agudelo, P., & Jones, G. P. (2016). Large-scale, multidirectional larval connectivity among coral reef fish populations in the Great Barrier Reef Marine Park. *Molecular Ecology*, *25*, 6039–6054. https://doi.org/10.1111/mec.13908

Williamson, M. J., Tebbs, E. J., Dawson, T. P., & Jacoby, D. M. P. (2019). Satellite remote sensing in shark and ray ecology, conservation and management. *Frontiers in Marine Science*, *6*, 135.

Wilson, P., Thums, M., Pattiaratchi, C., Whiting, S., Pendoley, K., Ferreira, L. C., & Meekan, M. (2019). High predation of marine turtle hatchlings near a coastal jetty. *Biological Conservation*, *236*, 571–579. https://doi.org/10.1016/j.biocon.2019.04.015

Wright, S. R., Lynam, C. P., Righton, D. A., Metcalfe, J., Hunter, E., Riley, A., Garcia, L., Posen, P., & Hyder, K. (2020). Structure in a sea of sand: Fish abundance in relation to man-made structures in the

North Sea. *ICES Journal of Marine Science*, *77*, 1206–1218. https://doi.org/10.1093/icesjms/fsy142

Wu, Z., Tweedley, J. R., Loneragan, N. R., & Zhang, X. (2019). Artificial reefs can mimic natural habitats for fish and macroinvertebrates in temperate coastal waters of the Yellow Sea. *Ecological Engineering*, *139*, 105579. https://doi.org/10.1016/j.ecoleng.2019.08.009

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: McLean, D. L., Ferreira, L. C., Benthuysen, J. A., Miller, K. J., Schläppy, M.-L., Ajemian, M. J., Berry, O., Birchenough, S. N. R., Bond, T., Boschetti, F., Bull, A. S., Claisse, J. T., Condie, S. A., Consoli, P., Coolen, J. W. P., Elliott, M., Fortune, I. S., Fowler, A. M., Gillanders, B. M., … Thums, M. (2022). Influence of offshore oil and gas structures on seascape ecological connectivity. *Global Change Biology*, 28, 3515–3536. https://doi.org/10.1111/gcb.16134