REVIEW

Influence of offshore oil and gas structures on seascape ecological connectivity

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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.
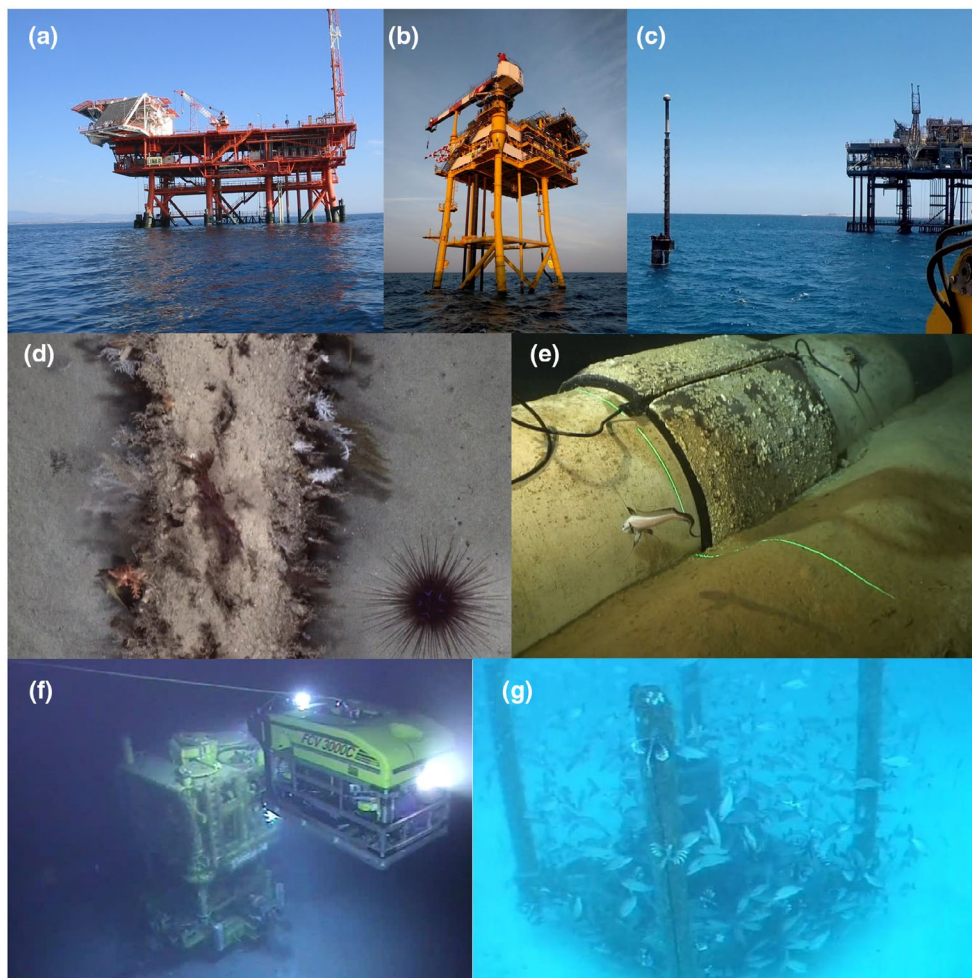
FIGURE 1 Examples of different offshore O&G infrastructure including (a) steel platform for methane extraction located in the Ionian Sea (Central Mediterranean Sea), (b) A18 gas-production platform (North Sea), (c) Harriet Alpha conventional steel platform and flare, (d) and (e) subsea pipelines, (f) 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)
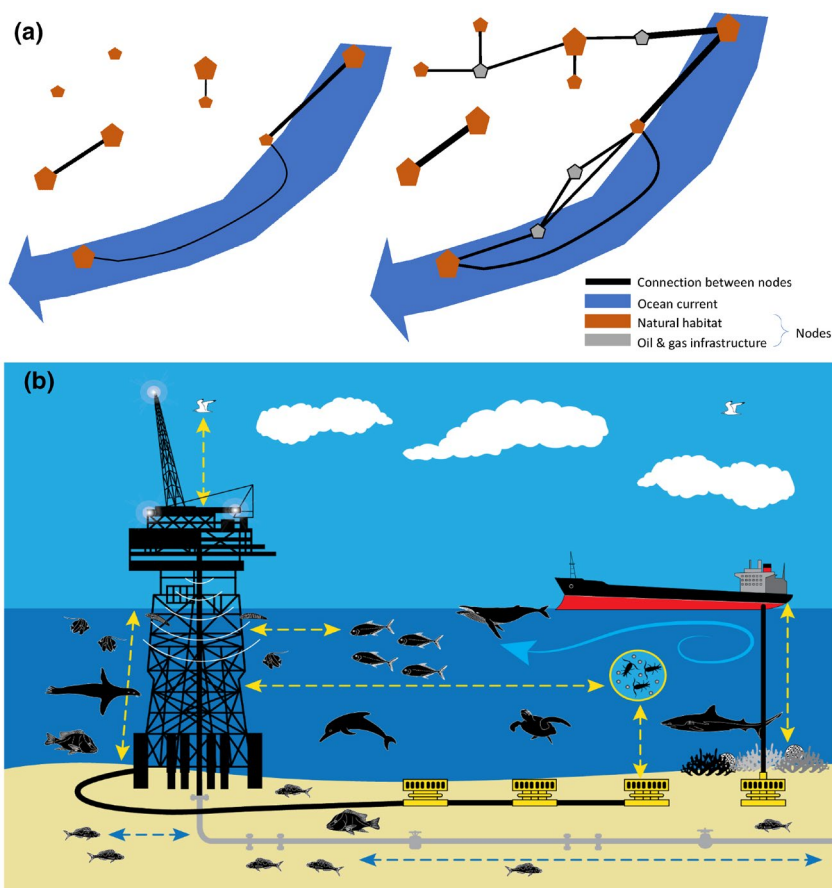
FIGURE 3 Extent of offshore O&G infrastructure and hotspots of marine biodiversity. Spatial layer of O&G infrastructure was obtained from Lujala et al. (2007). Taxa occurrence data from AquaMaps (Kaschner et al., 2019) and GBIF (GIBF 29 March 2021). Infrastructure layer is indicative of the presence 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
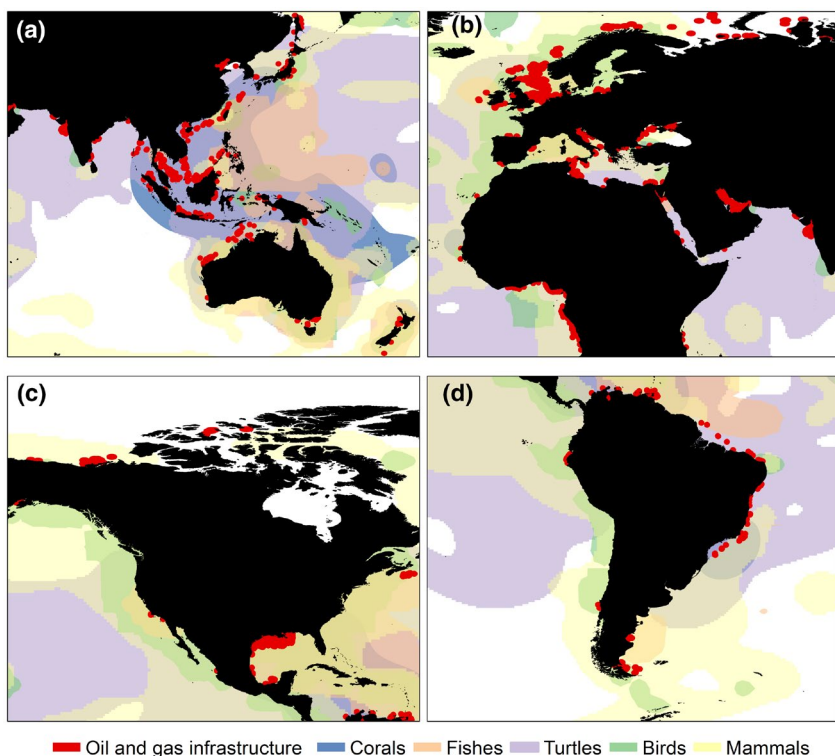
Figure 4a,b). Via SCOPUS, we used a systematic approach to locate relevant literature (Moher et al., 2015; Williamson et al., 2019) and experts. A list of search terms was developed, associated with four broad groupings: (1) O&G industry, (2) Connectivity, (3) Species and (4) Region (see Table S1). The search covered 1990 up to the date the search was performed (24 November 2020) and focussed

(a)

(b)

(c)
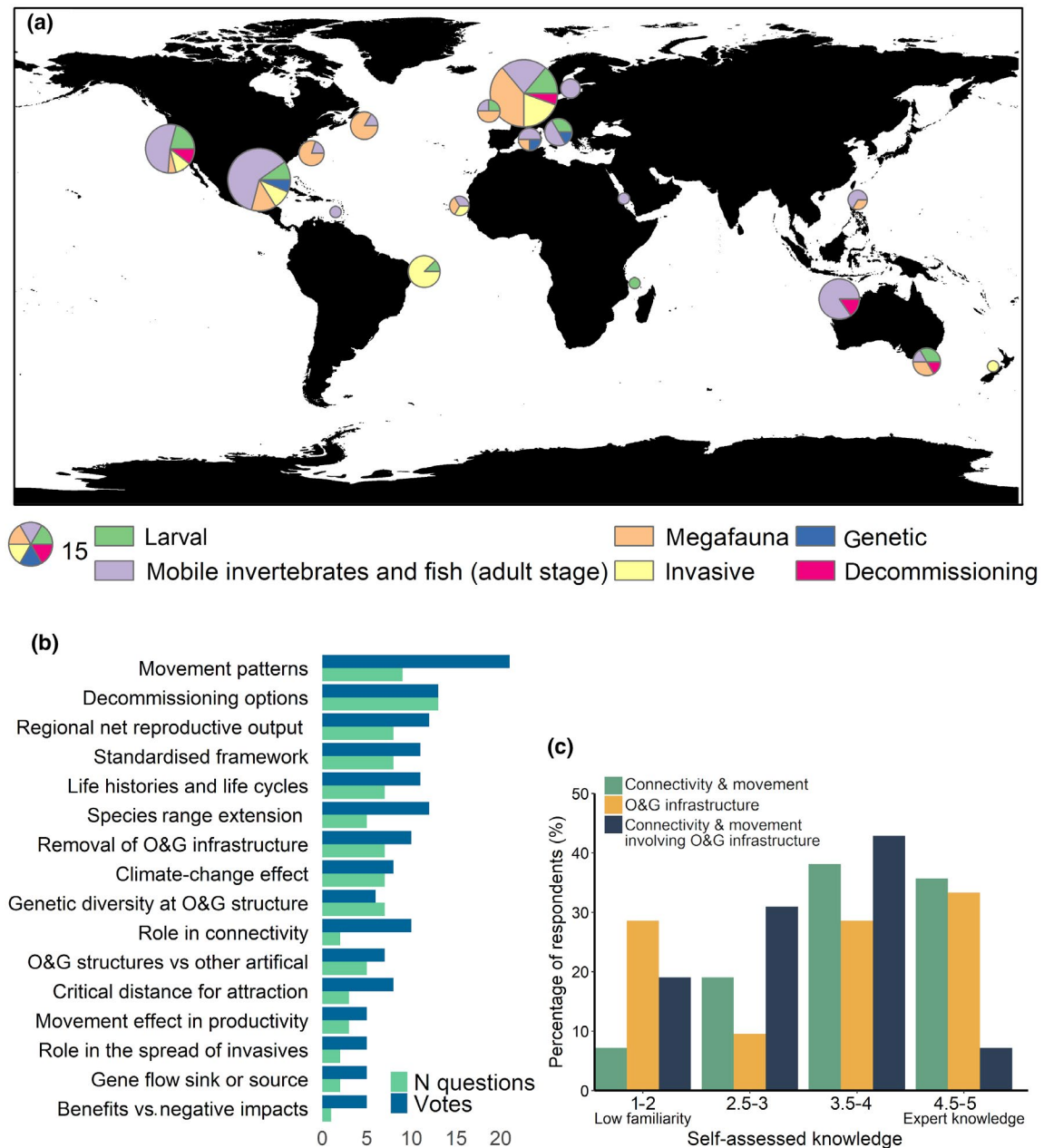
FIGURE 4 Summary of literature and expert opinion that informed this review and identification of priority research questions. (a) Relative contribution of each of the study areas of ecology and connectivity (see Data S1) with respect to O&G infrastructure that were identified during the literature search 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 over-arching 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
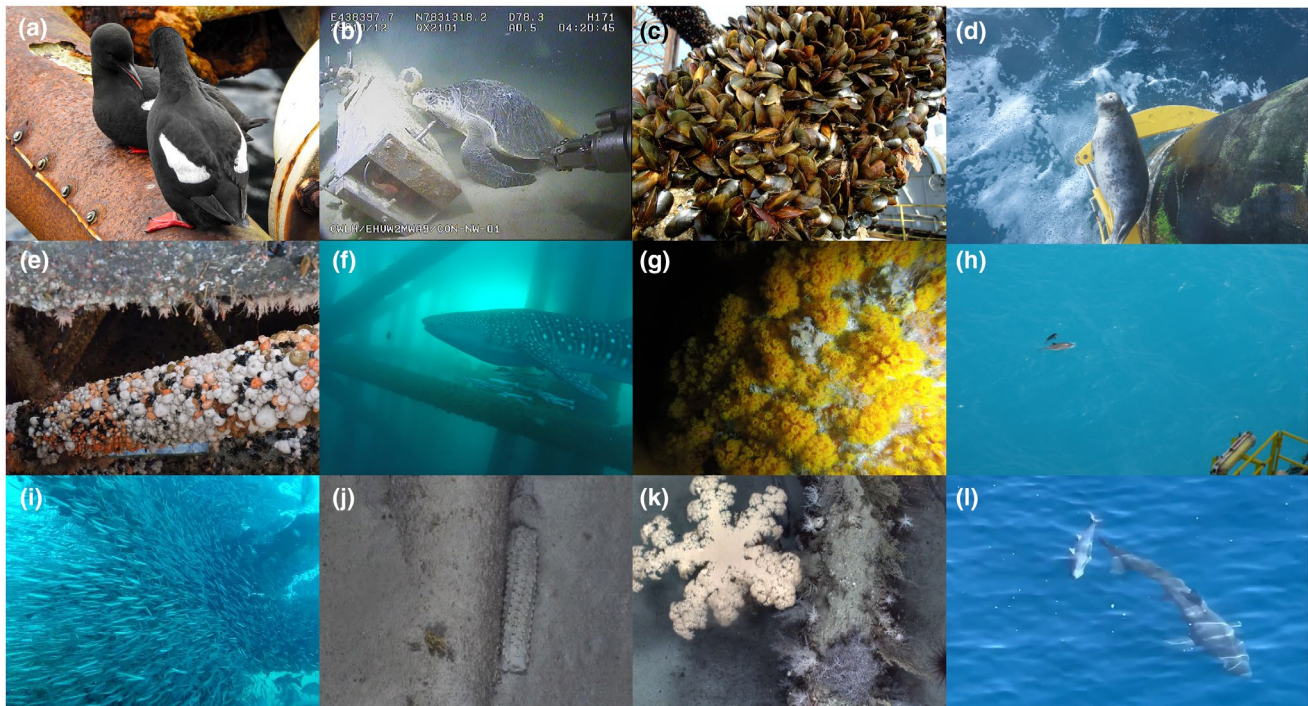
FIGURE 5 Fauna associations with offshore O&G infrastructure; (a) black guillemots on platform, (b) green turtle beside a subsea O&G structure, (c) *Mytilus sp.* mussels on jack-up-rig leg, (d) grey seal resting on North Sea oil platform, (e) Metridium senile anemones on jack-up-rig leg, (f) whale shark 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 'reefing' 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.

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CONFLICT OF INTEREST

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.

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