PLOS SUSTAINABILITY AND TRANSFORMATION

REVIEW

Haven or hell? A perspective on the ecology of offshore oil and gas platforms

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Abstract

Offshore oil and gas platforms (OGP) have been installed worldwide and initially with limited consideration given to the nature of their positive or negative long-term interactions with the natural marine habitats. However, as OGP reach the end of their useful life, with many being decommissioned and removed, it is timely to review the growing evidence of the association of marine biota with OGP to provide a summary and synthesis for policy makers and to give insight to decisions in increasingly crowded marine spatial plans. In the last decade, there has been rapid increase in studies concerning the ecological role of OGP. This research reveals strong contextual difference between platforms in different geographical regions, but all OGP add to local biodiversity particularly where hard substrata are introduced to areas dominated by depositional (mud and sand) habitats. This includes the attraction and increased productivity of fish, sessile invertebrates, and algae while also affecting change in the benthic habitats beneath platforms. There also evidence of the OGP changing local hydrodynamics conditions with effects on phytoplankton and local scour. In terms of the biota associated with OGP, water depth is a major driver of community type across systems. This study emphasises that while knowledge of OGP communities and species has improved, there are still significant knowledge gaps that may prevent the most environmentally beneficial decisions being made around decommissioning. There are few studies following the effect of decommissioning (topping, toppling, or removal) on the ecology of the systems as they change with time (longitudinal research) for the decommissioning event. There is also a need for more studies comparing the biodiversity and functionality of OGP system to artificial and natural reefs and habitats to better understand the ecological cost-benefit of decommissioning scenarios. Finally, commercial data is often unavailable and even when available, surveys are often conducted using varied methodology that prevents comparative analysis. By imposing/agreeing standards and sharing data around the ecological cost-benefit of decommissioning strategies, improve policy guidance concerning OGP planning, and management might emerge.

Citation: Fortune IS, Madgett AS, Scarborough Bull A, Hicks N, Love MS, Paterson DM (2024) Haven or hell? A perspective on the ecology of offshore oil and gas platforms. PLOS Sustain Transform 3(4): e0000104. https://doi.org/10.1371/journal.pstr.0000104

Editor: Jose Carlos Báez, Spanish Institute of Oceanography: Instituto Espanol de Oceanografia, SPAIN

Published: April 18, 2024

Funding: NH and DMP were supported by NERC-INSITE funding project FuECoMMS (NE/T010800/1). This work was also funded by Chevron Grant number: NDC-AP-001) through its Anchor Partnership with the UK National Decommissioning Centre. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

Author summary

When man-made structures are introduced into the ocean, they swiftly become hubs for diverse marine life. Initially, simple organisms like bacteria and algae take hold, but over time, these communities evolve into complex ecosystems, fostering a plethora of larger organisms such as molluscs and sponges. This transformation not only enriches local biodiversity but also serves as a magnet for mobile marine species, including fish, drawn from the surrounding marine environment. Consequently, offshore oil and gas platforms (OGP) and similar structures emerge as localised biodiversity hotspots, although their broader ecological significance remains a topic of debate. In our perspective review, we offer a comprehensive overview of OGP ecology spanning various organismal groups and geographic regions. This synthesis aims to illuminate the ecological dynamics at play, providing crucial insights into the potential management of decommissioning processes as these structures approach the end of their operational lifespan. The approach to decommissioning varies among nations, highlighting the need for scientific evidence regarding the ecological role of these structures—a pivotal factor in the decision-making process. Ultimately, the question arises: Are they sanctuaries or ecological liabilities, haven or hell?

1. Introduction

The natural heterogeneity of the ocean is being reduced as the impacts of the Anthropocene increase and biodiversity declines in response to anthropogenic pressures (fisheries, transport) and multiple stressors (pollutants, temperature, pH). Management options to remedy these challenges are difficult but include the expansion of marine protected areas and the increasing legislative control of industrial processes and procedures. However, since the advent of human civilization, we have been placing artificial structures in the marine environment for food production, transport, commerce, energy, recreation, and military purposes. The role of artificial structures in ocean ecology has been brought into focus by questions about the future sustainable management of new and soon-to-be decommissioned marine energy systems, including offshore oil and gas infrastructure and the rapid expansion of the offshore wind sector. A critical issue is the environmental legacy around marine structures and the expectation that new developments will take account of their installation and operational impact as well as end of life management. Globally, these issues are governed under the United Nations Convention on the Law of the Sea (UNCLOS) and the United Nations Environment Programme (UNEP) that sets the global environmental agenda within the United Nations system. However, relevant legislation under UNEP varies in the different regional seas with respect to how decommissioning must be achieved whether a "rigs to reefs" program is viable or if all structures must be removed, if possible, as designated by OSPAR (Oslo and Paris Conventions) for the Northeast Atlantic.

Globally, these platforms operate in a wide range of water depths from 10 to 3,000 m and from 1.6 to 400 km from the shore [1,2] and occur in all but the deepest oceans. As soon as any structure is placed in the sea, the colonisation of the surface begins, initially attracting organic coatings and then a succession of species, from bacteria and viruses to metazoa, rapidly developing over time [3–5] into a complex three-dimensional habitat [6].

Society is now entering a period where many oil and gas infrastructures have reached the end of their working lives. Deciding whether to completely remove these structures from the seafloor, or to leave in situ as an artificial reef, is imminent for many nations and corporations [7,8]. Given the increasing pace of decommissioning, it is timely to understand more about the ecological role and opportunity of platform ecosystems. Ecological metrics must be identified and the evaluation and the implications locally, and in the wider context of regional seas, should be acknowledged. Independent, evidence-based scientific research is vital to feed into the multi-criteria analysis of optimal decommissioning outcomes [9].

2. Methodology

This contribution is a perspective encompassing a "Web of Science" (WoS) and ScienceDirect (SD) searches of peer-reviewed literature on the ecology associated with oil and gas platforms (OGP), filtered by the authors in terms of relevance. Not all references found were cited especially where there was significant redundancy or were considered "out of scope" but are included in the bibliographic database (SS1) of 163 papers (2017 to 2023). The literature review builds on the previous publication by Fortune and Paterson (2018) [8]. The authors' included original research articles (i.e., not reviews, conference proceedings) using the terms: "oil"; "gas"; "platform"; "ecology"; "ecosystem"; and "environment" (search in English). These searches were then sifted for relevance to the current work but excluding onshore oil and gas, non-OGP marine structures (ship hulls, shipwrecks, wind and tidal renewable structures, and policy and engineering). Some trial searches were done on other platforms but revealed no further information. The search was limited to the terms above and did not include preprint online papers. Articles relating to microbes occurring internally in pipelines, and in relation to corrosion, were excluded, as beyond the scope of this review. All biological taxa (microorganisms, fish, invertebrate, mammals) were included in subsequent considerations, however. The literature search has been updated to 2023 (2017 to 2023) (using the method above with some additional articles acquired via algorithms on science sharing sites (such as "ResearchGate")). A total of 1,065 peer review articles were filtered to 116 articles fitting the criteria that were then subject to higher-level bibliographic analysis. The remaining literature that was cited (58), but not included in analysis of research papers, comprises review articles and those not specific to OGP but included to provide relevant wider context.

3. Research progression

It is not surprising that information around environmental aspects of offshore OGP is expanding rapidly as decommissioning gathers pace, as does the requirement to understand the broader environmental implications. For example, Web of Science publications citing "Oil and Gas decommissioning" were annually below 15 per annum until 2014, since then there has been an almost exponential rise with 60 publications in 2019 (with 651 citations), while in 2022 there were 224 publications. In addition, as numbers of publications and citations increase, research areas become more specific and focused. The largest number of papers are retrieved using general keywords such as the "ecology" of offshore structures and "biodiversity" but more specialist areas such as "connectivity" are on the increase while "genomics" is still relatively in its infancy (Figs 1–4).

Depending on the research question, sampling of the biota around OGP for ecological surveys varies widely and may occur over a depth gradient or across seafloor transects and at preselected distances from the structure. Few studies have included samples from both the local benthos and the biota attached to, or associated with, the structure [10,11]. The scale of studies varies from a single platform to multiple platforms and/or across regions. Most studies were comparisons between multiple settings (85%), while those at a single platform (15%) examined spatial variation between platform aspects, such as depth or distance from the platform. Details of publications concerning biological variables at individual, population, community, or ecosystem level or across temporal scales (diel, season, annual, multiyear) are given (Table 1),

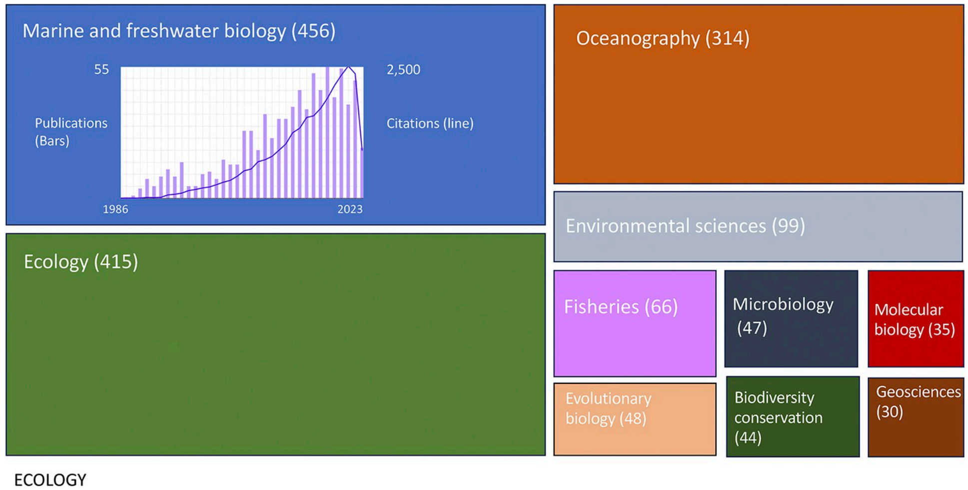

Fig 1. WoS TreeMap chart representing proportion of papers under the search "Ecology of offshore structures" subdivided by WoS assigned categories with relevant number of papers in brackets. Inset in top left quadrant is the number of publications (bars) and citations (line) per year from 1986–2023 (A) and 1995–2023 (B).

https://doi.org/10.1371/journal.pstr.0000104.g001

while abiotic drivers giving context to the communities of offshore structures are provided (Table 2).

Identifying and enumerating the biota (Fig 5) present around OGP provides an understanding of the local ecosystem dynamics and function, but also allows comparisons to the surrounding habitat, which supports understanding of the variation in biodiversity and heterogeneity created by the presence of OGP. However, data on mobile species is often difficult to collect although marine mammals, marine reptiles, and birds are incidentally observed at platforms (Fig 5), and there have been informative studies on fish distribution and abundance (Table 1). Analyses of microbial biodiversity or community composition provide an insight into biogeochemical cycling but are also relatively rare (Fig 5). For example, hydrocarbon degrading bacteria indicate the presence of hydrocarbons and play a role in

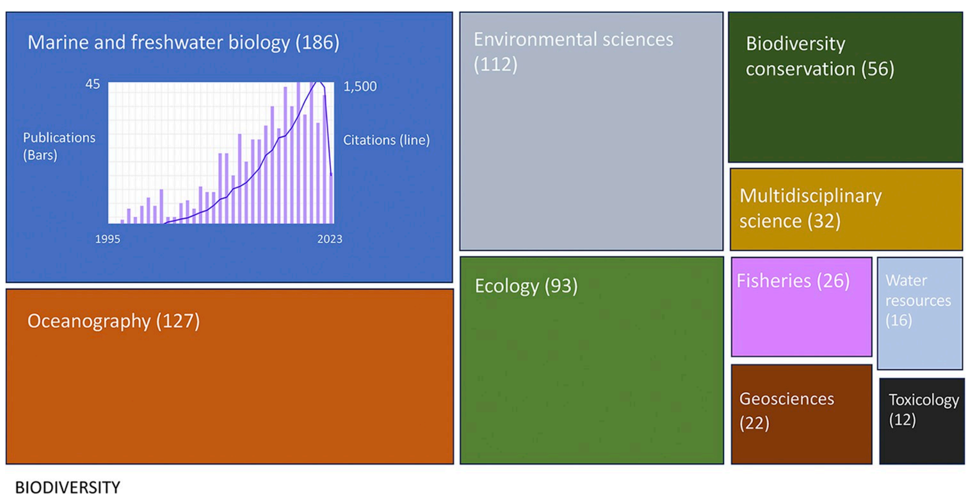

Fig 2. WoS TreeMap chart representing proportion of papers under the search "Biodiversity of offshore structures" subdivided by WoS assigned categories with relevant number of papers in brackets. Inset in top left quadrant is the number of publications (bars) and citations (line) per year from 1986–2023 (A) and 1995–2023 (B).

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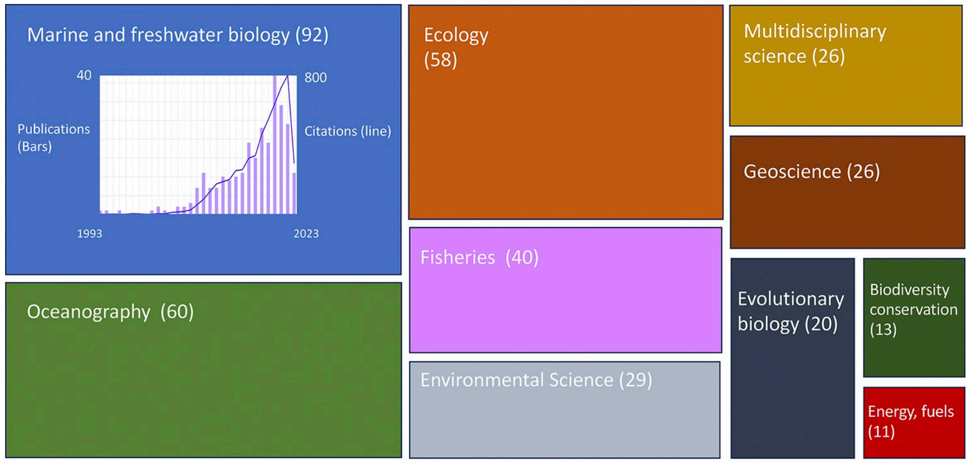

CONNECTIVITY

Fig 3. WoS TreeMap chart representing proportion of papers under the search "Connectivity of offshore structures" subdivided by WoS assigned categories with relevant number of papers in brackets. Inset in top left quadrant is the number of publications (bars) and citations (line) per year from 1993–2023 (A) and 1986–2023 (B).

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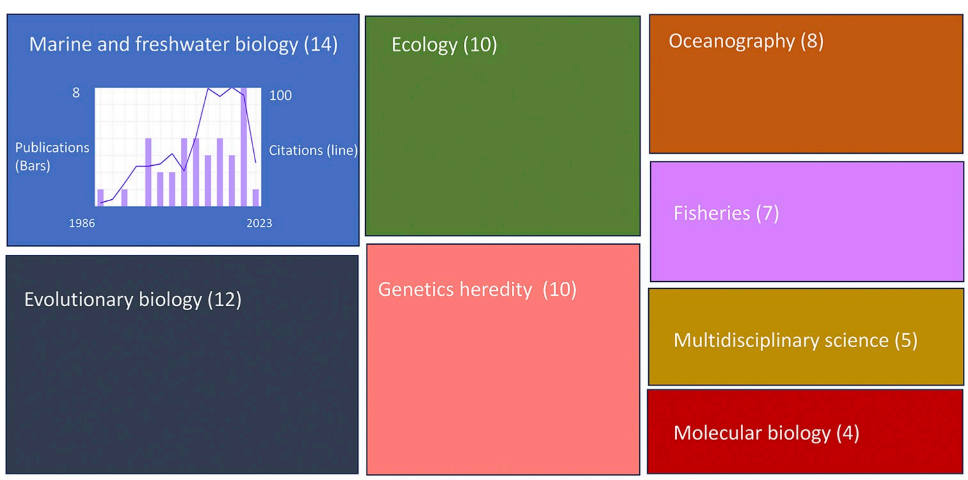
bioremediation of contaminated sites [12]. Taken together, appropriate biodiversity and taxon-specific abundance data might be used to analyse the structure of the community and to compare communities at different spatial and temporal scales but often the data falls short of scientific requirements [8].

4. Biodiversity

The science of "Island Biogeography" (IB) demonstrates the importance of island systems in the evolution and extinction of species [13]. A critical concern with IB is the breakup of natural habitats into relict patches (or islands) of former biodiversity which are then prone to species



GENOMICS

Fig 4. WoS TreeMap chart representing proportion of papers under the search (A) of "Connectivity of offshore structures" and (B), "Genomics of offshore structures" both subdivided by WoS assigned categories with relevant number of papers in brackets. Inset in top left quadrant is the number of publications (bars) and citations (line) per year from 1993–2023 (A) and 1986–2023 (B).

https://doi.org/10.1371/journal.pstr.0000104.g004

Table 1. Summary of biological variables in platform ecological studies, ordered by spatial scale, with relevant references.

Scale	Variable/metric	Relevant references
Individual	Size of individuals	[25,27,115]
	Growth rate	[43,140]
	Counts of fish	[10,22,25,27,34,36,51,69,91,109,115,128,144,145]
	Nursery function (presence of propagules)	[21,24,145,146]
Population	Density (% coverage)	[34,43,56,69,115,147,148]
	Population age structure	[142,149]
	Population genetic diversity	[93,94,150]
	Population traits	[10,144,149]
	Population growth (biomass)	[143,147]
	Reproductive potential	[15,82,84,149]
	Connectivity between populations	[19,29,98,102,109,151]
Community	Community Structure	[10,11,26,64,115,152,153]
	Species richness	[25,33,35,51,73,144]
	Species richness -DNA metabarcoding	[73,154,155,156,157]
	Biodiversity (α, β, γ) H'	[10,24,30,31,34,55,115,146]
	Abundance (total fish MaxN, thickness of epifauna)	[11,34,51,56,69,106,115,152]
	Biological production (community fish biomass)	[11,15,84,115,143]
	Functional diversity	[115,144]
	Trophic status (food web, carbon flow, phytoplankton level)	[27,56,64]
	Connectivity	[67,96,98,100,110,158,159]
	Invasive non-native species	[63 67,98,111,115,147,160]
	Comparison between platforms	[2,25,26,33,35,39,40,43,56,115,150, 153,161,162]
Ecosystem	Comparison between platform and seabed or reef	[10,11,33,62,149,163,164]
	Spatial variation at platform depth, height	[2,11,24,27,30,34,35,37,39,40,47, 58,63,115,128,142,146]

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extinction due to external pressures and decreasing genetic diversity. Marine infrastructure acts in the opposite way, creating "new" islands open to colonisation that increases local biodiversity and regional heterogeneity in both coastal and offshore waters [8]. Although these structures were not primarily intended to support marine life or enhance biodiversity, they

Table 2. Summary of abiotic context and drivers for ecological studies, ordered by spatial scale, with relevant references.

Scale	Variable/metric	References
Platform	Platform size and age	[24,34,51,58,115,166]
	Status—operational, reefed, topped, toppled	[27,30,64,149]
	Surface material (steel, concrete)	[114,172]
Environmental context	Spatial heterogeneity—multi-site; distance to shore, disturbance, system wide	[27,33,35,56,58,63,106,128,134,162]
	Water currents	[32,67,73,123]
	Temporal scale (diel, seasonal, annual)	[30,33,37,144,162]
	Sea surface temperature, salinity, TOC, grain size, SPM	[43,56,67,153]
Anthropogenic effects	Contamination legacy (drill cuttings, NORM)	[45,50,68,133,164,168,169,170,171]
	Recovery from disturbance (drilling or decommissioning)	[68,152,167,173]
	Fishing pressure/exclusion	[32]
	Nutrients (proximity of rivers)	[33, 115]
	Hypoxia	[165]

NORM, naturally occurring radioactive material; SPM, suspended particulate matter; TOC, total organic carbon.

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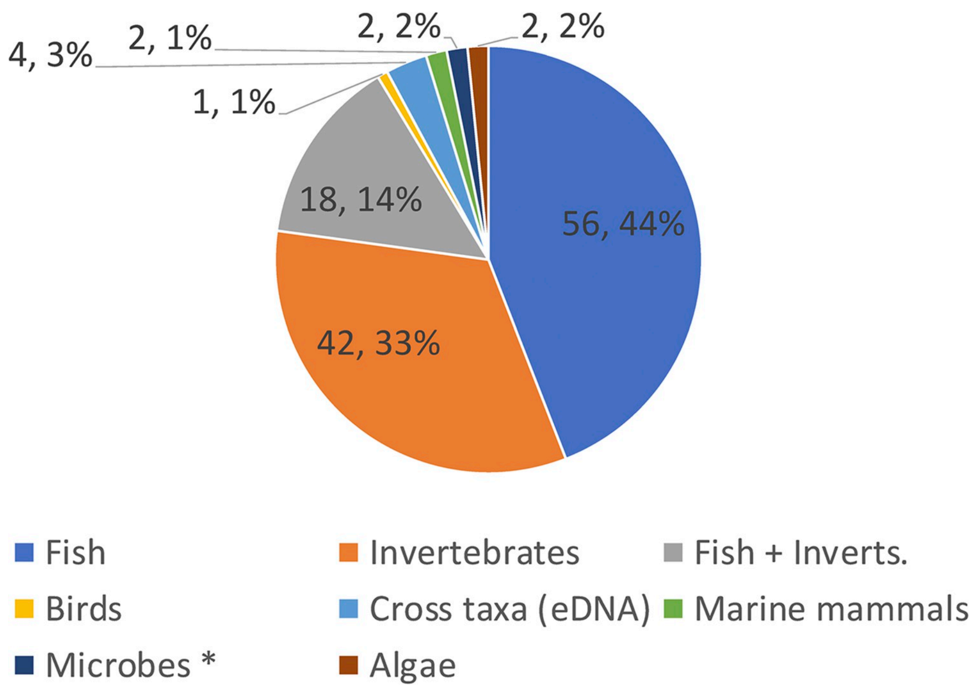

Fig 5. Pie chart showing the number and percentage of research articles by taxa (fish 56, 44%; invertebrates 42, 33%; fish + inverts. 18,14%; cross taxa (eDNA) 4, 3%; microbes 2, 2% (*including protists and protozoa); marine mammals 2, 2%; birds 1, 1%; algae 2, 2%, values based upon 116 research articles up to 2023).

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have contributed towards it, mimicking structural aspects of a natural reef and counterbalancing reef degradation and declining fish stocks [14] but also introducing risks associated with invasive species (Table 1, Section 8). The major groups of organisms associated with OGP will be discussed below.

4.1. Fish distributions

4.1.1. Structural complexity. OGP provide a large surface area (habitat) for the aggregation of large numbers of fish [15]. The three-dimensional arrangement of structural features over the seafloor surface is a fundamental property of coral reefs [16]. This complexity is positively linked to biodiversity and carrying capacity of habitats in both temperate and tropical ecosystems [17–19], with a possible relationship with their ability to recover from degraded states [20]. The ecological importance of complexity is often related to sheltered spaces and physical niches. For example, many OGP have a crossbeam at or near the bed (Fig 6) that are often either partially or totally undercut, creating a crevice, named by Love and York (2006) [21], as the "sheltering habitat" (Fig 7). Off California, a wide range of larger rockfish species occupy this sub-habitat. Similarly, "dwarf" and other small, schooling species tend to avoid the undercut crossbeam areas.

Another study by Meyer-Gutbrod and colleagues (2019) [22] in Southern California examined fish assemblages associated with structural elements of the platform structure, including the major horizontal crossbeams outside of the "jacket" (the platform substructure, typically fabricated from steel welded pipes and secured to the sea floor with steel piles), vertical jacket legs, and horizontal crossbeams that span the jacket interior. Fish densities were higher in transects centred directly over a vertical or horizontal beam, particularly along horizontal beams spanning the jacket interior, relative to either horizontal or vertical beams along the jacket exterior. The

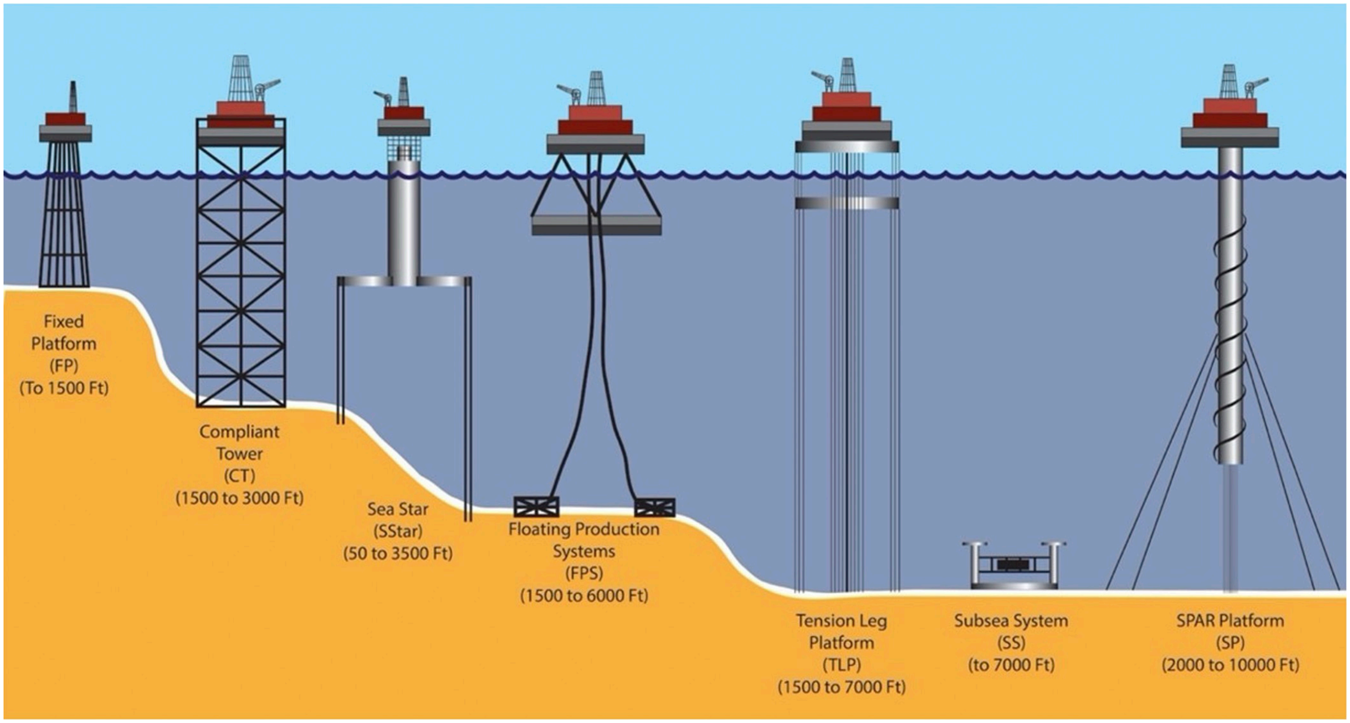

Fig 6. General schematic of platform structures (adapted by E. Carr after Scarborough Bull and Love, 2019). Anchored platforms vary in depth from shallow water (left) to 1,500 ft to the SPAR Platforms at 10,000 ft. The complexity of the structure also varies providing different levels of habitat provision.

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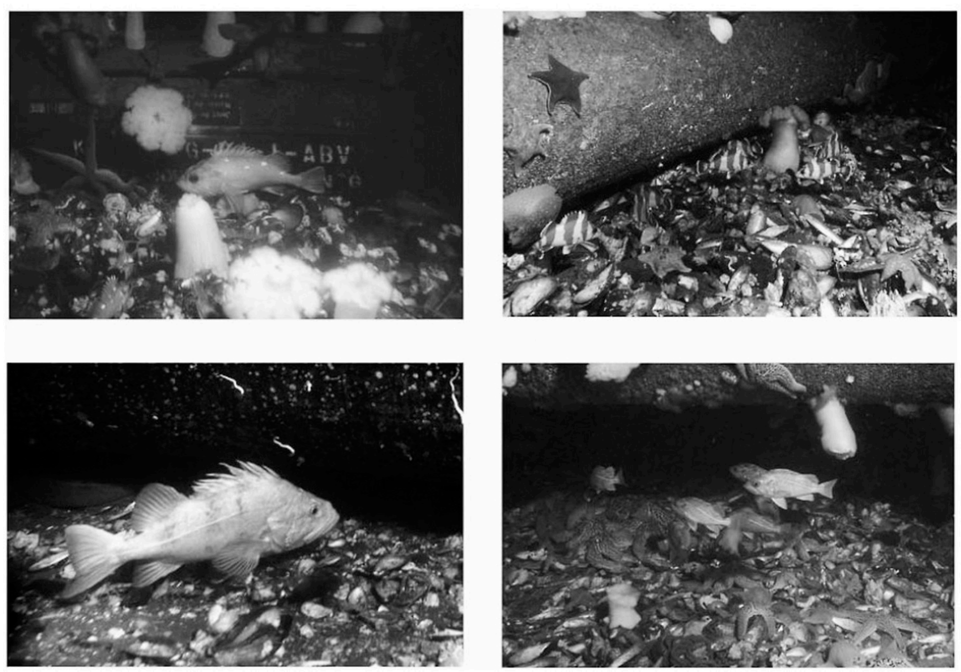

Fig 7. Extracted from Love and York [21] "Examples of four types of bottom beam structure: (A) at least some of the beam was visible, but the full width of the beam rested on the sea floor (greenspotted rockfish, *Sebastes chlorostictus*); (B) the beam was partially exposed, remaining in contact with the sea floor at its bottom, not its sides (flag rockfish, *S. rubrivinctus*); (C) the beam was completely exposed and formed an open crevice less than 0.5 m high (cowcod, *S. levis*); (D) the beam was completely exposed and formed an open crevice more than 0.5 m high (vermilion rockfish, *S. miniatus*)".

https://doi.org/10.1371/journal.pstr.0000104.g007

position of the "habitat" within the overall structure is an important characteristic affecting fish behaviour. The topping of platforms (the removal of surface structure to a specified depth) can result in the potential loss of 21% to 45% of the taxa present compared to the active platform. This agrees with the findings reported in Ajemian and colleagues [23], where toppling a platform (severing supporting legs and depositing OGP superstructure on the seabed) considerably altered the fish community structure on the platforms via removal of vertical complexity.

4.1.2. Water depth. Fish biodiversity at platforms varies across the water depth gradient. For example, quantitative analysis of ROV footage at 2 platforms (Dogger bank, German North Sea) show highest diversity and abundance at depths of 45 to 50 m around the footings and base of the platforms, with rock dump adding to the structural heterogeneity preferred by gadoids and reef-dependent fish. Variability in biodiversity between these 2 platforms may reflect abiotic (age) differences between the platforms and the seafloor heterogeneity offered by the presence of rock dump [24]. Similarly, fish recorded at California platforms are often reef-dependent and one group, the rockfish (genus *Sebastes*), dominates the community structure. Pelagic or semi-pelagic species (i.e., jacks, tuna, herrings, anchovies, and pelagic sharks) are either absent or very transient. Most of the fish living around these platforms (and nearby natural habitats) were relatively small (20 cm or less in length) [25].

Platform studies in the Gulf of Mexico (GOM) have reported depth as the most important driver of fish abundance and composition patterns, mainly thought to be due to food limitations that correlate to decreasing light [23,26]. Around most platforms, there are generally 2 fish assemblages: one in the midwaters and a second associated with the platform bottom [10]. However, many studies suggest that depth-specific patterns are a result of a complex suite of factors that require examination in greater detail [24,27,28]. For example, in common with species of natural reefs [29], many platform fish species alter their distribution as they mature (ontogenetic shift). Thus, juvenile fish around shallow water platforms may migrate to deeper waters as they grow (e.g., *S. paucispinis*). In contrast, in deeper waters, the population remains associated with the platform at the base [25]. Indeed, variations in the depth distribution of fish can vary over short time scales (e.g., diel variation) [30].

Artificial lighting at night (ALAN) is becoming a global problem often related to offshore man-made structures and vessels but also coastal conurbations [31]. Light at operational OGP has also been shown to influence the depth distribution of fish in the GOM with greatest numbers of fish counted in the shallow portions (<30 m) of lit platforms during the day, whereas for unlit platforms fish were mainly found at mid waters (30 to 60 m) [30]. Notably, fish numbers fell dramatically at both platform types at night, and while gear and sampling bias were partly responsible for this, some level of diel change caused by lighting is inferred, perhaps reflecting foraging behaviour or species avoiding nocturnal predation. Confounding factors such as input of food waste at manned platforms, versus unmanned or decommissioned platforms, may impact abundance of scavenger species. Thus, it is not yet possible to conclude consistent diel patterns in fish movements at platforms. More information on the effects of ALAN are needed [31].

4.1.3. Geographical variation. While research effort is uneven worldwide, studies from tropical regions suggest that fish biodiversity at platforms varies on a macro spatial scale across latitudes. In the Gulf of Arabia (average temperature 24˚C, salinity 44), platforms were shown to have a positive influence on fish diversity, correlated with proximity to the platforms, possibly as an indirect protection benefit of the safety exclusion zones around the platforms [32]. Fish species recorded included some rare for this region: such as ocellated waspfish (*Apistus carinatus*), crocodile toothfish (*Champsodon nudivittis*), Indian halibut (*Psettodes erumei*), and spotless lefteye flounder (*Arnoglossus aspilos*). The role of platforms as a refuge for rare species warrants further investigation.

In Northwest Australia, the number of fish species recorded was higher than from other latitudes (at least 57 fish species from 20 families were identified at a platform at 130 m depth compared to 40 species in GOM [30]; 10 species in North Sea, [26]; and 32 and 33 species in Adriatic and Ionian Seas [33]). The number of species present was uniform at different depths (21 to 28 species) suggesting habitat niche partitioning, and it was deemed likely that the fish present at the platform were rare to nonexistent in the surrounding Northwest shelf, due to lack of habitat and pressure from trawler fisheries [34]. Additional contributory factors to the high species number may include structure age and size/depth (23 years, 130 m) and improvements in monitoring methods. Comparisons between studies using different methods or between regions with specific abiotic and biotic environmental conditions are complex. For example, greater fish species numbers were reported in California (79 species in mid-water section of platforms); however, these numbers were obtained from an extensive dataset of 186 submersible or ROV dives over 18 years at 23 platforms, representing greater sampling effort [25].

4.2. Epifauna and benthos

Platforms can be an important source of habitat not only for fish, but also for epifauna, sessile, and mobile animals associated with surfaces (such as anemones, sea stars, and corals) [35–37] and the organisms that inhabit the sediments around the base of the structure (benthos). Hard structures may support assemblages rare in the surrounding areas, particularly in regions such as the Northern North Sea, where the seabed is predominantly characterised by soft sediments. OGP surfaces have been found to support *Desmophyllum pertusum* (formally *Lophelia pertusa*), an endangered stony coral (CITES list) with a preference for waters of 6 to 8˚C and at depths up to 1,000 m from below 50 m and with a higher growth rate compared to natural reefs [38–40]. *Desmophyllum* is the main reef-building species in deep-water coral reefs and creates complex habitats with high biodiversity on shelves, slopes, and seamounts [39,40]. *Desmophyllum* reefs can increase biodiversity by 3 times and are expected to play a role in the spreading of fauna [41]. *Desmophyllum* reefs qualify as vulnerable under the United Nations General Assembly Resolution 61/105 [42]. Motile invertebrates are also associated with offshore platforms that provide refuge and food availability [2,43,44]. While corals are important members of the epifaunal community, other groups also play a major role. For example, suspension feeding crustacean, such as amphipods, can clear water at an impressive rate and contribute faeces to the organic pool and while individually small, populations can reach high densities of up to 1 million individuals m^{-2} [44].

As well as the physical presence of the platform itself, a variety of operational platform-related activities (e.g., drilling, surface cleaning and maintenance, wastewater production) have the potential to influence the condition of the seafloor habitat near the platform [45]. Bacteria respond rapidly to environmental changes, such as hydrocarbon contamination due to installation and production activity around platforms, with a corresponding increase in hydrocarbon degrading bacteria and petrogenic polycyclic aromatic hydrocarbons (PAHs) [46]. Microbial community responses tend to be rapid (hours or days) compared to higher trophic levels [47], and crude oil consists of a mix of hydrocarbons and other compounds, including heavy metals [48], which will impact benthic microbial diversity. Most studies on benthic or microbial biodiversity in response to oil and gas activity have focused on acute pollution events [12], such as the Deepwater Horizon disaster [49], and not on the continuous chronic effect of the presence, or disturbance through removal, of the artificial structures on the surrounding seabed. Gillett and colleagues [50] examined the habitat condition of the benthos around 4 platforms in Southern California, and although there was an increase in low-level toxicity, the benthic macrofauna abundance near the platforms (250 m) was similar to reference sites away from the platforms, albeit at slightly lower in density.

However, the greatest impact on benthic communities is likely to be closer to the platform, and although industry often collect this data as part of routine and planned environmental surveys, this data is not easily available, nor is it collected for the purpose of scientific analysis which can make comparative analysis problematic. As well as changes to the invertebrate community on the artificial structure, offshore platforms have been reported to enhance surrounding benthic communities by altering flow patterns and subsequent deposition of organic matter, known as the "halo" effect [51,52]. These changes within the surrounding seabed are reflected in the macrofaunal and microbial community assemblages, and the sediment biogeochemistry. The affected area can be 15 times larger than the structure [53]. In the North Sea, active platforms have a 500 m exclusion zone in place, which limits anthropogenic activities such as trawling and dredging. Continental shelf sediments are increasingly acknowledged as significant stores of carbon [54] and these exclusion zones around active platforms provide an unofficial "marine protected area" status for the surrounding seabed, protecting the carbon stocks (and macrofauna within the sediments) from potential impact through anthropogenic activities [55]. With decommissioning activity in the North Sea under the regulatory framework of OSPAR, Decision 98/3, all platforms must be removed (unless a derogation has been granted), and this removal activity is likely to disturb the benthos on and around the structure, although these impacts have not yet been quantified [50]. The majority of work on invertebrate benthos has been on the structure of the communities and their abundance and biodiversity (Fig 8), with little consideration on the impact of the benthic biodiversity in the soft substratum around these structures.

4.2.1. Water depth. As with fish distribution, depth has consistently been a key variable in determining epifaunal abundance and community structure on platforms worldwide [35,37,56]. In shallow waters, changes in light level, wave force, and tidal exposure restrict the number of species, leading to competitive dominance by some specialists (i.e., mussels [*M. edulis*] and macroalgae). Similarly, increased suspended sediments or hypoxia at the deepest sections of the platforms may be limiting to some species (i.e., filter feeders) [56]. Vertical zonation of species in surveys of invertebrate assemblages, on platforms off California, show the shallower portions (<20 m) to be a thick carpet (>15 cm) comprising mussels (*Mytilus californianus*, *M. galloprovincialis*), encrusting bivalves (e.g., rock scallops, *Crassodoma gigantea*), and barnacles (*Megabalanus californicus*, *Balanus nubulis*). Below 20 m, water depth was the major driver of the invertebrate assemblages with little geographic variability among the platforms. At about 20 m, the mussel-dominated community gave way to assemblages characterised by other taxa. While the precise mix of these organisms varies among platforms, the major species include strawberry anemones (*Corynactis californica*), white anemones (*Metridium* spp.), and vase, foliose, and barrel sponges. Among other structure-forming sessile invertebrates, common deep-water coral species include *Desmophyllum pertusum*, *Leptogorgia chilensis*, *Placogorgia* spp., and *Acanthogorgia* spp. [36].

A similar depth gradient for invertebrate communities has been identified in temperate regions [24], and a study on the marine fouling assemblages on offshore gas platforms in the Southern North Sea [35] reported that species richness initially increased with depth, but decreased after 15 to 20 m. Three of the 5 platforms examined were fully covered with marine fouling at all depths, but composition and abundance of fouling varied over depth and along the distance from shore gradient. This depth and distance to shore gradient was also identified on epifaunal communities associated with 8 Dutch and 9 Danish offshore platforms [2]. Spatial analysis identified a northern and southern geographical cluster, and communities closer to the seafloor were characterised by higher diversity and species richness compared to communities found closer to the surface (<10 m). However, a platforms' distance from shore may not always influence species composition, as found in California [25].

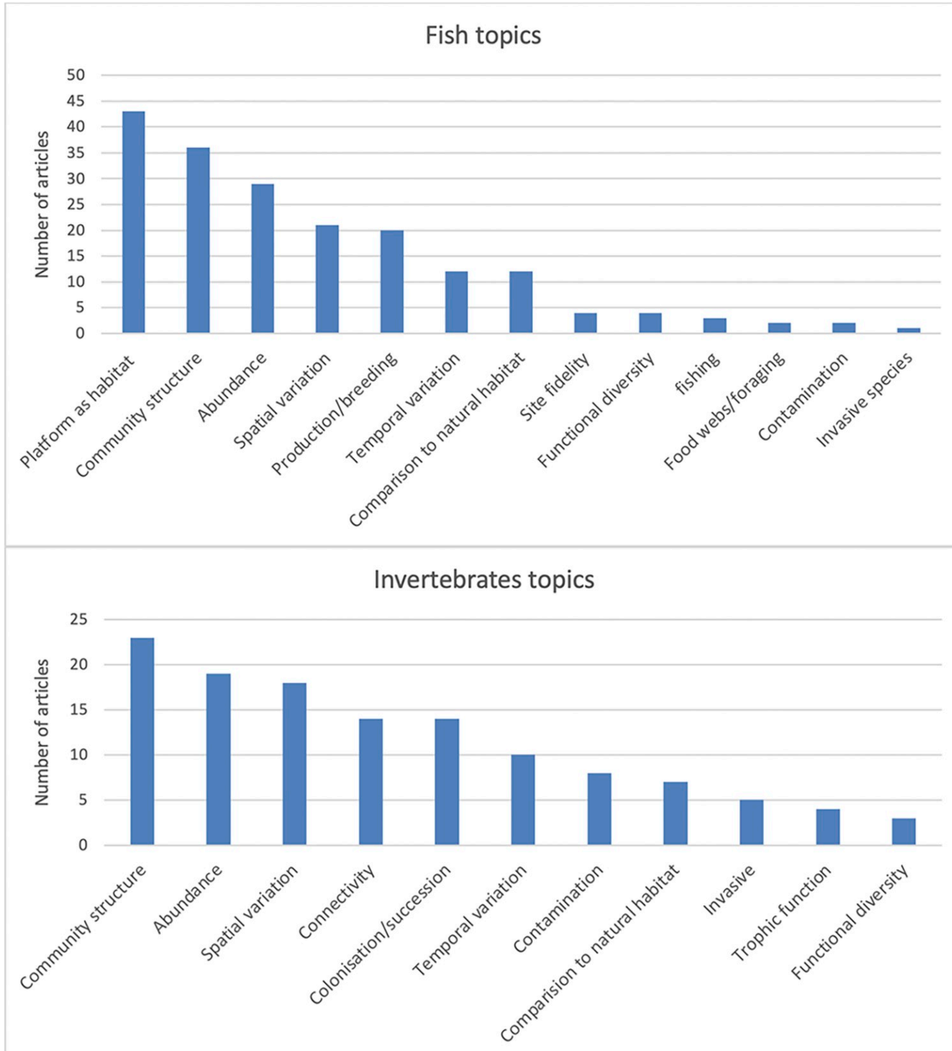

Fig 8. Ranking of research by topics concerning fish (above) and invertebrates (below), based upon 116 articles up to 2023 (headings assigned by authors).

https://doi.org/10.1371/journal.pstr.0000104.g008

Depth can act as a limiting factor for some sessile species, for example, corals are typically found at depths 60 to 140 m [57] and *Tubastrea* species occur from the surface to 75 m and are almost nonexistent below 100 m, while soft corals (*Nephthea* sp. and *Scleronephthya* sp.) are found at depths >100 m, and macroalgae are limited to the photic zone [34]. However, other sessile species, such as anemones (*M. dianthus*) and sponges, are commonly found at all depths [34,58]. Depth zonation on the surfaces of artificial structures may be influenced by the distribution of larvae in the water column, growth conditions (light, temperature, SPM), and competition or predation post-settlement [2,3,57,58].

4.3. Shell mounds

When shellfish (e.g., the mussels: *Mytilus californianus* and *M. galloprovincialis*) on the upper portions of the platforms are detached, through industry-mandated jacket cleaning, mortality or storms, they sink and accumulate in areas of low current flow creating local shell mounds. Such shell mounds are likely to occur in many regions, dependent on local scour forces;

however, scientific investigations have been limited to the Californian continental shelf. California shell mounds can be substantial (over 6 m high and 61 m in diameter) and create a hard, heterogenous substratum on the soft seafloor, providing both habitat and food for other organisms. Research has been conducted on "active" shell mounds (associated with intact platforms) and on "remnant" shell mounds (platforms removed) [59].

Water depth is probably the most important factor influencing the invertebrate assemblages of active shell mounds [60]. Densities of invertebrate taxa are often very high, for example, several surveys reported densities of sea star species (e.g., *Pisaster giganteus*, *Pisaster ochraceus*, *Pisaster brevispinis*) that were 30 to 100 times higher than reported in natural habitats [61–63]. Studies have also been conducted on 4 "remnant" shell mounds, the "4-H" platforms, in the Santa Barbara Channel. These mounds are within a depositional oceanographic regime and the shells were mostly covered by sediment. The invertebrate assemblage differed from an active mound at the same depth [59]. The likely reason for these changes is the cessation of the food and shell subsidies (mussels and associated organisms) to the benthos [62] previously provided by deposition from the standing platforms. There is the tacit suggestion that remnant shell mounds will gradually be covered with sediment. However, surveys conducted in 2019 on 2 additional remnant mounds, portray a more complex picture [37]. These shell mounds, where jackets were removed 30 years before, were composed of exposed shells, free of sediment, and supported a diverse fish and invertebrate assemblage and suggest a longer-term impact of artificial structures on marine heterogeneity. Knowledge on shell mounds in other regions, or at other types of artificial structures, is currently lacking.

4.4. Algal biodiversity

While little is reported on algal biodiversity on OGP, communities often consist of foliose or filamentous red [61] or green algae (*Cladophora rupestris*, *Ulva lactuca*, *Ulva intestinalis*) [26]. Notably, in the tropical waters of Northwest Australia where light can extend to 70 m, encrusting brown algae comprised almost half of the total surface growth in the upper 25 m of the platforms [24]. These brown algae decreased markedly below 25 m and were followed by hard corals (*Tubastrea coccinea* and *T*. *micranthus*) as the next most common surface coloniser. These coral species may out-compete other coral species especially on new/cleaned surfaces [34,63].

5. Food webs

Food webs represent the flow of energy through trophic levels from the primary producers through various levels of consumers. Primary producers on and around OGP comprise attached macroalgae and phytoplankton but also some microbial forms such as cyanobacteria and diatoms [64] attached to the platform surfaces. Organic matter (trapped within bivalve colonies) provides an additional food resource. In contrast, the carbon in coastal food webs is often mainly derived from microphytobenthos (benthic diatom mats) [65,66].

The influence of phytoplankton on the growth of platform epifauna was modelled, as part of a wider study, using chlorophyll a data, on the m-km scale, from 34 platforms, over 18 years in the North Sea [56]. The model predicted phytoplankton to be a key driver in determining epifaunal growth, (along with water depth) in a nonlinear relationship, with epifaunal growth stabilising at higher phytoplankton concentrations (0.93 mg Chl a m^3). This suggests other limiting factors, such as competition for space, also influence epifaunal growth.

Sessile and mobile invertebrates and planktivorous/herbivorous fish feed upon phytoplankton and suspended organic material in prevailing currents associated with the platforms [67,68]. These primary consumers, in turn, provide food to mobile secondary consumers [69] and finally apex predators (i.e., large predatory fish and seals) [34]. For example, harbour seals (*Phoca vitulina*) are reported to rest on platforms 200 km from shore and these artificial haul-out sites may allow individuals to travel further offshore to forage [70].

In addition, birds have been noted to feed off platforms, for example, the European herring gull, (*Larus argentatus*) was reported to catch lumpsucker (*Cyclopterus lumpus*) in surface waters then consume the catch on the platforms [24]. More recently, some species have begun to colonise offshore structures, as noted for the black-legged Kittiwake (*Rissa tridactyla*) in the North Atlantic and often achieving higher productivity than in a natural setting [71]. Against a general trend of climate-driven seabird decline [72], this refuge may become an important factor to maintain populations [71].

Finally, the production of faeces (and pseudo faeces) by associated biota combined with the action of sediment microorganisms and meiofauna, cycle nutrients, and organic matter back to primary producers [73].

6. Productivity and abundance

To fully understand pressure responses, habitat value, and ultimately improve conservation planning, studies have been increasingly focusing on the functional ecology of marine ecosystems [74–76]. The biodiversity of an ecosystem can often determine how the overall system functions [77–79] and indicators of ecosystem function such as secondary production (i.e., fish biomass) can be measured and rates and relationship to biodiversity compared between settings [64,80]. Research on biological production at platforms has focused mainly on fish. In assessing fish abundance, secondary production represents the formation of new biomass from the growth of all individuals in each area over a specified period and indicates energy flow through an ecosystem. It is a powerful tool for evaluating ecosystem function because it incorporates multiple characteristics of a community of organisms such as density, body size, growth, and survivorship into a single metric.

Platforms off California have the highest fish production per m^2 of seafloor of any marine habitat studied [15]. There has been relatively little fishing around California platforms and partly because of this, the reproductive output for some species is higher than for natural habitats [81,82]. However, in the Gulf of Arabia, a net positive impact of the platforms on fish abundance did not equate to increases in fish biomass (g/m^3 wet weight) [32]. This discrepancy may demonstrate the patchy distribution of fish, smaller-sized species, or a nursery function. Notably, most California platforms serve as nursery grounds for several fish species (primarily rockfish, genus *Sebastes*, and the blacksmith damselfish, (*Chromis punctipinnis*)) [83]. During a given year, hundreds of thousands of juveniles may recruit out of the plankton to a single platform and densities were highest in midwaters and around bases. However, because survival of young fish varies greatly between years, it is not possible to predict the densities of young fish around platforms in any given year. On average, densities of these young fish are lower on shell mounds and natural habitats compared to platforms. Based on manned submersible surveys, Love and colleagues [83] estimated a minimum of 430,000 juvenile bocaccio (*Sebastes paucispinis*) at 8 platforms, *"equating to about 20% of the average number of juvenile bocaccio that survived annually over the species' entire range and contributing 0.8% of the additional amount of fish needed to rebuild the [overfished] Pacific Coast population."* Although some variance was observed, 10,000 to 30,000 fish were found at platforms at any one time, and since more than 1,000 platforms are found in similar water depths, these structures influence the fish abundance of the region, especially reef fish species that require structure.

Similar findings were reported in the central Gulf of Thailand, where a study by Harvey and colleagues [10] estimated that the platform biomass of fish was at least 4 times higher per unit area than some of the world's most productive coral reefs. A total of 43 species of fish were recorded on the platforms and 5 reference sites with most fishes on platforms categorised as coral reef or coral reef-associated species. Secondary production was observed in the region, where a spawning aggregation of bigeye trevally (*Caranx sexfasciatus*) was identified at a platform situated in the same area [84]. It was concluded that the platform site had characteristics conducive to spawning for multiple species [85–87]. This work demonstrated that platforms can provide suitable conditions for reproductive success. This is also supported by a novel analysis using imaging sonar [88] which compared 7 toppled jacket systems to an adjacent coral reef and found that although biomass did not vary significantly, larger individuals were found at the rigs to reef sites. It has also been found from the Arabian Gulf that the diversity of reef fish is greater associated with platforms than on related natural reefs sites. This was partly attributed to overfishing but also suggesting the platforms assemblages would not serve as reservoirs for the diversity of natural reefs under current conditions [89].

Species have also shown seasonal increases in their abundance in areas with high densities of artificial structures in the North Sea, such as platforms, wrecks, and turbines [90]. Data from baited fish traps at the decommissioned Miller platform found significant numbers of Saithe (*Pollachius virens*) and suggest a series of turnovers of individual fish using platforms, perhaps regulated at seasonal scales [91].

Several factors will affect species vulnerability. For example, aggregate extractions and other marine developments will pose a threat if they are located at or near to important spawning areas where fish aggregate. Although there is the potential for increased foraging opportunity, the aggregative behaviour and site fidelity exhibiting by a range of species make them more vulnerable to anthropogenic impacts (fishing) and predation [84,92]. The way that fish species interact with highly developed regions, including their productivity, abundance, and vulnerability, provides an indication of potential impacts for future addition and decommissioning of platforms [90]. While there is consensus that artificial structures influence fish abundance at the local scale, more evidence is required on the potential impact of structures on fish recruitment to the wider marine environment [34] and the impact of their removal.

7. Connectivity

The marine life associated with OGP are part of a wider ecosystem of interconnected populations [10,93]. The movement of individuals and genes, e.g., fish, gametes, and larval stages of sessile invertebrates carried to and between platforms and natural systems is known as connectivity. The biodiversity of offshore structures should largely depend on the supply of propagules and the size of the available space. However, establishing assemblages are often quite isolated from donor systems and represent only a subset of the available genetic diversity from the donor population. There is some evidence that this "filter" acts to reduce the genetic diversity associated with some populations on offshore structures, for example, the serpulid worm —*Pomatoceros triqueter* [94].

The ecological benefits of connectivity are: (1) population dispersal; (2) settlement, shelter, and foraging opportunities; and (3) enhanced genetic diversity and resilience against multiple stressors. Disadvantages of connectivity are the potential spread of invasive non-native species or infectious disease agents [95–99].

The world's ocean is dynamic and changing and so it is natural that marine species extend and reduce their ranges based on their relative tolerance and requirements. Nishimoto and colleagues [100] modelled the potential trajectories of fish larvae at 3 platforms off California. They found that, while there was seasonal variability, larvae were most likely to travel northwards and be entrained in the Santa Barbara Channel. The implications are that fish larvae produced at platforms may travel substantial distances before potentially setting out on either natural habitats or other platforms. Also, juveniles of the economically important rockfish, bocaccio (*Sebastes paucispinis*), tagged at a platform were recaptured years later inhabiting natural reefs [101] demonstrating that at least some of the young that recruit to platforms survive and seed natural habitats, confirming the role of platforms in the wider ecosystem. Madgett and colleagues [84] reported that platforms in the Gulf of Thailand modify/influence the movement patterns of mobile species and contribute to regional reproductive output, where fertilised eggs and larvae from the platform location may travel to the nearby natural reefs or mangrove forests (approximately 150 km away). In temperate regions, a study by Henry and colleagues [102] simulating the connectivity of *Desmophyllum pertusum* predicted that platforms in the North Sea play a role in conservation of the species and restoration of marine protected areas.

However, novel species transported to an ecosystem naturally or by man that become established and cause "damage" to the recipient ecosystem are termed "invasive" [103]. In addition to the sometimes-careless transportation of novel species in ballast waters and attached to ships, we are also providing new habitats that may encourage the spread and establishment of invasive species [104] and these include offshore structures and pipelines. In some cases, offshore activity fulfils both roles, with decommissioned structures being moved to new locations, taking their ecological complement with them [105,106]. Efforts to model the importance of rig sites and artificial reef development as "stepping stones" for the spread of invasive species [107] requires more attention as management options for invasives are limited and expensive [108] but knowledge of linkages that could be prevented or broken would be an advance in their control.

Lowe and colleagues [29] demonstrated that some reef species (rockfish, *Sebastes* spp. and lingcod, *Ophiodon* e*longatus*) showed strong site fidelity to platforms. Fish tended to move from shallower platforms more often than from a deeper one. Lowe and colleagues [29] state that fish "*can navigate between the habitats [platforms and natural habitats] and that platform habitat*, *despite having higher densities of conspecifics*, *may be of higher quality to some individuals than natural reefs*." Anthony and colleagues [109] translocated fish (rockfish and lingcod) away from 3 platforms and to natural reefs (11 to 18+ km away). Approximately 25% of these fish returned to their home platforms, some taking as little as 10.5 h to return with lingcod having the highest probability of homing.

Understanding the level of residency on platforms 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. Studies to-date indicate connectivity between structures and the wider environment. However, the impact of artificial structures on modifying the movements of mobile species or the dispersal of gametes of sessile species remains a critical knowledge gap [110]. More molecular work is needed not only to understand the connectivity between structures but also the molecular consequence of population isolation and genetic drift.

8. Comparisons to natural habitat—"Novel ecosystems"

In terms of system heterogeneity, the critical aspect is the variation in biodiversity between the community of organisms that develop on a structure and the surrounding natural ecosystems (beta diversity). This will depend on several factors including the contextual variation between the natural habitat and the hard substrata offered by the platform, the relevant supply side ecology and, often, operational activities such as local waste disposal and biofouling removal.

Often platforms are emplaced in surroundings dominated by soft substrata of sands, silts and mud immediately providing a new type of substratum for colonisation. Secondly, the material they are made of is man-made, largely marine concrete and/or metal. Thirdly, their vertical relief and an open lattice structure offer multiple niches to biota and allows easy dispersal of marine life (Figs 6 and 7). Fourthly, the upper parts of platforms introduce new intertidal zones which allow the settlement of intertidal biota, including macroalgae, in offshore locations [111,112]. Finally, the presence of the platforms physically alters localised water flow and the seafloor conditions, leading to local scouring or changes in sedimentation patterns [73]. For example, all platforms on the Californian continental slope are sited on soft seafloors, although in some instances (e.g., Platforms Hidalgo, Grace, A, B, and C) natural reefs exist within a few kilometres of the platform. The fish communities and abundance at platforms and shell mounds were almost totally different from, and far more diverse, than those of natural seafloors [25].

These distinct habitats result in the formation of "novel ecosystems," where an ecosystem has been altered by human activity and has distinct ecological characteristics not found at natural sites in the region [113,114]. For example, platforms can act as "stepping-stones" in soft sediment-dominated environments by facilitating the presence of fish and invertebrate species that might not otherwise occur in these areas [33,100,115]. Non-native species (including invasive species) can colonise and establish beyond their usual range, and thus influence the native habitats and their associated environment [56,93,116]. However, this "stepping-stone" theory is ecologically complex, as most of the fauna on many artificial reefs comprise typical "fouling communities" as opposed to a true reef community although some species overlap between the two habitat types [105,107]. Little is known about the fitness of individuals that occupy artificial reefs [117] compared to natural reefs, artificial reefs that provide lower fitness advantages may become "ecological traps" (increased mortality rates and reduced fitness) [118]. A study by Madgett and colleagues [119] on oil and gas pipelines found that although the pipeline habitat had an assemblage composition more similar to soft sediment than reef habitats [120], on a functional level (using a trait-based approach), the pipeline and reef habitats were more similar and may indicate that they share specific physical drivers of community structure (e.g., structural complexity) and environmental conditions (e.g., hydrodynamics, food sources). This study suggested that the concept of "novel ecosystems" reflects greater complexity than revealed by measures of community composition. Further research is needed to investigate the ecosystem function of platforms and the fitness of species associated with oil and gas structures.

Empirical scientific studies comparing platforms to natural reefs are lacking [15]. Where a novel ecosystem has emerged with potentially significant ecological value, it is recommended that offshore platforms can be assessed under the novel ecosystems concept using existing decommissioning decision analysis models as a base [114]. Responses by fishes to artificial habitats have been reported to be species-, location-, and habitat-specific, [6,121,122] stressing the importance of assessing decommissioning options on a case-by-case basis.

9. Environmental context

It is important to understand the environmental context of the different regions where platforms are concentrated. Every ecosystem is different and needs to be evaluated as such, and just because reefing has been successful in a certain area (e.g., the GOM), it does not mean it would automatically be an ecologically beneficial exercise in other regions such as the North Sea, California, or Australia. Environmental variables such as nutrient input, salinity and surface water temperature, and anthropogenic pressures vary across regions, and have a fundamental impact on marine ecosystems including those associated with artificial structures. For example, epifaunal richness is partially explained by regional oceanographic variations

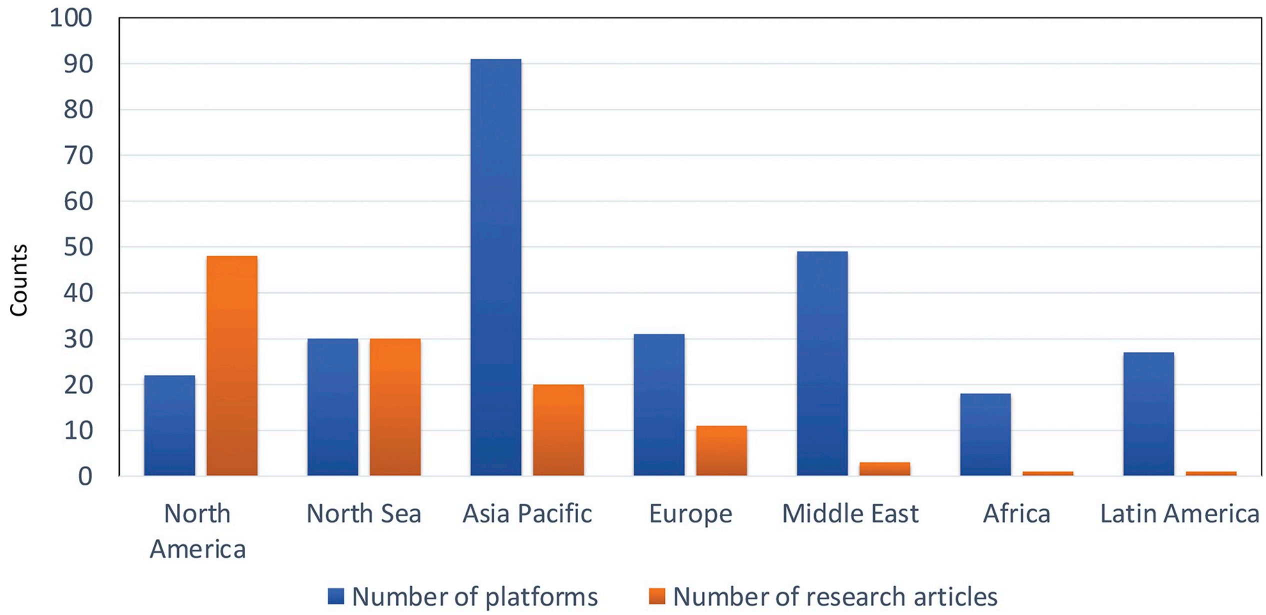

Fig 9. Number of articles vs. number of platforms by region, as of November 2023 (Asia Pacific includes South China Sea, New Zealand, and Australia; Europe includes Mediterranean and North East Atlantic). Source: Baker Hughes (rigcount.bakerhughes.com).

https://doi.org/10.1371/journal.pstr.0000104.g009

including sea surface temperature and suspended sediment concentration [58,111]. The direction of prevailing currents can influence both growth and species richness, depending upon the orientation of the platforms, presumably due to food and larval propagule supply [69,123] and current direction is a significant consideration for the dispersal of larvae and propagules. However, there is little empirical data on the potential role of artificial structures as havens within the wider scale environmental context (i.e., by providing shading and shelter). Examples of differing environmental context are described below.

Considerations must vary across regions, and it is apparent from the literature that some regions with significant offshore oil and gas extraction are underrepresented, for example, Latin America returned no peer reviewed literature in the current search although there may be many "grey" studies. Unsurprisingly, North America and the North Sea returned the largest number of publications. Asia Pacific, Middle East, and West Africa were intermediate (Fig 9). This important bias may be partly due to the growing use of floating oil production operations and jack up rigs compared to fixed platforms in some regions as well as varying research priorities. Only 2 of the 82 articles examined multiple regions [110].

9.1. Gulf of Mexico

There are over 4,500 petroleum platforms distributed throughout the GOM, from Alabama to Texas, exposing platform-associated ecosystems to a relatively wide range of abiotic environmental conditions [63]. The Mississippi River has an important biogeographic influence on the variation in environmental conditions in the GOM and general fish populations of offshore platforms [124–128]. Salinity gradients and hypoxic events greatly influence both the populations of fish close to coastal Louisiana and seasonally within the water column of platforms along the entire Gulf coast. As a result, euryhaline fish species of lookdowns (*Selene vomer*) and sheepshead (*Archosargus probatocephalus*) are common in the shallow waters associated with platforms off Louisiana. The north-central and northwestern regions of the GOM consist almost exclusively of soft sediment habitats, and it is estimated that platforms contribute nearly 30% of the entire Gulf "reef" habitat and biodiversity [115]. The lack of reef habitat may have been a limiting factor for snapper populations during the first 100 years of the fishery and OGP platforms then contributed reef habitat across the Gulf that increased the carrying capacity of the red snapper fishery [129,130]. Red snapper is now one of the most popular recreational and commercial species in the northern GOM and fish of less than 8 years are now most abundant in areas with more platforms and artificial reefs [131].

Despite the variation of environmental conditions introduced by Mississippi River discharge, a study by Bolser and colleagues [128] found that many GOM fishes were found to associate with platforms over a relatively wide range of environmental conditions and platform characteristics, suggesting that specific conditions and distinct platform characteristics may not be as important as the simple number of available platforms for determining the distributions of many platform-associated fishes in the GOM. In contrast, when focusing specifically on red snapper, a study by Brown-Peterson and colleagues [129] found that the vertical distribution of red snapper within platforms is significantly predicted by temperature, salinity, seafloor depth, and dissolved oxygen. It has also been reported that structure type is important for predicting the distribution and size of mature, but not immature female red snapper among various artificial reef types in the GOM [130].

9.2. California

Platforms off California are situated on a narrow continental shelf [25] that is subject to seasonal changes in nutrient input caused by coastal upwelling. This differs substantially from the thousands of platforms in the GOM [63] located both nearshore and offshore in waters across a range to trophic levels from eutrophic to oligotrophic conditions [25]. It is notable that beginning in the late 19th century and accelerating by the mid-20th century, the ocean off California has been subject to large-scale perturbations. Fishing, both commercial and recreational, [15] has been the most important source of these pressures, although both pollution and coastal development (particularly in-filling of wetlands), climate-mitigated changes in oceanographic variation (e.g., upwelling), have also had an effect, thus our present understanding of the seafloor assemblages does not reflect pre-perturbation conditions.

Offshore platforms in California provide a significant refuge for commercially important rockfish species [15,131] and contrary to observations in the GOM, California platform fish assemblages tend to resemble those found on nearby natural habitats [132]. However, unlike the GOM, there are no quantitative estimates of the extent to which platforms contribute to the total amount of "reef" habitat in the Pacific OCS region [7]. It is important to note that in California, where there are only 27 platforms, their role in providing habitat for economically important species makes individual platforms ecologically significant. Conversely, in more industrialized areas such as the GOM with thousands of platforms, the ecological value of an individual platform is not necessarily as high within a regional context and may not be an important ecological consideration [114].

9.3. North Sea

The North Sea has been considerably transformed by the oil and gas industry, and reserves have been exploited there for over 5 decades [102]. However, infrastructure is aging and wells are reaching the end of their economic life so there is now an emerging era of decommissioning required. However, there is a high degree of uncertainty regarding the environmental impacts of infrastructure removal and how environmental status will be impacted. With only a few North Sea sites decommissioned to-date, there are not many empirical studies on the environmental impacts of decommissioning compared to other regions (e.g., GoM) and understanding the scale of industrial impacts in the region remains a complex task.

There are important differences in environmental context between the North, Central, and Southern regions of the North Sea. The Southern North Sea is shallow (approx. 30 to 70 m) with depth increasing in a northerly direction (>100 m) [67] and seasonal stratification of the water column occurs in Northern and Central regions. In contrast, in the shallow Southern region, the water column is well-mixed. Deeper water and weak tidal currents in the Central and Northern North Sea allow residual deposits of drill cutting (DC) piles to accumulate and the legacy of historic oil-based mud continues to influence the distribution and abundance of benthic fauna at some platforms [69]. A study by Henry and colleagues [68] reported that impacts to benthic communities persist for at least 6 to 8 years in the Northern and Central North Sea but were undetectable in the South. Drill cuttings piles have also been reported to be microbiologically heterogeneous, dominated by known hydrocarbon-degraders, compared to nearby natural sediments [133].

It is apparent that there is a higher quantity of studies conducted in the Southern North Sea compared to the other 2 regions, mainly focused on benthic communities. In the Southern North Sea, a study by Almeida and Coolen [56] reported that macrofouling biomass reached maximum values at intermediate depth, and minimum values near the sea floor and surface and were mostly affected by depth, chlorophyll concentration, and proximity to shore. Surface temperature of the seabed did not affect growth rates of benthic organisms. This agrees with a previous study [35], where species richness showed a significant nonlinear relation with water depth from a low richness in shallow waters increasing with depth until 15 to 20 m, after which richness decreases again. Depth zonation of organisms on platforms in the Southern North Sea was also found to influence benthic communities [26] that concluded that "topping" or "toppling" decommissioning strategies could eliminate communities that are unique to the upper zones. Klunder and colleagues [73] investigated the long-term effects of a gas platform in the southern North Sea on the surrounding benthic community and reported clear variation in the grain size in the environment surrounding the gas platform, where a higher percentage of silt was found in the residual current direction (i.e., in the "shadow" area of the structure), while coarser sediment was found close to the artificial structure. This grain size variation affected the number of benthic fauna families and species composition in the vicinity of the platform and in the direction corresponding to the predominant currents.

Fish abundance has been reported to be mainly driven by the regional variations of water depth, sea surface temperature, and bed type [134] and an abundance and biodiversity of marine mammals have been observed around installations, with several taxon-specific correlations identified between number of sightings and environmental parameters (depth and latitude) or installation characteristics (installation aerial footprint) [70].

A regional comparison was conducted by Schutter and colleagues [2] where the effect of location and depth on epibenthic North Sea fauna using Dutch platforms located in the Southern North Sea at depths ranging from 26 to 46 m, and Danish platforms located about 400 km further north in seas ranging from 40 to 66 m in depth. Species diversity was not significantly different between geographical clusters and communities did not change significantly with depth. However, communities closer to the seafloor (maximum depth minus 5 m) were characterised by higher species diversity and species richness compared to communities found closer to the surface (<10 m).

Platforms in the North Sea have been reported to be biologically connected, with organisms originating from some platforms reaching and substantially augmenting those at others [35]. North Sea oil and gas installations have the strong potential to form highly interconnected regional network of anthropogenic coral ecosystems capable of supplying larvae to natural populations downstream, with larvae becoming competent to settle over a range of natural deep-sea, shelf and fjord coral ecosystems including a marine protected area [135].

10. Knowledge gaps and recommendations

10.1. Knowledge gaps

The research output described above greatly increases our knowledge of platform ecosystems and the impact on the marine environment. Cooperation between industry, academia and governance is developing (e.g., the INSITE programme) [135] and can further support the understanding of the multiple biological and physical variables of the system. INSITE is an independent research program funded by industry, "The Natural Environment Research Council" (NERC) and "The Centre for Environment, Fisheries and Aquaculture Science" (Cefas). The purpose is to better understand the influence of man-made structures on the ecosystem of the North Sea (REF: https://insitenorthsea.org/).

However, there remain a number of general but important deficiencies; observations of fish and invertebrate populations at platforms prior to removal/reefing are minimal or nonexistent in a number of global regions and even limited for offshore California, one of the best studied regions, globally.

The attraction/production debate is still on-going and central to the problem of establishing additional productivity is the knowledge of when and for how long different species are resident on a reef (site fidelity, [131,24]), and how species are directly interacting with the platform habitat. Although empirical studies comparing platforms to natural reefs are lacking, much research to-date has reported fish and epifaunal communities associated with platforms to be different. There is no data on the functional implications of these novel ecosystems associated with platform habitat, and it is therefore unknown if these systems have long-term ecological value. There has also been little research conducted on the impact of platforms on marine food web structure, and studies tend to focus on certain ecological components such as commercial fishes. The examination of diets and trophic interactions, and identification of sources of primary production incorporating the entire food web is needed to better understand the role and connectivity of platform habitats and is fundamental for the protection, management, and restoration of ecosystems.

The impact of artificial structures on modifying the movements of mobile species or the dispersal of gametes of sessile species remains a critical knowledge gap [110], and understanding the level of residency on platforms 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. In addition, comparison of growth rates and body burden of potential contaminants between fish at platforms and nearby natural reefs/seafloor will aid the comprehensive habitat assessments of platforms. This would provide a comparative basis for examining relative productivity, seasonal changes, and nursery function. Targeted long-term field monitoring and a variety of scientific techniques are required to address these knowledge gaps, for example, basic underwater observations and surveys, data analyses, and modelling to support biodiversity, density, biomass, and seasonal, annual production analysis using multiyear scientific observations. A more strategic approach, using accepted biological fieldwork standards including concomitant observations at nearby seafloor and natural reefs, would be beneficial to the industry and society and there is some progress in this direction. For example, the INSITE Programme [135] and ongoing discussion in terms of the commissioning of offshore wind sites and licensing. This also includes the ideas of net gain and how a more holistic view should be adopted [136]. This should eventually lead to more understanding of the entire package of ecosystem

Table 3. Knowledge gaps and their impact on understanding (ranking based on authors' opinions).

Number	Knowledge gap	Impact (H/M/L)	Likelihood of timely resolution (H/M/L)	Future risk (H/M/L)
1	Acute lack of data for some geographic regions			
2	Lack of seasonal and longitudinal studies			
3	Lack of comprehensive, inclusive habitat assessment			
4	Understanding of decommissioning impacts			
5	Lack of coherence in data collection methods (including ROV)			
6	Trophic levels not equally represented (e.g., ornithology, microbiology, sea mammals)			
7	Functional understanding of community contributions			

Key: H = High probability, M = Medium probability, Low = Probability. Colour key: Red (poor), Orange (medium), Green (good).

https://doi.org/10.1371/journal.pstr.0000104.t003

function and services delivered by offshore artificial structures and eventually towards their coherent valuation in both monetary and nonmonetary terms. Our personal view of the major knowledge gaps we have identified, ranked in order of importance to understanding platform ecosystems are given (Table 3).

While we are gaining a greater understanding of ecosystems associated with platforms, we know less of the long-term impacts of habitat removal incurred through permitted decommissioning activity, which is forecast to increase in the near future. Focused ecological management strategies for decommissioned oil and gas structures are lacking [137,138] and it remains unclear what, if any, management measures would be enforced for platforms that are reefed or remain in situ following decommissioning. In addition, new information is always emerging and recently the relative blue carbon benefits of leaving existing systems in place, with their accumulated biomass, but which also avoids the environmental and financial cost of disposing of the material attached to the rigs has been recently described [139]. This adds to the increasing evidence base of the ecological value of oil and gas structures and raises further questions on how these sites should be managed. There is also an increasing awareness of how marine structures placed in the environment can be designed to enhance biodiversity [140] and while this was considered beyond the scope of this review it is an area of increasing attention, can we promote biodiversity by the nature and design of emplacements? This movement shows increasing societal awareness of the importance of marine systems.

10.2. It's all about the data

It has become apparent that while some ecological data from platforms is available across regions, it is quite disparate, lacking in consistency of approach and methodology. It would be beneficial to achieve an international, coordinated, set of standards or protocols for gathering and submitting scientific data.

"Progress in Best Environmental Practice (BEP) could be made if industry, federal government, state artificial reef coordinators, federal and state scientific branches (i.e., BSEE–BOEM; TPWD–Harte Research Institute/TAMU) found some common ground for a shared web portal to link knowledge gaps with 'discoverable evidence' i.e. data that is collected but not publicly available." (Steve Truchon, Pers. Comm. 2020).

By sharing environmental data, industry and science could make cost efficiencies by reducing duplication and allowing monitoring efforts to be efficient. Government-backed environmental data facilities, such as EMODnet in Europe could play a role in hosting data in a format that is standardised, ensures ownership and confidentially [141].

Supporting information

S1 File. In support of the review, the standards for systematic evidence syntheses in environmental research was applied and the information provide via an excel workbook as included in the supplementary information.
(XLSX)

Acknowledgments

We acknowledge in-kind support from Net Zero Technology Centre and the University of Aberdeen through their partnership in the UK National Decommissioning Centre. Also E. Carr for graphical assistance.

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