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Offshore energy structures in the North Sea: Past, present and future

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ABSTRACT

Offshore man-made structures (MMS) such as oil and gas (O&G) platforms, pipelines and wind energy developments are present in shelf seas worldwide and can potentially influence ecosystem dynamics and services. The number, type and age of these structures is changing as the wind energy sector expands whilst O&G structures reach the end of economic viability and are decommissioned. The North Sea is an area which supports major offshore energy production and consequently has a particularly high density of MMS which, according to the OSPAR 98/3 decision, will need to be removed after cessation of operations. To inform effective policy decisions, a comprehensive understanding of the impact of MMS on North Sea ecosystem is required. A major challenge to this is the lack of a comprehensive MMS database with up-to-date and accurate metadata (e.g. structure type, installation date) and locations. We found that existing databases are spatially restricted and/or contain conflicting locational data and, when present, metadata. When used in scientific studies to support policy decisions, such gaps and errors limit inference and could lead to spurious results. Here we develop a comprehensive spatial database of MMS including O&G platforms, pipelines and wind turbines in the North Sea. This allowed examination of temporal trends in how North Sea MMS have changed in number, type and location. The generated database will be useful for a range of stakeholders ranging from ecologists, engineers, policymakers, industry advisors and geoscientists. Indeed, such a database is fundamental for robust research studies required to inform effective and sustainable policy decisions, including review of the OSPAR 98/3 regulation.

1. Introduction

Offshore man-made structures (MMS) such as oil and gas (O&G) platforms, pipelines and wind energy developments are present in shelf seas worldwide. While there have been rapid increases in marine renewable energy over the past 10–15 years, there have been concurrent declines in the number of O&G developments, with many reaching the end of economic viability leading to their decommissioning (process of ending operations of an energy structure) and subsequent repurposing or removal [5]. In 2022, there were over 12,000 offshore platforms globally, with particularly high concentrations in the North Sea, Gulf of Mexico, Australia, and California [27], and over 125 windfarm developments globally [43].

The North Sea, a busy, industrialised shelf sea, is an area of rapid change in the MMS seascape. MMS in the form of O&G platforms were first installed in the 1960 s, and decommissioning is now underway for many [5]. Regulations under the OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations mandate that MMS must be removed after cessation of operations, with limited exceptions. Although O&G is currently the focus of decommissioning, wind turbines and associated structures will also need to be removed once they reach the end of operational life under the current legislation. The aim of the OSPAR Decision 98/3 is to avoid dumping of MMS into the sea. Central to this decision is the concept that leaving a clean seabed is deemed to be the least environmentally impactive option overall [29]. However, there is limited information on the multitude of impacts on the marine ecosystem and its services on an ecosystem wide and long-term scale of the presence of MMS, and thus uncertainty regarding the consequences of MMS being left in situ or removed [11]. The estimated decommissioning cost for North Sea offshore installations are projected to be between €80 and €100 billion, with the UK and Norway, the largest O&G producers in the North Sea, bearing the majority of the expense [41]. The expansion of the 'rigs-to-reef' scheme in the Gulf of Mexico has led to calls for more flexibility in decommissioning policies in the North Sea, with options for structures to be partially or entirely left in place [12, 41].

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Studies worldwide have demonstrated that MMS can have a multitude of potential environmental impacts from the construction phase through operation to decommissioning and removal ([11] e.g. [17,35,39]). Some of these impacts can be perceived as positive and others negative, however, for the most part the magnitude of impacts on a population or ecosystem level are unknown [11]. Once in place, such MMS can act as artificial reefs; providing hard substrate where sessile organisms colonise and, due to enhanced habitat and/or feeding opportunities, mobile invertebrates and fish aggregate and, in some cases the MMS result in increased productivity [7,23]. Such concentrations in biomass can also, in part, be driven by the shelter provided by the lack of commercial fishing within and around these structures (*de facto* Marine Protected Areas) [14]. Studies have shown use of MMS by some individual marine mammals and seabirds for feeding, resting or breeding [9,34]. MMS can act as a vector or 'stepping-stones' for native and non-native species and aid species connectivity [1,40]. O&G structures are also associated with increased levels of pollutants in surrounding areas, such as drill cuttings, which need to be considered [3]. Studies have indicated that any impacts of MMS on the ecosystem are likely mediated by structure traits including age, structure type, material, and number of legs [2,15]. How such impacts may change as these structures are no longer in use and degrade or are removed is unclear.

We are entering a period of unprecedented change in the MMS seascape of the North Sea resulting in an urgent need to increase our understanding of the impacts of MMS on the ecosystem and its services, to underpin its sustainable management and to contribute to future policy decisions [27]. UK funding programs, including Influence of man-made structures in the ecosystem (INSITE; https://insitenorthsea.org); and Offshore Wind Evidence and Change (OWEC) Programme; Ecological consequences of offshore wind (ECOWind; https://ecowind.uk/), have been launched to boost scientific research in this field. Given the North Sea is a shallow shelf sea which lacks natural, hard substrate, MMS can influence larval and benthic communities on a local and North Sea-wide scale [4,7]. Most studies have focused on limited numbers of structures or specific study areas [6,8,24]. Such studies are critical to understanding the mechanisms of impact. However, to understand the cumulative and potential future impacts of the changing seascape and the influence of changing benthic communities on other trophic levels, it is imperative that such focused studies are complemented by North Sea-wide studies [42]. The limited number of such studies have all utilised one of the two North Sea-wide MMS databases: OSPAR Offshore Installations and EMODnet (Table S1). However, studies have highlighted that there are issues with these datasets including missing structures, errors in location, lack of metadata, and outdated data [31]. The lack of a single consistent dataset hampers efforts to make comparisons between different studies with different modelling techniques and scenarios [19,28,31]. This further hinders the research efforts needed to make robust policy decisions for the North Sea. There have been calls for a consistent, high-quality dataset for offshore structures in the North Sea [11,28,31].

In response to these calls, here we review the two available North Sea-wide datasets to summarise current issues and omissions. We then address these by combining data from multiple sources (e.g. national databases and decommissioning reports) to generate a single comprehensive North Sea-wide dataset of O&G platforms, pipelines, and wind turbines and their associated structures. Finally, we use the generated dataset to explore, for the first time, how the seascape of the North Sea has changed through time, and specifically examine how the current period of rapid change compares to historic changes with development of O&G.

2. Methods

2.1. Study area and structure types

The study area considered was the North Sea (defined as ICES Statistical Areas IVa-c; Fig. S1). The following structure types were considered: fixed O&G platforms, floating O&G platforms, O&G pipelines, and wind turbines and associated structures (substations, met masts and lidar masts within wind farms). Pipelines that were partly within the IV area were also included. O&G platforms were categorised into fixed and floating platforms according to [13] (Fig. S2).

2.2. Compiling data sources

Databases were identified by examining the literature from a search on Google Scholar using the keywords 'North Sea', 'North Sea offshore structures', 'North Sea decommissioning', 'man-made structures', 'offshore installations', 'oil and gas platforms', 'pipelines', 'offshore windfarms'. Each country-specific governmental database for offshore structures was identified using the OSPAR website (https://odims.ospar.org/en/datastreams/) and the INSITE interactive website (https://www.insitenorthsea.org/blog/2019/insite-interactive-a-ground-breaking-tool/). An additional data source (Edina Marine Digimap, https://digimap.edina.ac.uk/) was identified from a literature search on the University of St Andrews library services using the same keywords as above. All input datasets compiled are found in Table S1 and S2. All available UK Government decommissioning reports (https://www.gov.uk/guidance/oil-and-gas-decommissioning-of-offshore-installations-and-pipelines) were examined to identify missing structures not present in the other data sources and to compare/supplement metadata and locations from other data sources. 4C Offshore data source was only used to compare freely available metadata with associated wind turbines.

Data sources underwent a quality control procedure whereby all locations and metadata available for each individual structure in each database were compared against all other data sources and against company/operator websites and decommissioning reports where available (Table S1, S2). For O&G platforms and wind turbines, the latitude and longitude values from the middle of the structure (6 decimal places) were compared against values from all other available data sources (including decommissioning reports and company/operator websites where available for O&G platforms). For pipelines, shapefiles from all data sources were overlaid in QGIS to identify differences in routing and locations (QGIS.org, 2022. QGIS Geographic Information System).

The metadata fields included were based on their potential to mediate ecological impacts of MMS (Tables S3-S5). If there were any discrepancies in the location or metadata values (e.g. installation date) obtained from difference sources, the values in operator/company websites, decommissioning reports were assumed to be most reliable. If not available, then values that matched across at least two data sources were assumed to be the most accurate. For pipelines, installation dates were not reliably available, therefore, the final database does not contain installation dates.

2.3. Examining Trends over time in the North Sea Landscape

Using the databases constructed above, temporal trends by structure type were examined. The total number of O&G platforms present in the North Sea each year from 1966 (first platform) to 2022 was calculated and mapped in 10-year increments (Fig. 6). A final figure for platforms and pipelines was also produced for March 2023 (Fig. 7). If date of platform installation was not available, date of first oil or gas was used as a proxy ($n = 4$). Fixed platforms for which there was no installation date, date of first oil or gas, or removal date ($n = 4$) were not considered for this section (platforms removed: P6C, Emshorn Z1A did not have installation or date of first oil or gas, P9-Seafox 1 did not have removal dates, Jackdaw had not been installed yet). Floating platforms used for short-term purposes such as short-term jack ups for drilling or temporary accommodation ($n = 62$) and single points mooring (SPM) monotowers ($n = 2$) were not considered. Given installation dates for pipelines were not available, temporal analysis was not possible.

2.4. Results

A total of 18 data sources (excluding decommissioning reports and company/operator websites) were examined (Table S1, S2). For O&G platforms we reviewed nine data sources, only two of which were North Sea-wide data sources. For pipelines, a total of five number were reviewed and for wind turbines a total of four.

After a rigorous quality control procedure of cross-checking data sources, we were able to identify, for each data source, where metadata were: (i) available and correct, (ii) available but contained inaccuracies or missing values, and (iii) not available (Figs. 1, 3, 4). We also identified instances where locations of O&G platforms were incorrect (Fig. 2).

2.4.1. O&G platforms and pipelines

The two North Sea-wide data sources (OSPAR Offshore Installations and EMODnet) contained various categories of O&G subsea structure including wellheads, manifolds, and others as well as platforms. Neither data source had a single category pertaining to platforms. The OSPAR database contained 11 categories of structure (including different variations of spelling and formatting, Table S6). Five categories encompassed O&G platforms, totalling 665 O&G platforms in ICES area IV (Table S6, [13]).

For the EMODnet data source, there were 15 categories of structure (including different variations of spelling and formatting, Table S6), seven of which encompassed O&G platforms (Table S6, [13]). There was

Fig. 1. Radar Diagrams showing each of the O&G platform data sources and where data attributes were either 1.) Unavailable 2.) Available but contained inaccuracies or missing values 3.) Available and correct. Type E-Type Extra, # Legs-Number of legs, FL/Fixed-Floating or Fixed, Op-Operator, First O/G-Date of First Oil or Gas, Date Inst-Date of Installation, Date Decom-Date of Decommissioning, Pl Remov-Date of Planned Removal, Ab/Pr-Absence or Presence, Man/Unm-Manned or Unmanned. NSTA-North Sea Transition Authority, UKHO-UK Hydrographic Office.

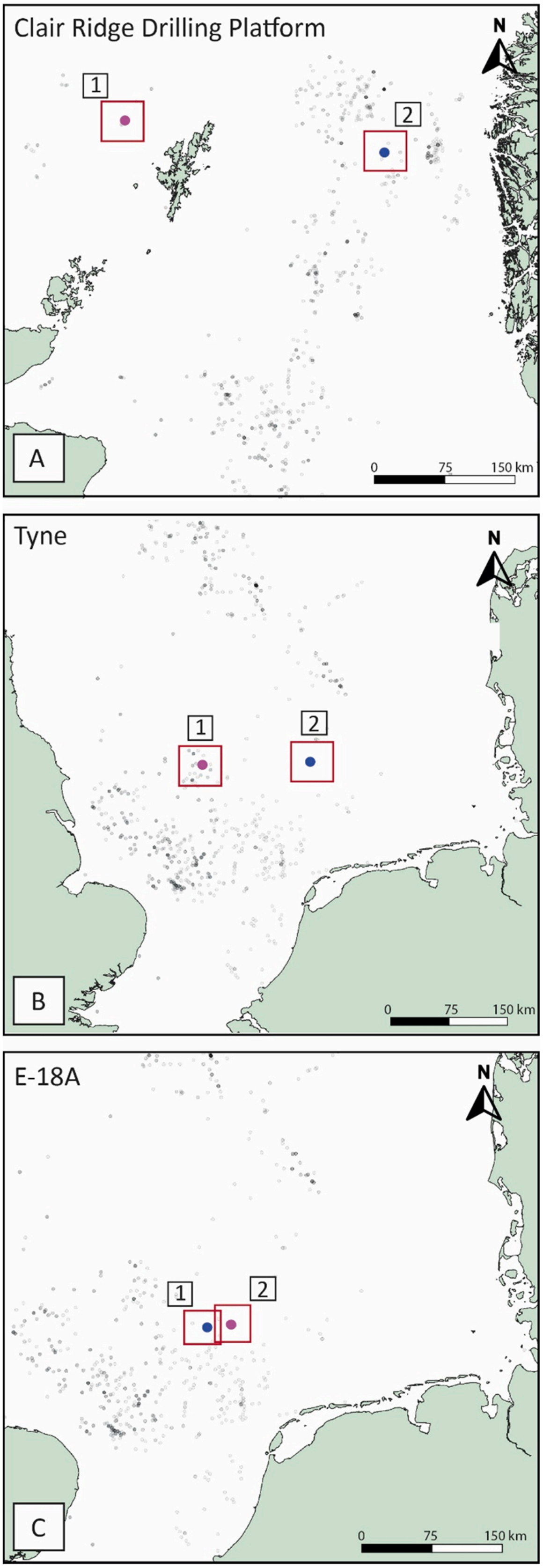

Fig. 2. Examples of discrepancies in locations of platforms between the true location (1; pink) and the location given in OSPAR data source (2; blue) for Clair Ridge DP (A), 277 km discrepancy Tyne Platform (B), 139 km discrepancy, and E18-A (C), 25 km discrepancy.

a total of 599 platforms in the ICES area IV. Some platforms, including Brae B, Miller B, Goldeneye, Murchinson, Welland and Loggs Platfoms, were missing. Both North Sea-wide data sources differed in number of platforms to our final database (590). Furthermore, a total of 63 mismatches in locations of platforms between the two North Sea-wide data sources were identified (Fig. 2, Table S7).

For the most part, country-specific data sources (Table S1) contained an accurate total number of current platforms. However, this did not appear to be the case for the North Sea Transition Authority (NSTA) data source which includes UK sector subsea structures and platforms. We examined two versions of this data source released in: 2019 and 2022. Eleven platforms which had been decommissioned (but still present in the North Sea according to operator websites) had been removed in the most recent update (March 2022). In the 2019 version, all platforms contained an installation date, however, 69% were erroneously listed as installed in 2002. Only 15% of all platforms were found to have correct installation dates. In the newer version, 35% of platforms had installation dates. Other data sources in the British sector for O&G platforms had limited metadata. Country-specific data sources in the Danish and Dutch sector contained few metadata fields and inconsistent formatting. The Norwegian Petroleum Directorate data source contained the most accurate and complete metadata compared to other country-specific data sources.

For pipelines, inconsistencies and missing metadata such as installation dates were a particular problem amongst all the data sources, including the only North Sea-wide data source, EMODnet. Often lengths and diameters had missing values. For some data sources, installation dates were not given and when they were (e.g. NSTA) they included inaccuracies and typographical errors (see footnotes Table S1). Pipeline routing was consistent between the data sources with few exceptions.

2.4.2. Wind turbines and associated structures-metadata and locations

For wind turbines and associated structures, all location and metadata presence in multiple data sources were consistent. There were two main issues in the available wind energy data sources: 1.) the lack of recent updates 2.) The lack of a single data source which contained comprehensive metadata fields (Fig. 4, Table S5).

2.5. Examining spatial and temporal trends of MMS in the North Sea

2.5.1. O&G platforms and pipelines

According to our database, the total number of O&G platforms in the North Sea as of March 2023 is 590 (Table 1); 559 (95%) of these are fixed with the remainder being floating (31). Since 1966 (first fixed platform), 113 fixed platforms have been decommissioned but not yet removed, and 138 have been decommissioned and removed. Since 1976 (first floating platform), 36 floating platforms have been decommissioned and removed.

The number of fixed platforms increased until around 2009, was stable between 2009 and 2017 as the number being installed and removed was similar and has since declined. For floating platforms, there was also an upward trend from 1976, but then since 1999, there have been decreases as well as increases between the years (Fig. 5). Spatial-temporal changes are seen in Figs. 6 and 7.

2.5.2. Wind turbines and associated structures

The first North Sea windfarm (Horns Rev 1) became operational in 2002, with 80 wind turbines. As of March 2023, there were 92 windfarms with 4293 windfarm structures (4209 turbines). The largest annual percentage increase in windfarm structure numbers was 50% between 2012 and 2013.

3. Discussion

This study provides a much needed [11,31], consistent, comprehensive database of both current and historic offshore energy structures

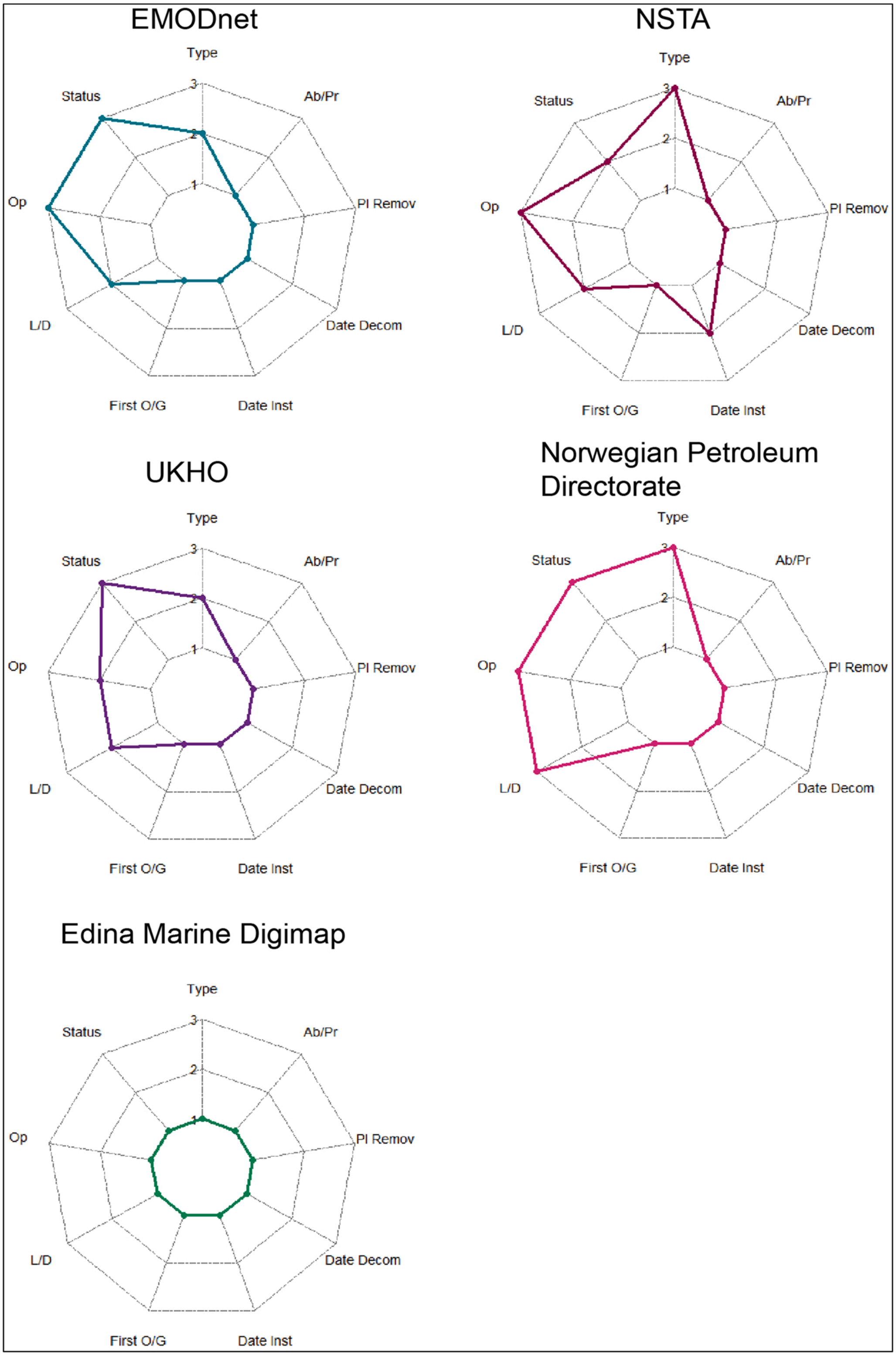

Fig. 3. Radar Diagrams showing each of the pipeline data sources and where data attributes were either 1.) Unavailable 2.) Available but contained inaccuracies or missing values 3.) Available and correct. Op-Operator, L/D-Length and Diameter, First O/G-Date of First Oil or Gas, Date Inst-Date of Installation, Date Decom-Date of Decommissioning, Pl Remov-Date of Planned Removal, Ab/Pr-Absence or Presence. NSTA-North Sea Transition Authority, UKHO-UK Hydrographic Office.

in the North Sea. In brief, we reviewed all data sources available and through a quality control process used these data to 1) generate a database of the locations and associated comprehensive metadata of North Sea O&G platforms, pipelines, and wind turbines 2) examine, for the first time, how prevalence of both O&G and wind farm structures have changed through time.

We found that the two North Sea-wide offshore energy structure data sources (OSPAR Offshore Installations and EMODnet) differed in their accuracy in terms of both number of MMS present, locations, and associated metadata. The most important limitation was missing

Fig. 4. Radar Diagrams showing each of the wind turbine data sources and where data attributes were either 1.) Unavailable 2.) Available but contained inaccuracies or missing values 3.) Available and correct. # Turbines-Number of Turbines, Year Comm-Year of Commissioning, Year Const-Year of Construction, Pl Comm-Year of Planned Commissioning, Pl Cons-Year of Planned Construction, Dist-Distance to Coast, Found-Foundation, # Sub-Number of Substructures, Total-Total Number of Structures. UKHO-UK Hydrographic Office.

Table 1
Number of Fixed and Floating Platforms in each country jurisdiction in the ICES Area IV in North Sea in March 2023 according to our new database.

Country	Total Number of Fixed Platforms	Total Number of Floating Platforms	Total
United Kingdom	260	20	280
Norway	77	11	88
Netherlands	159	0	159
Denmark	61	0	61
Germany	2	0	2
Belgium	0	0	0

structures and incorrect locations, which affected both data sources. Furthermore, the number of inconsistencies in structure category in these, and some country-specific data sources, may have led to some relevant O&G platforms in these datasets unintentionally being overlooked by researchers. OSPAR are aware of the limitations and inaccuracy of locations of structures in their data source and are working to rectify issues [30]. Neither of the two data sources provided comprehensive metadata (Fig. 1) of structure traits (e.g. number of legs, type of structure) which are known to mediate structure impacts on biological communities at a local scale [2,15].

Previous studies using North Sea-wide offshore energy structure databases have not been able to consider metadata. Furthermore, our study highlights the potential that there were likely inconsistencies in the data used in previous studies which may limit their comparability and even robustness of findings. Our comprehensive North Sea-wide database will allow these structure traits to be investigated on multiple temporal and spatial scales, and consideration of traits known to mediate impacts on the ecosystem. For example, accurate locations, installation and removal dates are imperative for connectivity studies such those conducted in INSITE 1 (https://insitenorthsea.org): ANCHOR (Appraisal of Network Connectivity between North Sea subsea oil and gas platforms) and EcoConnect (Assessing the Ecological Connectivity between man-made structures in the North Sea). Given such studies investigate the role of MMS in terms of connectivity, larval dispersal and plankton transfer, it is crucial to know exactly where and when MMS are in place, particularly as structures in close proximity (networks of

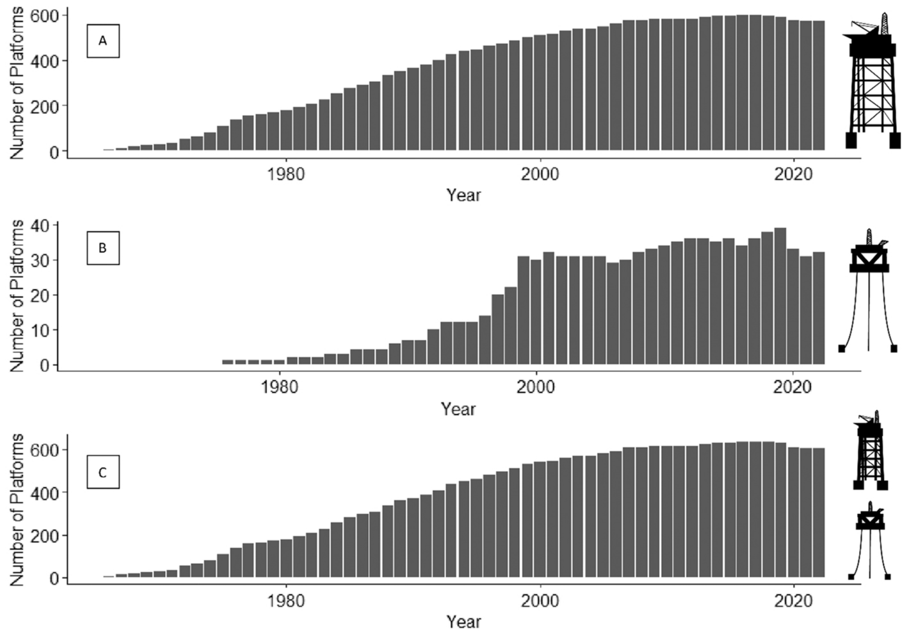

Fig. 5. Trends in number of O&G platforms from 1966 to 2022. A-fixed O&G platforms, B-floating O&G platforms, C-both types of platforms combined.

structures) may have different ecological impacts than those in isolation. This database will aid in future modelling studies, facilitating robust, comparable results between different modelling techniques [31]. Such studies are crucial to effectively inform decommissioning, management options and marine spatial planning in the North Sea.

More broadly, as well as understanding the impacts of structures on the ecosystem, this database can be used to inform marine spatial planning of the North Sea as it provides up to date and accurate temporal and spatial information of MMS from two of the most important industries in the North Sea: oil and gas and wind energy. This information was not readily available beforehand and allows for study and assessment of the interactions between these two industries and also between other sectors such as shipping [22]. This also allows for future conflict resolution between sectors, such as wind energy and fisheries, supporting the sustainable development of the North Sea's Blue Economy [20]. Currently, the seven countries that border the North Sea all have their own spatial claims, different governing systems, and differing commitments for environmental protection [20]. Given this database spans all the countries surrounding the North Sea, bringing together all data sources available for all the countries, there is an encouragement for future cross-border cooperation, data sharing and transparency. This currently only happens in frameworks such as the OSPAR Convention. Our database can also inform European Union's Marine Spatial Planning Platform, which is a platform which aims for member states to share knowledge on marine spatial planning methods in order to accommodate the trend of increasing competition for marine space, especially in industrialised seas such as the North Sea [22].

Data collation, processing and quality control procedures are a major undertaking. Although considerable effort was made to identify gaps in previous data sources and correct errors, there are still gaps in the final database. Gaps in metadata include installation dates for pipelines and for some O&G platforms. In cases where installation dates for platforms were not available, date of first production was used. Data from other platforms suggest that the date of production is usually between 1 and 3 years after the date of installation. It should also be noted that the status of O&G platforms in terms of manned vs unmanned refers to during operation; it is likely that once decommissioned manned platforms are no longer manned.

Moving forward, we present recommendations for maintenance and improvements of these North Sea-wide structures databases, which likely require input from industry and regulatory bodies. In the short-term, the datasets produced in this study should be used to flag the identified issues with the contributing datasets. Longer-term, we appeal for the dataset provided here to be adopted by a cross-country organisation such as OSPAR and used as the standard North Sea wide structure database. There are multiple obstacles that need addressing to facilitate efficient maintenance of a North Sea wide database with appropriate metadata. Based on our findings we recommend the following be agreed across countries for country level datasets: key metadata that should be considered, nomenclature for fieldnames, field types (e.g. free text, numbers) and contents (e.g. choice of structure type) and missing data; timing and frequency of updates; and Release Notes available with each update. This would facilitate the combining of these country-level datasets. More specifically, more work is required to have an effective database of pipelines. It is currently impossible to determine which parts of pipelines are buried, trenched, or exposed. This remains a limitation to understanding the impact of pipelines on the ecosystem and fishers given ecological interactions can differ depending on burial vs exposed status [32–34]. Furthermore, for effective analysis of the impact of structures on the environment, it is crucial to know exactly how pipelines are decommissioned (left exposed in situ, buried, partially removed, or completely removed). The 98/3 OSPAR decision does not include pipelines and individual countries establish their own pipeline decommissioning policy. However, further research is needed to recognise the long-term impacts of leaving pipelines in situ to inform future best practices in pipeline decommissioning [32,33].

In this study, the historic changes in the presence of MMS across time were examined and compared to the current period of change. The increases in O&G platform installation from 1966 to 2009, shows the investment in O&G exploration and production in the North Sea [10]. After 2009, the time series suggest a period of stagnation in the number of new O&G platforms as numbers of platforms being installed and removed were similar. In the next 30 years it is expected that there will be large-scale decommissioning and removal of O&G infrastructure [25]. These temporal trends in the number of platforms have not been previously quantified, likely due to lack of accessible data on installation and removal dates.

Regarding offshore wind turbines, the steady increase seen from 2002 to 2022 is predicted to continue given there are 17 windfarms currently under construction and 16 more approved projects in the

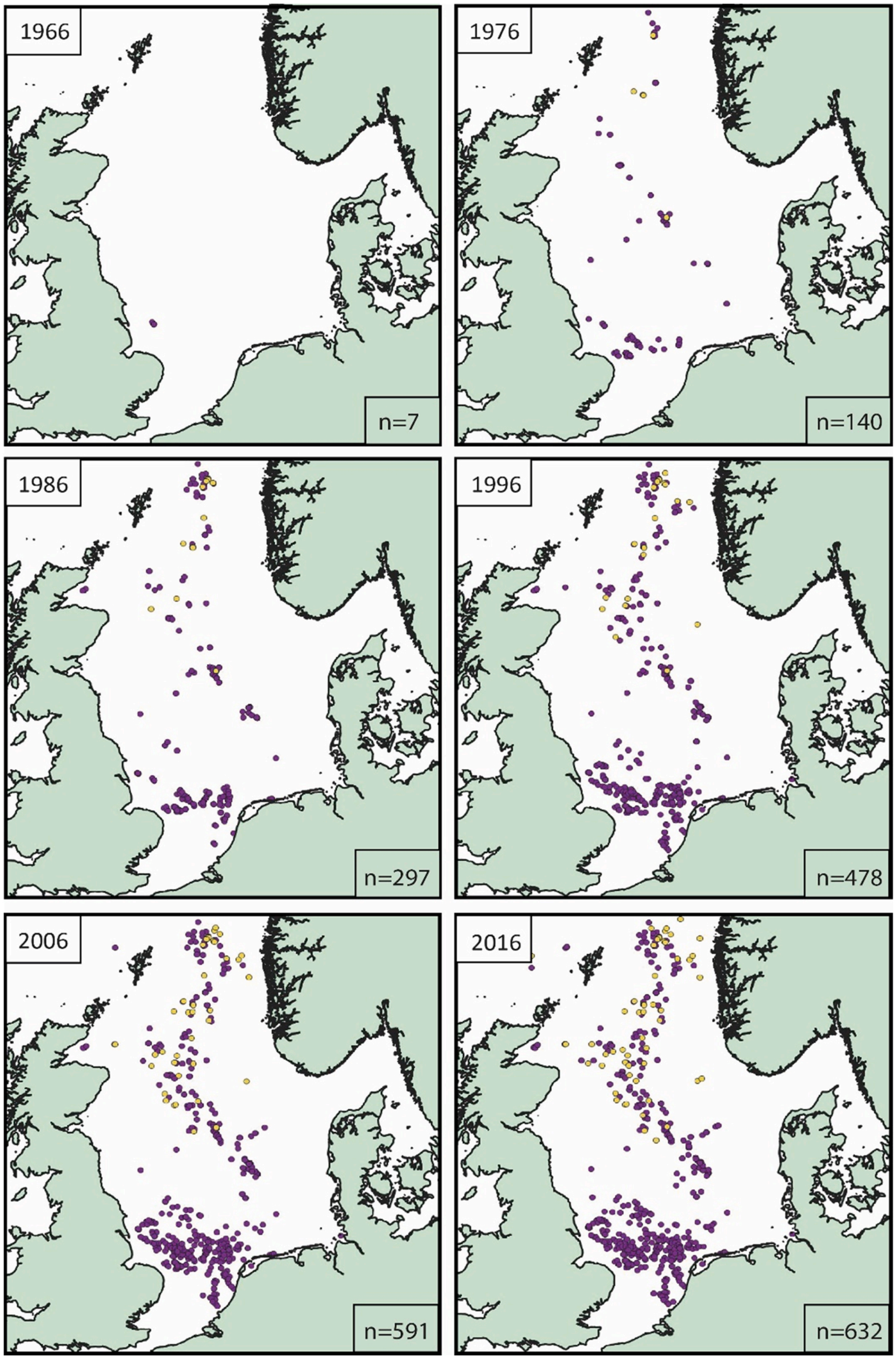

Fig. 6. Changes in North Sea seascape from 1966 to 2016. Fixed platforms in purple, Floating platforms in yellow.

North Sea (Results). The resulting number of structures is unprecedented. Indeed, there are currently 4293 wind turbines and associated structures compared to 590 platforms in the North Sea (March 2023). It is projected that this continued increase in the number of wind turbines being installed will intensify construction noise, vessel traffic and pile driving activities in the North Sea much more than previous installations of platforms which are at a much smaller scale [21]. It will also likely increase disturbance for marine mammals and fish [18,37]. However, many of the proposed windfarms are projected to have floating wind turbines, which do not require pile driving to be fixed onto the seabed but do have other potential impacts such as risk of entanglement for marine mammals and fishing gear [26]. One of the key knowledge gaps is the ecosystem level effects at different phases of wind energy projects in close proximity, and in association with O&G activities. The seascape

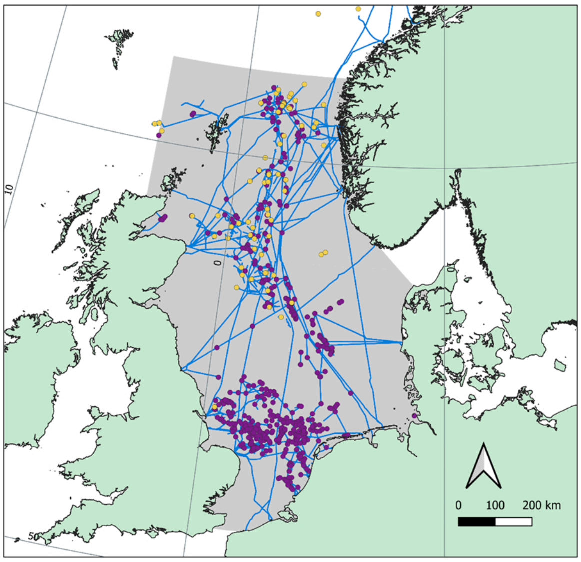

Fig. 7. Current O&G platforms and pipelines (March 2023). Yellow dots-floating platforms, purple dots-fixed platforms, blue lines-pipelines, grey shading-ICES Area IV.

may have areas of windfarm construction next to an area of operating windfarm acting as an artificial reef. Understanding the dynamics in terms of attraction and repulsion and quantifying these impacts will need an up-to-date MMS database. Additionally, predictions for the offshore wind energy seascape indicate larger areas taken up by windfarms. With the North Sea being the centre for European offshore wind energy expansion, a key consideration in terms of ocean management is the displacement of fishers, especially bottom trawlers which will have limited access to these areas [36,38]. And lastly, there are almost seven times more wind turbines compared to O&G platforms in the North Sea (Results). Decommissioning these wind turbines once they reach the end of their operational life will be a major challenge in the next 30–40 years [16].

4. Conclusion

We have demonstrated that the most commonly used North Sea wide MMS data sources have significant issues in terms of data quality and quantity which has limited studies of the environmental impacts of MMS in terms of robustness and ability to consider structure traits. Our study addresses the urgent need for a comprehensive dataset for MMS in the North Sea. Critically, our openly available datasets (see Data Statement) provide verified structure locations across the North Sea and the metadata that will be fundamental to an understanding of how structure traits mediate structure impact on the ecosystem. As such, this dataset will be fundamental for the ecological research required to inform policy decisions, such as any the review of the OSPAR 98/3 decision, and to future marine spatial planning in the North Sea. In addition, it will be of use to engineers, industry advisors, geoscientists and geographers.

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CRediT authorship contribution statement

MCIM conducted the study with support and input from all co-authors. The manuscript was prepared by MCIM with help from DJFR, and input from MIDC and SR. DJFR led conception and management of the study. We have no potential conflicts of interest to disclose.

Data Availability

All final databases underpinning this publication can be accessed at https://doi.org/10.17630/338d5ba4-5e09-443f-9c08-013d24050c81 [Martins et al, 2023]" along with updates and release notes.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2023.105629.

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