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REVIEW ARTICLE

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UK deep-sea conservation: Progress, lessons learned, and actions for the future

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Abstract

1. Despite a relatively long history of scientific interest fuelled by exploratory research cruises, the UK deep sea has only recently emerged as the subject of targeted and proactive conservation. Enabling legislation over the past 10 years has resulted in the designation of marine protected areas and the implementation of fisheries management areas as spatial conservation tools. This paper reflects on progress and lessons learned, recommending actions for the future.
2. Increased investment has been made to improve the evidence base for deep-sea conservation, including collaborative research surveys and use of emerging technologies. New open data portals and developments in marine habitat classification systems have been two notable steps to furthering understanding of deep-sea biodiversity and ecosystem functioning in support of conservation action.
3. There are still extensive gaps in fundamental knowledge of deep-sea ecosystems and of cause and effect. Costs of new technologies and a limited ability to share data in a timely and efficient manner across sectors are barriers to furthering understanding. In addition, whilst the concepts of natural capital and ecosystem services are considered a useful tool to support the achievement of conservation goals, practical application is challenging.
4. Continued collaborative research efforts and engagement with industry to share knowledge and resources could offer cost-effective solutions to some of these barriers. Further elaboration of the concepts of natural capital and ecosystem services will aid understanding of the costs and benefits associated with human–environment interactions and support informed decision-making in conserving the deep sea.
5. Whilst multiple challenges arise for deep-sea conservation, it is critical to continue ongoing conservation efforts, including exploration and collaboration, and to adopt new conservation strategies that are implemented in a systematic and holistic way

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and to ensure that these are adaptive to growing economic interest in this marine area.

KEYWORDS
biodiversity, coral, fishing, habitat management, marine protected area, ocean reef

1 | INTRODUCTION

The 'deep sea' (defined in the context of this paper as waters deeper than 200 m, after Gage & Tyler, 1991) covers approximately 40% of the UK marine area. The oceanographic characteristics of the UK deep sea gives rise to a diverse array of deep-sea ecosystems; from expanses of deep-sea muds inhabited by polychaetes, xenophyophores, and urchins, to complex benthic habitats of cold-water coral reefs and sponge communities. It is now widely recognized that deep-sea organisms are of critical functional importance (e.g. Thurber et al., 2014). Many of the UK deep-sea habitat types have been classified as vulnerable marine ecosystems (VMEs) (Bullimore, Foster, & Howell, 2013; Davies et al., 2015; Davies, Howell, Stewart, Guinan, & Golding, 2014), considered to be of particular conservation concern because of their uniqueness or rarity, functional significance, fragility, low recovery rates, and structural complexity (FAO, 2009). However, direct pressures associated with anthropogenic activities, such as fishing practices and hydrocarbon extraction, are reported to be affecting the health of deep-sea ecosystems (e.g. Davies, Roberts, & Hall-Spencer, 2007). Moreover, indirect pressures are placing an increasing burden on resilience; for example ocean acidification as a result of climate change is altering seawater carbonate chemistry, with particular implications for many biogenic habitats including cold-water coral reefs (Levin & Le Bris, 2015).

It is only relatively recently that the deep sea has emerged as the subject of targeted and active conservation action driven by legislation. Prior to this, conservation activities had been driven by sectoral activities and *ad hoc* events and opportunities. For example, the Oslo–Paris (OSPAR) Convention Decision 98/3 on the Disposal of Disused Offshore Installations, which prohibits the dumping or leaving in place of disused offshore petroleum installations within the OSPAR maritime area, was taken following the Brent Spar incident in the mid-1990s (Jordan, 2001). However, the evidence-base underpinning this recommendation is criticized (Bellamy & Wilkinson, 2001) and the decision remains under review.

Enabling legislation underpinning more targeted conservation action in the UK deep sea began in 2008, with the transposition of the requirements of the EU Habitats (92/43/EEC; European Commission, 1992) and the EU Wild Birds (2009/147/EC; European Commission, 2009) Directives into domestic law, known as the Conservation of Offshore Marine Habitats and Species Regulations 2017 (Defra, 2017). One of the requirements of the Directives is for European Member States to put in place special areas of conservation (SACs) and special protection areas (SPAs) as a contribution to achieving 'favourable conservation status' of particular habitats and species listed within their annexes.

In 2009, the UK Marine and Coastal Access Act (Defra, 2009) set a landmark in the potential to conserve the UK deep-sea environment; giving powers to Ministers for the designation of Marine Conservation Zones to complement existing spatial protection measures and to conserve the range of marine life for which marine protected areas (MPAs) are considered an appropriate conservation tool. These pieces of legislation are critical instruments towards ensuring the UK achieves its marine protection obligations, as outlined under a range of conventions to which the UK is a signatory, such as the OSPAR Convention (OSPAR, 1998) and the Convention on Biological Diversity (United Nations, 1992).

Moreover, environmental policies for fisheries management introduced under the United Nations, the North-East Atlantic Fisheries Commission, and the European Union aim to conserve deep-sea fish stocks and non-target species, as well as associated deep-sea habitats and species. In UK waters, management measures in the form of fisheries closures, permits, and quotas, are being implemented to deliver against these policy drivers.

With growing economic interest in seabed resources (Bowden, Rowden, Leduc, Beaumont, & Clark, 2016), deep-sea governance and management is becoming increasingly critical to ensure the protection and sustainable use of fisheries and deep-sea ecosystems (Benn et al., 2010). It is timely to take stock of conservation efforts within the UK deep-sea environment, reflecting on progress and lessons learned to date, and to translate these into actions for the future; recommendations from which are of relevance at a global scale. To this end, this paper is divided into three sections: progress in developing our understanding of the UK's deep-sea environment; progress towards taking conservation action in the UK deep-sea environment; and lessons learned, challenges encountered, and future actions for deep-sea conservation.

2 | PROGRESS IN DEVELOPING AND CONSOLIDATING OUR UNDERSTANDING OF THE UK DEEP-SEA ENVIRONMENT

2.1 | A brief history of deep-sea understanding and exploration

Our understanding of the UK deep-sea environment is the result of more than 100 years of research, pioneered in the 1800s by a number of British marine scientists. As the naturalist Edward Forbes remarked: “it is in the exploration of this vast deep-sea region that the finest field for submarine discovery yet remains” (Forbes, 1859); a statement which is still true to this day.

Forbes proposed the ‘azoic theory' in 1844 from his research aboard the *HMS Beacon*, surveying marine life in the Aegean Sea. He observed that in the ‘eighth region' (up to depths of approximately 420 m): “the number of species and of individuals diminishes as we descend, pointing to a zero in the distribution of animal life as yet unvisited” and estimating a “zero of animal life probably about 300 fathoms” (approximately 550 m) (Forbes, 1844). Whilst the azoic theory was disproved by the British marine biologists George Charles Wallich and Charles Wyville Thomson in 1860 and 1868–70 respectively (Anderson & Rice, 2006), Forbes' other significant research from the survey included a collection of marine animals dredged from different depths, which led to a proposal that the sea bed presented a series of zones or regions with associated communities, including a zone of deep-sea corals (Anderson & Rice, 2006). This proposal formed the beginnings of our marine habitat classification systems to this day.

Further notable deep-sea discoveries were made by Wyville Thomson and William Carpenter in 1868–1870 aboard the *HMSS Porcupine* and *Lightning*, when they collected a range of animals including echinoderms, corals, and sponges from the deep waters off the British Isles and the Mediterranean (Thomson, 1873). As deep-sea biologist John Gage pointed out in an opinion piece in 2003 (Gage, 2003), this research in the deep-sea waters off Europe was the beginning of our understanding of deep-sea biology. Following the *Porcupine* and *Lightning* expeditions, one of the most influential expeditions for deep-sea science was instigated—the *HMS Challenger* expedition. Setting sail from Portsmouth, UK in 1872 and led by Wyville Thomson, this global expedition delivered many new findings for the deep sea, including ~4,700 new species and the discovery of the Mariana Trench.

In the 1970s–1990s there was a significant renewed research interest in deep-sea ecology, with a focus on the Rockall Trough region of the UK deep sea. This was led by the Scottish Marine Biological Association (now the Scottish Association for Marine Science) and notably Prof. John Gage, and Drs John Gordon and John Mauchline. While Gage's focus was on benthic biology, Gordon and Mauchline focused on deep-sea fish. Regular research cruises until the mid-1980s, and sporadically thereafter, enabled a significant step forward in our understanding of UK deep-sea biology.

2.2 | An evolution in collaboration, technological advances, and building ecological understanding

The physical constraints of the deep sea meant that the technological and financial demands of exploration were high. However, legal provisions to enhance the protection of the marine environment have driven increased investment to improve the evidence base for the UK deep sea. Over the last 20 years, this investment has resulted in an increase in collaborative research and utilization of recent advances in technology, which have enabled a steady improvement in knowledge of the deep sea in UK waters.

With exploration for oil and gas moving into the deeper offshore waters to the west of Shetland from the mid-1990s (Bett, 2003), a collaborative strategic environmental assessment process was initiated by UK Government. In 1996 and 1998, the Atlantic Frontier Environmental Network, an initiative including deep-sea academics, specialist contractors, regulators and the oil and gas industry commissioned two widespread regional surveys of areas to the north and west of Shetland and the Rockall Trough, with the aims of mapping the sea bed, developing knowledge of deep-sea communities and, importantly, investigating the potential environmental impacts of the oil industry (Bett, 2003).

These survey efforts were continued via the Department of Trade and Industry (now the Department for Business, Energy and Industrial Strategy) who commissioned three Atlantic Margin Environmental Surveys from 1999 to 2002 (Bett, 2007a,b; Bett & Jacobs, 2007) and a sequence of oil and gas Strategic Environmental Assessments around the UK from 2001 to 2018 to continue to build understanding of the environmental effects of the industry. During the Strategic Environmental Assessment surveys, increasingly advanced technology was used including multibeam, side-scan sonar and underwater imagery techniques (Bett, 2012; Howell, Davies, Hughes, & Narayanaswamy, 2007; Narayanaswamy et al., 2006). These were instrumental in many of the discoveries made, such as that of deep-sea sponge aggregations of *Ostur*, and the Darwin Mounds (Bett, 2001).

Following this initial drive, further collaborative research was developed through the Special Area of Conservation (SAC) identification process to meet requirements of the EU Habitats Directive (92/43/EEC; European Commission, 1992). For example, as part of the joint-partnership project ‘Mapping European Seabed Habitats', a research survey with involvement from the Joint Nature Conservation Committee (JNCC), the Marine Institute in Ireland, the British Geological Survey, and the University of Plymouth was undertaken in 2007. The project delivered new data on the topography, geology, and biological communities of the Explorer and Dangaard Canyons of the UK South West Approaches, which were previously understudied areas (Davies, Guinan, Howell, Stewart, & Verling, 2008). Furthermore, geological and biological data were acquired from collaborative surveys of the Rockall Bank (between 2005 and 2006, Howell, Davies, Jacobs, & Narayanaswamy, 2009) and of the Anton Dohrn Seamount and East Rockall Bank in 2009 (Davies et al., 2015; Long, Howell, Davies, & Stewart, 2010; Stewart, Davies, Long, Strömberg, & Hitchen, 2009).

These surveys resulted in the development of one of the first broad-scale habitat maps for seabed features in the area. These maps included occurrences of Annex I habitats (formally listed under the EU Habitats Directive) such as *Lophelia pertusa* cold-water coral ‘reefs', expanding on initial distribution data for this species on the Scottish continental shelf and slope collated by Wilson (1979) and before him Le Danois (1948). Additional data collection for the Rockall Bank was undertaken in 2011 during the collaborative survey, JC060, led by the National Oceanography Centre (Huvenne, 2011). This survey identified further examples of live cold-water coral colonies on the

North-West Rockall Bank, and bedrock and biogenic reef and coral rubble on the East Rockall Bank (Howell, Huvenne, Piechaud, Roberts, & Ross, 2014). Collation of data from these collaborative surveys, amongst others, were paramount to the identification of areas for designation as Special Areas of Conservation (JNCC, 2011, 2012).

Collaborative efforts, together with technological advances, have been key to improving ecological knowledge in the UK deep sea. For instance, they have led to the recording (and subsequent conservation priority listing) of several habitat types in the UK deep-sea area. This includes several OSPAR listed habitat types (such as 'coral gardens'; 'deep-sea sponge aggregations'; and 'sea pen and burrowing megafauna') considered to be under threat/subject to decline across the North-East Atlantic (OSPAR, 2008). Entirely new species and ecosystems have also been discovered and/or confirmed in the last 10 years, such as a deep-sea cold-seep in the Hatton–Rockall Basin (named the 'Scotia seep'; Neat et al., 2019). In addition, the increasing use in -omics techniques are shedding light on the ecological importance and potential innovative use of deep-sea ecological resources, such as the diverse array of microbes that inhabit the deep sea (Radax et al., 2012). For example, recent investigations into the biomedical potential of microbial communities associated with deep-sea sponges has found Actinobacteria as a promising source of natural products active against multiple clinically relevant bacterial pathogens (Xu et al., 2018).

The improved accessibility of remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), including submarine gliders, together with advances in older technologies such as deep-sea landers (e.g. Balfour, Williams, Cooke, Amoudry, & Souza, 2015), have facilitated the use of less-destructive and more time-efficient survey techniques. The manoeuvrability of ROVs enables effective investigation of the sea bed with improved control compared to, for example, towed or drop-down cameras (JNCC, 2018a); AUVs can collect several days' worth of geophysical, biological, and oceanographic data, independently of a vessel (JNCC, 2018b). During the research cruise in 2011, JC060, the use of new technologies such as ROVs and AUVs enabled more detailed studies of coral occurrence on the steep to near-vertical slopes of Rockall Bank than had previously been possible (Huvenne, 2011). Furthermore, implementation of sensor technologies such as moorings and surface floats, as well as larger-scale observatories, are enabling longer-term data collection of physical and biogeochemical parameters (Levin et al., 2019). However, these technologies still have their limitations, including challenges with accuracy and communications, high costs and long data-processing times (Levin et al., 2019).

Increasing research efforts and technological advancements have also highlighted the increasing threats and pressures the deep sea is facing from anthropogenic activities. By the early 2000s, photographic imagery techniques aboard research vessels were used to report the impacts of bottom trawling on deep-sea soft sediment habitats (Roberts, Harvey, Lamont, Gage, & Humphery, 2000). During the JC060 survey, ROV dives at the Darwin Mounds indicated that much of the coral community previously known to occur in the area had not recovered after trawling impacts >10 years earlier (Huvenne, 2011). Marine litter was also identified from footage from multiple UK deep-sea surveys (Pham et al., 2014) highlighting extensive examples of marine litter occurring down to 4,500 m depth in UK waters (e.g. at the Wyville Thomson Ridge and the Dangaard and Explorer Canyons). ROVs were also used by the Scientific & Environmental ROV Partnership using Existing Industrial Technology (SERPENT) project to assess impacts of oil and gas drilling in deep sea. Waters. Jones, Gates, and Lausen (2012) found that 10 years after exploratory hydrocarbon drilling in the Faroe Shetland Channel, limited megafaunal recolonization occurred within an area of visible drill cuttings, although outside of the disturbed area partial recovery was apparent. Emerging technologies have therefore highlighted with greater clarity the need for further collection and consolidation of deep-sea ecological knowledge in systematic and accessible ways to inform conservation action.

2.3 | Progress in consolidating information for conservation action

Alongside collaborative research efforts and technological advances, which have led to improvements in the evidence base for the UK deep sea, there has also been progress in how this information is collated, stored, and categorized. Extensive efforts have been made in the last decade to collect and store marine environmental data at local, national, and international levels, for example the Marine Environmental Data Information Network (MEDIN, 2019) and the European Marine Observation and Data Network (EMODnet, 2019). More specifically, access to and sharing of deep-sea data is advancing, with new online portals making these data more easily accessible to multiple users. A deep-sea node of the Ocean Biogeographic Information System (OBIS, 2019)—a global data sharing platform—has been established, aimed at providing improved open-access to high-quality environmental deep-sea data and information. Furthermore, the International Council for the Exploration of the Sea (ICES) have developed, and update annually, an open access database and web mapper of VME habitat and indicator data from across the North Atlantic (ICES, 2016).

When it comes to data categorization, marine habitat classification systems are considered a useful tool in supporting the conservation of marine biodiversity (Howell, 2010). They define habitats in a standardized way, allowing similar data to be consistently assigned to particular habitat types so that one habitat can be compared with another. The Marine Habitat Classification for Britain and Ireland is the most comprehensive marine benthic classification system in use for UK waters (Connor et al., 2004). The addition of a deep-sea section in 2015 was a significant development, achieved once again through collaborative efforts (Parry et al., 2015). This process harnessed available empirical data and ecological understanding, gathered from UK deep-sea surveys, to classify a set of biotopes known to occur in the UK deep-sea environment (Bullimore et al., 2013; Howell, 2010; Howell, Davies, & Narayanaswamy, 2010; Piechaud & Howell, 2013) (Figure 1).

Biological, ecological, and environmental data collation and analysis are vital for furthering understanding of deep-sea biodiversity and ecosystem function. However, data to facilitate knowledge of the response

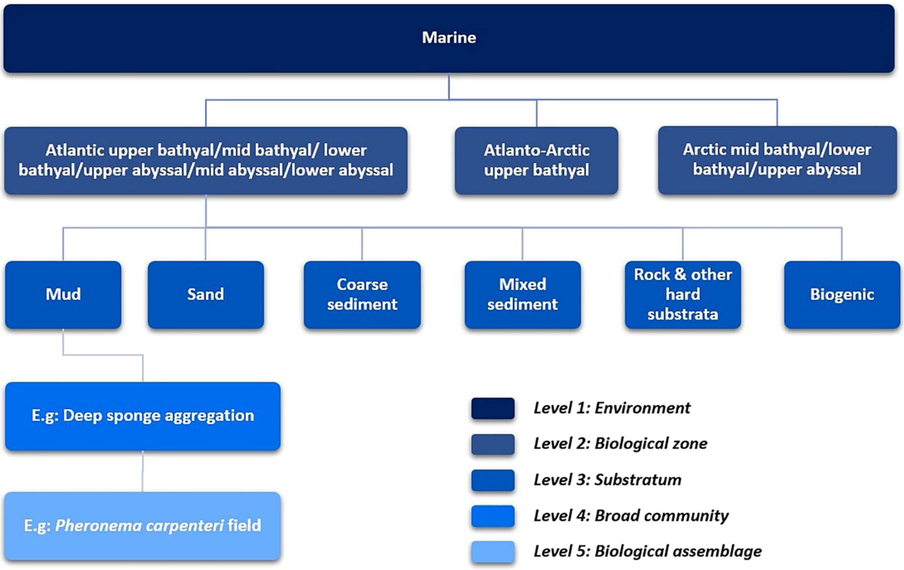

FIGURE 1 Structural levels of the deep-sea section of the Marine Habitat Classification for Britain and Ireland (re-drawn from Parry et al., 2015)

of biodiversity to natural and anthropogenic disturbance are also critical (Cunha, Hilário, & Santos, 2017). Collating current data and knowledge on the range of human activities and associated pressures occurring across the UK deep sea is a key step in progressing successful management and sustainable use of these ecosystems. The Marine Life Information Network (MarLIN) project has developed the Marine Evidence-based Sensitivity Assessment (MarESA) method, which aims to assess the resistance (i.e. tolerance) and resilience (i.e. rate of recovery) of biotopes listed within the marine habitat classification to a range of marine pressures (Tyler-Walters, Tillin, d'Avack, Perry, & Stamp, 2018). However, the deep sea has remained a significant gap due to limited evidence on the effects of pressures on deep-sea communities. Nevertheless, work by JNCC is collating the evidence available to address this gap (e.g. Last & Robson, 2019), which will support understanding of human-associated pressures affecting the deep sea.

3 | PROGRESS TOWARDS TAKING CONSERVATION ACTION IN THE UK DEEP-SEA ENVIRONMENT

Two primary forms of conservation action have taken place in the past 10 years in the UK's deep-sea environment: (i) the identification and designation of MPAs for habitats and species of conservation concern; and (ii) the recommendation and implementation of fisheries management measures. At the time of writing, over one quarter of the UK deep-sea environment was covered by MPAs and fisheries management measures—subject to various levels of active management (Figure 2). When including the 800-m ban on bottom trawling, this statistic increases significantly to over 90%.

3.1 | Marine protected areas

The establishment of MPAs has been a fundamental tool for the protection of marine ecosystems from the impacts of anthropogenic pressures around the globe (O'Leary et al., 2016). At the time of writing, 355 MPAs have been formally designated across all UK waters covering 25% of the UK marine area (JNCC, 2018c). To date, the identification and designation of MPAs has taken a 'feature-driven' approach; targeted towards specific habitats, species, ecological processes, and features of geological/geomorphological interest.

In the UK deep sea, protection efforts were initially focused towards examples of what would be classed as 'Annex I reef habitat' under the EU Habitats Directive (European Commission, 1992), The first UK deep-sea MPA, Darwin Mounds, was officially designated in 2008 (under the auspices of a ban on trawling implemented earlier in 2004, see case study below) for the protection of Annex I Reefs. However, legislative requirements under the Marine & Coastal Access Act 2009 (Defra, 2009) called for the development of an MPA network that represents the range of features present in the UK marine area and noted this may require the designation of more than one MPA for each type of feature. For the first time, this enabled MPAs in the UK deep sea to be designated for a representative range of features, where they are considered a suitable conservation tool, that would contribute to the conservation and/or improvement of the marine environment.

There are currently 14 deep-sea MPAs in the UK: six SACs under the EU Habitats Directive for the protection of reefs; two Marine Conservation Zones under the Marine & Coastal Access Act 2009 for the protection of cold-water coral reefs and soft-sediment communities of the deep sea bed; and six Nature Conservation MPAs also designated under the Marine & Coastal Access Act 2009 for the protection of a range of features classed by OSPAR as threatened and/or declining including deep-sea sponge aggregations and coral gardens (see OSPAR, 2008), as well as more representative examples of soft-sediment communities (Table 1; Figure 2).

Although enabling legislation in the UK for MPA designation has been introduced in a piecemeal fashion, MPA network development has followed the same guiding principles as set out by the OSPAR Convention, namely: (i) MPAs should be designated in areas that best

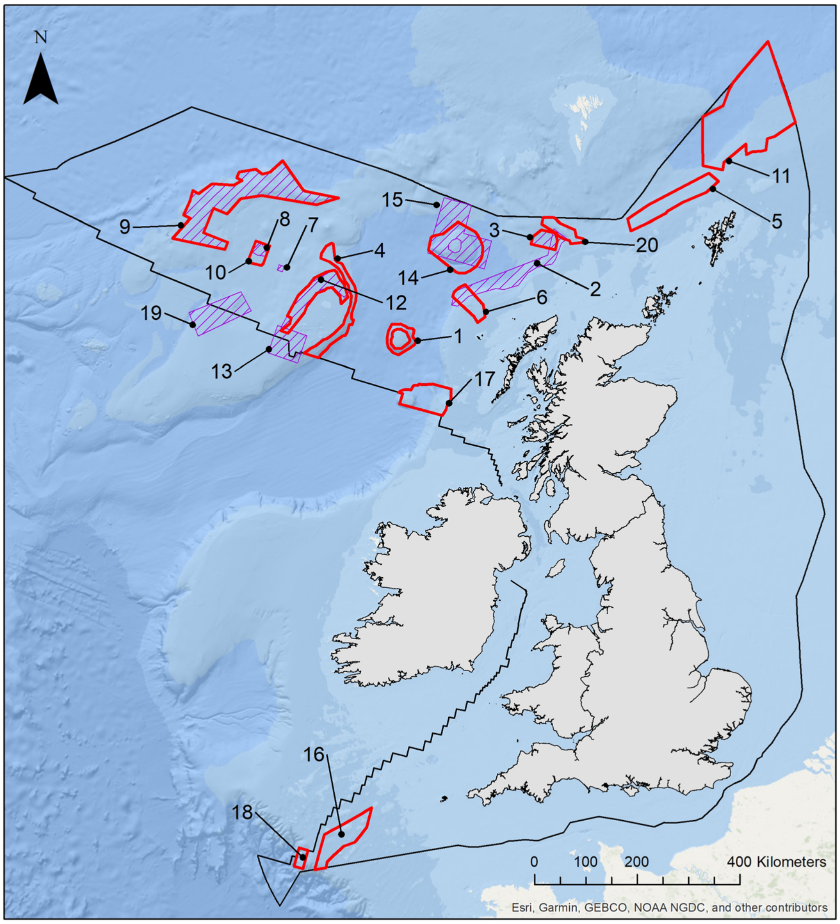

FIGURE 2 Spatial conservation measures in the UK deep-sea environment

represent the range of habitats, species and ecological processes and where MPAs are considered an appropriate conservation tool, with greater proportions of particularly threatened and/or declining features included (the principle of 'features'); (ii) MPAs should protect examples of the same features across their known biogeographical extent to reflect known sub-types (the principle of 'representativity'), (iii) MPA connectedness should be considered, approximated in the absence of dispersal and fine-scale oceanographic data by ensuring the MPA network is well distributed in space and noting where scientific understanding is further developed that the MPA network should reflect locations where a specific path between identified places is known (e.g. critical areas of a life cycle for a given species) (the principle of 'connectivity'); (iv) the replication of features in separate MPAs within a given biogeographic area is desirable and that the size of individual MPAs should be determined by the purpose of the MPA and be large enough to maintain the integrity of the feature(s) intending to be protected; and (v) MPAs should be managed to ensure the protection of the features for which they were selected and to support the functioning of an ecologically coherent network (the network principle of 'management'; adapted from OSPAR, 2006a, 2006b; Johnson et al., 2014).

Given that the implementation of appropriate management measures for deep-sea MPAs in the UK is still progressing, it is premature to determine their effectiveness in delivering conservation and/or improvement to the marine environment against their stated conservation objectives. Moreover, designation work in the UK deep sea is still ongoing. The 2018–19 Programme for Government (Scottish Government, 2018) included a commitment to consult on the creation of a national deep-sea marine reserve to complement the existing MPA network in Scottish waters. The use of large-scale MPAs such as marine reserves reflects ambitions for a more ecosystem-scale approach to marine conservation in the UK deep-sea environment; an approach advocated by others when developed to be complimentary to existing MPAs (e.g. Wilhelm et al., 2014). Indeed, large-scale MPAs offer the opportunity to explore conservation opportunities for wider components of the marine ecosystem such as deep-water

TABLE 1 Evolution of the UK deep-sea marine protected area (MPA) network

Site name	Designation type	Underpinning legal driver	Year of establishment	Protected features
Darwin Mounds	Special Area of Conservation	EC Habitats Directive (Conservation of Offshore Marine Habitats and Species Regulations 2017)	2008	'Reefs' (biogenic)
North-West Rockall Bank			2010	'Reefs' (biogenic, stony)
Wyville Thomson Ridge			2010	'Reefs' (bedrock, stony)
Anton Dohrn Seamount			2012	'Reefs' (bedrock, stony, and biogenic)
East Rockall Bank			2012	
Hatton Bank			2012	
The Canyons	Marine Conservation Zone	The Marine & Coastal Access Act 2009	2013	Deep-sea bed, cold-water coral reefs
Faroe-Shetland Sponge Belt	Nature Conservation MPA	The Marine & Coastal Access Act 2009	2014	Deep-sea sponge aggregations, offshore subtidal sands and gravels, ocean quahog aggregations, continental slope, a range of geological/geomorphological features
Geikie Slide & Hebridean Slope				Burrowed mud, offshore subtidal sands and gravels, offshore deep-sea muds, continental slope, a range of geological/geomorphological features
Hatton-Rockall Basin				Deep-sea sponge aggregations, offshore deep-sea muds, a range of geological/geomorphological features
North-east Faroe-Shetland Channel				Deep-sea sponge aggregations, offshore deep-sea muds, offshore subtidal sands and gravels, a range of geological/geomorphological features
Rosemary Bank Seamount				Deep-sea sponge aggregations, seamount communities, seamounts, a range of geological/geomorphological features
The Barra Fan & Hebrides Terrace Seamount				Burrowed mud, seamount communities, offshore subtidal sands and gravels, offshore deep-sea muds, orange roughy, continental slope, seamounts, a range of geological/geomorphological features
South-West Deeps East	Marine Conservation Zone	The Marine & Coastal Access Act 2009	2019	Deep-sea bed

fish and to account for factors such as bentho-pelagic coupling in the marine environment. Nevertheless, the deep-sea MPA network in the UK is believed to represent the range of deep-sea biodiversity for which MPAs are considered to be an appropriate conservation tool, but also provide replication for features of conservation interest (Chaniotis et al., 2018).

3.2 | Fisheries management measures

Fisheries management in the UK deep sea is driven by several pieces of legislation, including the United Nations Convention on the Law of the Sea (United Nations, 1994) and the Common Fisheries Policy (European Commission, 2013). Portions of the UK extended continental shelf claim (see The Continental Shelf [Designation of Areas] Order, 2013), which fall beyond the Exclusive Economic Zone (see Exclusive Economic Zone Order 2013), such as Hatton Bank and the Hatton–Rockall Basin, are regulated by the North-East Atlantic Fisheries Commission. This is a Regional Fisheries Management Organization and is responsible for the management of fish stocks and for taking measures to protect wider ecosystems in High Seas areas (areas outside the jurisdiction of country waters). In those portions of the UK extended continental shelf claim regulated by the North-East Atlantic Fisheries Commission, fisheries measures for resource management can come in various forms: fisheries closures (temporary or permanent), fishing permits, quotas, regulations on vessel metrics and gear types, and move-on rules to prevent significant adverse impacts on VMEs; as such they may indirectly benefit marine conservation.

TABLE 2 Overview of deep-sea fisheries management measures in the UK

Fisheries management measure	Description	Date of entry into force
EU Darwin Mounds closure	EC Regulation No. 602/2004: vessels are prohibited from using any bottom trawl or similar towed nets operating in contact with the bottom of the sea for the protection of deep-water coral reefs.	2004
NEAFC/EU North-West Rockall Bank	NEAFC Rec. 19 2014—as amended by Recommendation 09:2015 and Recommendation 10:2018 & EC Regulation No 40/2008: vessels are prohibited from using any bottom trawl or similar towed nets operating in contact with the bottom of the sea for the protection of deep-water coral reefs	2007
NEAFC/EU Rockall Haddock Box	NEAFC Rec. 19 2014 & EC Regulation No.1224/2009: closed to all fishing except with longlines for the purposes of protecting cold-water corals for the purposes of conserving juvenile haddock grounds.	2009
NEAFC Hatton Bank fisheries closure	NEAFC Rec. 19 2014—as amended by Recommendation 09:2015 and Recommendation 10:2018: these areas have been closed by NEAFC to all forms of bottom-contacting gear for the protection of VMEs such as corals and sponges.	2014
NEAFC West Rockall Mounds fisheries closure		2015
NEAFC Hatton–Rockall basin fisheries closure		2018
EU Blue ling protection areas:	EC Regulation No. 227/2013: restriction of blue ling catch during the spawning season.	2013
Edge of Rosemary Bank, Edge of Scottish Continental Shelf		
Restriction on demersal trawling below depths of 800 m	Regulation 2016/2336: applies to all EU waters and represents a complete ban on all forms of demersal trawling below 800m.	2016
Requirements for the reporting and protection of VMEs below 400 m	EC Regulation No. 2016/2336: applies to all EU waters and represents a requirement for Member States to identify where VMEs are known to or are likely to occur and for the prohibition of demersal gears in these areas.	2016

Fisheries management measures in the deep-sea area of the UK Exclusive Economic Zone are broadly focused on two main drivers: (i) measures designed to conserve deep-sea fish or non-target species for traditional stock and resource management, particularly those with life-history characteristics which make them vulnerable to over-exploitation, and (ii) measures specifically designed to protect deep-sea habitats such as VMEs. In practice, these two drivers are not mutually exclusive, and in many cases these regulations form the basis for the management of fishing activity in deep-sea MPAs. Notably, revisions to the EU deep-sea fishing regulations, which came into effect in January 2017 (2016/2336) (European Commission, 2016), are arguably more ambitious in scope than previous versions including provisions to restrict deep-sea fisheries to areas that have already been fished, a restriction on demersal trawls in waters below 800 m, and requirements to identify and protect VMEs in waters below 400 m (Table 2; Figure 2).

3.3 | Case study: conserving the Darwin Mounds

First discovered in 1998 during The Atlantic Frontier Environment Network survey (Bett, 2001), the Darwin Mounds are composed of coral colonies growing on sand mounds occurring at about 1000 m depth (Masson et al., 2003). They are located approximately 160 km north west of Cape Wrath, Scotland, at the north end of the Rockall Trough. Although the coral habitat on top of the mounds is formed primarily by *Lophelia pertusa*, another cold-water coral, *Madrepora oculata*, is also present. The thickets of cold-water corals provide habitat for a variety of marine macro-organisms, including fish, echiuran worms, brittlestars, starfish, and sponges (Bett, Billett, Masson, & Tyler, 2001; Costello et al., 2005), but also meio- and micro-organisms such as nematodes and foraminifera, often associated with the xenophyophore *Syringammina fragilissima* occurring in substantial numbers within the sediments of the mounds (Bett, 2001; Hughes & Gooday, 2004; Huvenne, Bett, Masson, Le Bas, & Wheeler, 2016; Van Gaever, Vanreusel, Hughes, Bett, & Kiriakoulakis, 2004).

Considerable damage to the area caused by deep-water trawling was first observed in 2000 (Bett, 2000; Wheeler, Bett, Billett, Masson, & Mayor, 2005). In response to a request by the UK, the European Commission introduced 'emergency measures' in 2003, under the reformed Common Fisheries Policy, to ban bottom trawling in a 1,380 km^2 area surrounding the Mounds, which became permanent in 2004. At the time, this represented the first example of an offshore fisheries closure being introduced primarily for nature conservation purposes as opposed to the management of fish stocks (De Santo & Jones, 2007). In 2008, the UK Government submitted the Darwin Mounds as a candidate SAC under the provisions set out in the EU

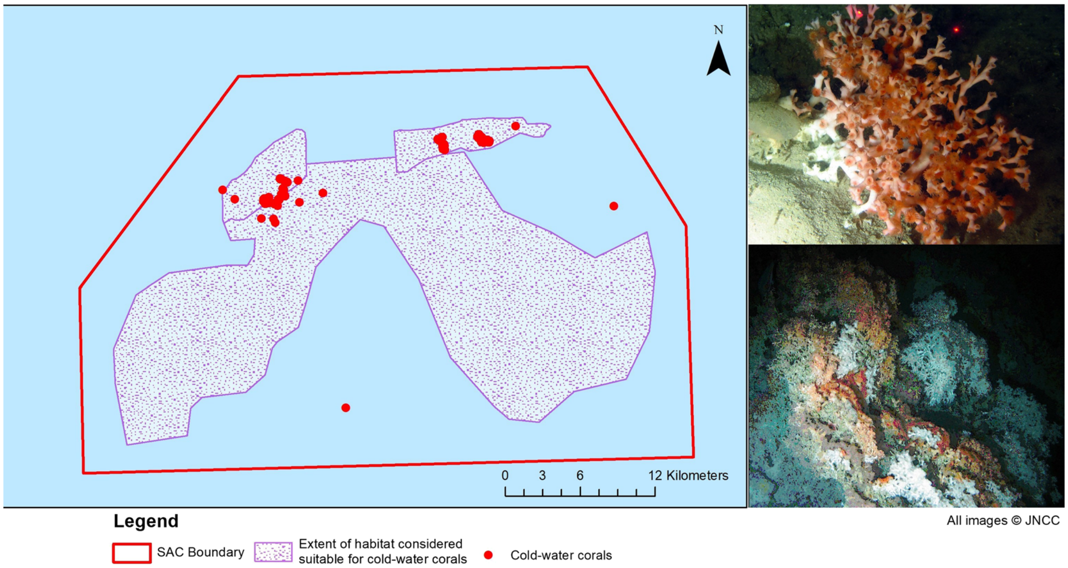

FIGURE 3 The Darwin Mounds Special Area of Conservation (SAC), showing the known distribution of cold-water corals and example images of *Lophelia pertusa* from the site

Habitats Directives (European Commission, 1992) for the protection of biogenic 'reef' habitat (namely reefs formed by the cold-water coral *Lophelia pertusa*) (Figure 3).

Subsequent surveys that have taken place to assess the effectiveness of the fisheries closure in achieving the conservation objectives of the SAC have shown that, whilst the closure has been successful in reducing fishing pressure on the cold-water coral reefs and in preventing further damage to the feature, there have been no signs of reef recovery since the fisheries closure was brought into force (Huvenne et al., 2016). While the reason for the absence of recovery is unknown at present, it might be linked with life history factors such as reproduction, larval dispersal and connectivity. Indeed, *Lophelia pertusa* at the Darwin Mounds SAC does not appear to exhibit sexual reproduction, displaying a high number of genetic clones and likely low recruitment rates of sexually produced larvae (Le Goff-Vitry, Pybus, & Rogers, 2004; Waller & Tyler, 2005). It appears that larval recruitment for recovery might be reliant on immigration, with larval supply to the Darwin Mounds SAC shown to be predominantly derived from Rosemary Bank Seamount (Ross, Nimmo-Smith, & Howell, 2017). Nevertheless, the Darwin Mounds SAC represented the first instance in the UK deep sea of two conservation actions being combined: an MPA designation and a fisheries closure.

4 | LESSONS LEARNED, CHALLENGES ENCOUNTERED AND FUTURE ACTIONS FOR UK DEEP-SEA CONSERVATION

Whilst understanding of the ecology and functioning of the UK deep-sea environment has improved significantly, there is much to reflect on to improve the way in which deep-sea heritage is conserved for generations to come.

4.1 | Improving knowledge of biodiversity

New deep-sea habitats and species are continuously being discovered and described following survey campaigns and research cruises (e.g. Bett, 2012; Huvenne, 2011; Neat et al., 2019), and understanding of speciation and phylogeography in the deep sea is increasing globally (Buhl-Mortensen et al., 2017; Easton et al., 2017). Advances in data collection technologies (e.g. Jones, 2009; Wynn et al., 2014) and development of predictive modelling approaches (e.g. Davies, Wisshak, Orr, & Roberts, 2008; Rengstorf, Yesson, Brown, & Grehan, 2013; Ross & Howell, 2013) have proven to be beneficial tools for improving knowledge of deep-sea biodiversity, habitat presence, and distribution, and bringing with them progress in conservation action (as reflected in the evolution of the implementation of MPAs and fisheries management measures). However, there are still extensive gaps in fundamental knowledge of deep-sea biodiversity and ecosystems, not only in the UK but on a global scale (Levin et al., 2019).

A European Marine Board position paper on "critical challenges for 21st century deep-sea research" (Rogers et al., 2015) reported stakeholder responses from a 2015 consultation regarding perceived gaps and limitations in deep-sea knowledge. Basic research was the most commonly identified priority action; in particular research targeted towards ensuring that sustainable development of the deep sea accounts for growing economic interest. Encouragingly, it was shown that the UK is exceeding many other European countries in terms of number of deep-sea publications (based on the ISI Web of Knowledge databases from 2004-2014), contributing to around 11% of scientific papers, versus <2–9% for other European countries, and a similar number to Germany at 12%. Common responses on perceived gaps included the need for long-term monitoring and sampling of fauna and environmental parameters to improve understanding of spatial and temporal variation, as well as basic data on the tolerance of deep-sea species to trawling impacts. Some of the most commonly perceived barriers to building this knowledge base included lack of funding and shortcomings in infrastructure (e.g. cost of ship time and lack of permanent deep ocean observation infrastructure).

Such deep ocean observation infrastructure does exist, and long-term monitoring of deep-sea sites outside UK waters is being achieved by multidisciplinary ocean observation programmes such as the Porcupine Abyssal Plain Sustained Observatory (PAP-SO), coordinated by the National Oceanography Centre. PAP-SO is the longest running open-ocean observatory in Europe and gathers long-term data from the atmosphere and sea surface down to the sea floor (at 4800 m depth), to the west of the UK in areas beyond national jurisdiction (Hartman et al., 2012). Within UK waters there are no current long-term observation programmes for deep-sea biology, although there are historical long-term biological monitoring sites established and run by Prof. John Gage of the Scottish Association for Marine Science at 2,900 m depth in the southern Rockall Trough, and 'Station M' at 2200 m at the base of the Hebridean Slope. There are also oceanography-focused programmes such as the Extended Ellet Line, run by the National Oceanography Centre and Scottish Association for Marine Science. This runs to the west of the UK, from the Rockall Trough inside the UK Exclusive Economic Zone, out to Iceland, measuring a range of oceanographic parameters and providing opportunity for additional data collection on annual surveys (e.g. Read, 2011).

However, even with these initiatives, and other global observation programmes, measurements are sparse due to the vastness of the ocean (Levin et al., 2019). One project aiming to address this lack of baseline data is the Deep Ocean Observing Strategy, initiated by the scientific community, which has ambitions for improved coordination and expansion of observation in the deep sea for environmental variables such as salinity and dissolved oxygen (Levin et al., 2019). These long-term monitoring programmes and projects will continue to support our understanding of changes in deep-sea communities and their environment over time, through establishment of baselines and improved understanding of natural versus anthropogenic variation.

4.2 | Developments in collaborative research efforts

The benefits of research collaboration are now well-established. Advancement in deep-sea science can, and will continue to, be achieved through better communication and continued join-up between industry, government agencies, and the research community a view also held by Levin et al. (2019) in their review of global observing needs for the deep sea. Data collected by industries to inform, for example, environmental impact assessments and compliance monitoring, can also be valuable for scientific research (Macreadie et al., 2018). The SERPENT project, which collaborates with the oil and gas industry to share knowledge and resources with the aim to improve understanding of deep-sea ecosystems worldwide, is a prime example. Through SERPENT, the oil and gas industry has provided video footage from the deep-sea sponge grounds in the Faroe Shetland Channel, assisting researchers in furthering the understanding of UK deep-sea ecosystems (Gates et al., 2017; Vad et al., 2018). Offshore industries can, in turn, benefit from collaborative work by developing a better understanding of the environment in which their activities take place, but also of how changes to that environment, whether biologically, from climate change, or in the context of changing management and the legal framework, can impact on their sustainability and longevity (Macreadie et al., 2018). These types of collaborative initiatives offer one way forward in furthering understanding of the ecology and conservation priorities for the UK deep sea.

Furthermore, the Foresight Future of the Seas report states that "Interdisciplinary marine science will be critical to furthering understanding of the sea, its value, and the impact of climate change and human activities on the marine environment" (Defra, 2018a). The United Nations' Decade of Ocean Science for Sustainable Development (from 2021 to 2030) should be a significant driver in bringing together ocean researchers at a global level to further conservation efforts over the next decades.

4.3 | Advances in technology

Advances in technologies have been crucial in progressing understanding of the deep sea, with technologies such as ROVs and AUVs being increasingly accessible and used. Improvements to technologies such as deep-sea landers, enabling additional environmental parameters to be measured, will also facilitate increased understanding of deep-sea ecosystem diversity and vulnerability, and collaboration with industry for use of such technologies, as shown through the SERPENT project, can support higher levels of survey coverage than would be achievable through independent scientific research alone (Macreadie et al., 2018). However, there remain several issues associated with their use, including long data processing times and high costs.

One developing method to help manage these challenges is the development of artificial intelligence for image analysis. For instance, following the collection of 140,000 images from a single AUV dive at Rockall Bank during the 2016 DeepLinks cruise, Piechaud, Hunt, Culverhouse, Foster, and Howell (2019) investigated the use of automated imagery techniques through computer vision (CV) to explore whether the time needed for manual image annotation could be reduced. They found that CV would currently be best applied to specific taxa that can be reliably identified (e.g. xenophyophores) but was less effective for more morphologically complex taxa. Whilst more research and development is needed to improve these types of CV techniques, continual improvements in technology and artificial intelligence could bring significant changes to methods of collection and analyses of deep-sea data in the future.

Novel techniques such as the use of environmental DNA may also increase both the amount and rate of accumulation of biodiversity data from the marine environment (Valentini et al., 2016). The development of novel inexpensive *in situ* samplers and sensors that can perform processing and analytics using genetic assays will revolutionize understanding of deep-sea ecosystems (McQuillan & Robidart, 2017). At present, both the application of environmental DNA techniques and the development of sensors are in their infancy and require further research; the next decade, however, will probably see significant developments in this field.

4.4 | Data collation and storage

A major barrier to successful advancement of deep-sea science is the "lack of an ability to share data in a timely and efficient manner" (Rogers et al., 2015). This can appear somewhat surprising given efforts over the last decade towards creation of various tools aimed at sharing and collating data related to the deep sea (e.g. the MEDIN and EMODnet networks, OBIS portal and ICES VME mapper). In fact, Murray et al. (2018) report that although many of the issues relating to the archiving, safeguarding, and availability of data are being managed, awareness and uptake of these tools across the full range of data collectors and users (e.g. offshore industries) is low. This may be due to the perception of reputational risk as well as financial challenges, for example establishing how data management will be paid for. Collaborating to develop trust and understanding between industry and researchers through projects such as SERPENT is a positive step to mitigating some of these challenges (Macreadie et al., 2018). In addition, development of open-access data sharing platforms, such as the initiatives provided through OBIS and ICES, provides a cost-effective mechanism to manage and share data.

4.5 | Furthering knowledge of threats, pressures, and impacts

Pressures and threats associated with anthropogenic activities occurring in the UK deep sea are expected to intensify in the future, particularly as coastal resources dwindle and demands for goods and services from the deep-sea increase (Armstrong, Foley, Tinch, & van den Hove, 2012). If left unmanaged, these pressures are likely to alter the provision of deep-sea ecosystem services by impacting on core processes and ecosystem function, as well as causing a decrease in biodiversity (Niner et al., 2018; Van Dover et al., 2017). Current levels of resource utilization are unlikely to be sustainable, although lack of knowledge hinders understanding of what constitutes sustainable, resource-efficient utilization (Vinde Folkersen, Fleming, & Hasan, 2018). This same lack of fundamental knowledge and understanding of the deep sea prevents the establishment of solid baselines to subsequently inform management plans for specific activities and allow for reliable environmental impact assessments (Rogers et al., 2015).

Continued investment is required in deep-sea research on cause and effect. Impact studies have, to date, focused on the most commonly-occurring activities causing pressures to the deep sea such as fisheries trawling, long-lining, and oil and gas extraction (e.g. Althaus et al., 2009; Fosså, Mortensen, & Furevik, 2002; Gage, Roberts, Hartley, & Humphrey, 2005; Gass & Roberts, 2006; Gates & Jones, 2012; Järnegren, Brooke, & Jensen, 2017). However, few impacts resulting from these pressures have been well-studied. In addition to these already known pressures, scientists will need to consider the threats of climate change and its effects on deep-sea biodiversity (Levin & Le Bris, 2015; Sweetman et al., 2017). Projections of change from climate pressures in the deep sea have recently been made using three-dimensional fully coupled earth system models. Under a 'current emissions' scenario in Representative Concentration Pathway 8.5, these models predict that the north-east Atlantic will be most affected by reduced pH, most severely at bathyal depths, as well as deoxygenation and a decline in export particulate organic carbon flux (FAO, 2019). Changes in these environmental variables and associated effects on biodiversity will need to be monitored and assessed over the long term if the implementation of management and mitigation measures can be successful. Moreover, policy approaches such as MPAs and other spatial management tools designed to improve the resilience of marine ecosystems to localized anthropogenic pressures will need to be adaptive and responsive to the potential implications of climate change in the deep sea, for example, changes in species distribution (Jackson, Davies, Howell, Kershaw, & Hall-Spencer, 2014).

While the MarLIN project and on-going work by the JNCC means that the sensitivity and resilience of a range of biotopes listed within the marine habitat classification, including the new deep-sea section, are being assessed for a range of marine pressures, there is much to gain from improving understanding of the functional importance and response mechanisms of a more widespread range of species and habitat types (e.g. soft-sediment and microbial communities) than those most commonly researched (e.g. cold-water coral reefs). However, it can be challenging to obtain data on such species and habitats; in part because they are not easily observed or assessed using current popular methods and technologies. Nevertheless, furthering our understanding of these systems will be critical in the near future, as it is likely that different systems, species, and habitats will respond differently to anthropogenic impacts and climate change (Glover & Smith, 2003). A more holistic understanding and evidence base, encompassing a variety of species and habitats representative of the UK deep sea, will be vital for the implementation of effective protection measures.

4.6 | MPAs and fisheries management

Due to the timeframes over which enabling legislation for the protection of the UK deep-sea environment have been put in place, the implementation of spatial protection measures such as MPAs and fisheries management measures has taken a largely piecemeal approach. However, UK Government and the Devolved Administrations have made decisions to act on conservation interests against a backdrop of relatively poor information by adopting a precautionary approach. This precautionary approach is advocated by others, based on the argument that in the face of increasing anthropogenic pressures, taking action to safeguard biodiversity in data poor situations is preferable to taking no action at all (e.g. O'Leary et al., 2012).

Reviews of UK deep-sea conservation need to critically assess the effectiveness of existing spatial protection measures in protecting the range of marine life for which these measures are appropriate and consider the efficacy of associated management in meeting stated conservation aims. Seabed habitats (which have been the primary focus of targeted conservation action to date) are just one component of the UK deep-sea environment. There are many other components including bony fish, elasmobranchs, and cetaceans that also utilize this area as part of their life histories (Macleod, Simmonds, & Murray, 2003, 2006; Swift et al., 2002; Weir, Pollock, Cronin, & Taylor, 2001) and these will require consideration as part of spatially focused or broader marine conservation strategies.

A more systematic and ecosystem-scale approach to conservation planning in the deep sea is now required, which accounts for the evolving understanding of how components of deep-sea ecosystems are linked (Evans, Peckett, & Howell, 2015; Wilhelm et al., 2014). There are already moves in the UK towards a more ecosystem-scale approach to marine conservation in the deep-sea environment, for example by exploring options for the creation of a large-scale deep reserve around Scotland (Scottish Government, 2018). At the same time, design and management of the UK deep-sea MPA network needs to be adaptive to account for emerging understanding of how the deep-sea environment responds to pressures and threats, and the functional importance of these ecosystems to human well-being (Ban et al., 2013).

Perhaps one of the most challenging aspects of MPA network design is the adequate incorporation of MPA network connectivity (Johnson et al., 2014) and indeed this may well call for trans-national collaboration (Metaxas, Lacharité, & de Mendonça, 2019), although very few have tested this in practice (e.g. Baco et al., 2016). An assessment of the connectedness of the UK deep sea MPA network has been made by Ross et al. (2017) with respect to cold-water coral reef habitat. However, whilst useful, it is not yet clear how such information might be practically included in network design. In an environment that is dominated by ecosystems typified by slow-growing and vulnerable species, it is perhaps timely to consider the implementation of more active intervention strategies such as deep-sea restoration techniques, rather than the simple reduction or removal of pressures associated with human activities; particularly as evidence to date suggests that the latter may not be wholly effective in delivering against stated conservation aims (e.g. Huvenne et al., 2016).

4.7 | Deep-sea restoration: a reality for the future?

Conservation action in the UK deep sea to date has focused on the legislative implementation of MPAs and other spatial protection areas; on the premise that the effective implementation of management measures will, in the longer-term, give rise to the recovery of damaged ecosystems and help safeguard those areas that have not been subject to damage from human activities, so that the biodiversity value and the services that the deep sea provides may be safeguarded for generations to come. These types of conservation strategies belong to the 'avoidance' category of action (Van Dover, 2014; Van Dover et al., 2017), meaning that the most straightforward means to mitigate a threat is to avoid its occurrence in the first place. Whilst being an important building block for conservation, avoidance measures may not always be feasible, possible, or effective—for instance if an activity is unavoidable for issues of over-riding public interest, or in cases where licences for activities have already been granted so that there are existing use rights in place.

Discussions around deep-sea restoration and rehabilitation have gained momentum around the globe (Macreadie, Fowler, & Booth, 2011; Van Dover, 2014; Van Dover et al., 2014), with a general consensus that, while it is likely to be more technically complex (due to the remoteness of the deep sea) and much more costly than coastal restoration (by several orders of magnitude), it is not unfeasible and should be given due consideration (Van Dover et al., 2014). Indeed, it is timely to consider restoration and biodiversity offsetting opportunities as more of a reality for the future in a UK context; given mention to the aim of embedding the concept of 'net gain' into the planning system as part of UK Government's 25-Year Environment Plan (Defra, 2018b) and as a component of their wider aim to ensure that we are the first generation to leave the environment in a better state than we inherited.

Unassisted, or passive, restoration, where a system is allowed to naturally recover over time once the threat is removed, can in certain contexts be effective. For instance, seabed communities have been observed to naturally recover over time following cessation of aggregate extraction on the continental shelf (e.g. Simonini et al., 2007). However, this lowest-cost approach may not always be effective in the deep sea, particularly where recovery needs more than simple removal of pressures that led to degradation in the first place. For example, following deep-sea nodule mining trials, seabed communities had still not returned to pre-mining conditions after nearly 4 years in the Central Indian Basin (Ingole, Pavithran, & Ansari, 2005), and after over 26 years in the Clarion–Clipperton Fracture Zone (Miljutin, Miljutina, Arbizu, & Galéron, 2011). Similarly, in the UK, *Lophelia pertusa* reefs had not showed signs of natural recovery following 8 years of a fishery closure (Huvenne et al., 2016; see the Darwin Mounds case study).

In the deep sea, effective restoration and rehabilitation may require some assistance (assisted natural recovery) or more active measures such as transplantations and translocations. Although, to our knowledge, large-scale active deep-sea restorations are not yet being undertaken anywhere around the globe, small-scale projects testing the feasibility of cold-water coral restoration and rehabilitation have been conducted. Translocation trials of *Lophelia pertusa* were quite successful in both the Gulf of Mexico (>91% survival, clear growth, and signs of asexual reproduction after a year; Brooke & Young, 2009) and in the Swedish Koster Fjord (76% survival and 39% size increase after 3 years; Dahl, 2013). In addition, a study in Sweden showed that low-current electrolysis in sea water (a method used for tropical coral restoration which promotes mineral accretion) led to higher growth and asexual reproduction rates of *Lophelia pertusa* kept in laboratory conditions (Strömberg, Lundälv, & Goreau, 2010). This method could be coupled with restoration techniques such as transplantation and translocation to increase efficiency and success. In the UK, we could not find evidence of active restoration being undertaken to date in the deep sea. However, a team in Scotland tested the development of an automated cold-water coral transplanting and monitoring robot (Lea-Anne Henry, personal communication)

The reality is that restoration costs are still prohibitively high (Van Dover et al., 2014). In such instances, offset schemes could be considered, whereby loss of biodiversity in one location is compensated by an increase either in the same location, or elsewhere where restoration is more easily achieved. Various types of offsetting are possible, but their application and ethics when related to the deep sea have been criticized (see discussion in Van Dover et al., 2017). In particular, Van Dover et al. (2017) explain that one of the fundamental ethical issues regarding deep-sea biodiversity offsetting is that "this practice assumes that loss of largely unknown deep-sea species and ecosystems is acceptable" (Van Dover et al., 2017). More than an ethical issue, loss of deep-sea biodiversity from anthropogenic pressures, whether offset or not, will be inextricably linked with loss of ecosystem function and associated services.

4.8 | Deep-sea ecosystem services: a natural capital perspective for the UK?

'Ecosystem services' and 'natural capital' are two emerging concepts used to better understand and manage natural resources, based upon trade-offs between social, economic and environmental perspectives. These concepts can be effective and useful tools for environmental decision-making and could be applied to the deep sea. Crucially, however, these concepts rely on a detailed understanding of the underlying ecological processes and valuation, which is challenging to achieve in practice (Armstrong et al., 2012; Thurber et al., 2014; Vinde Folkersen et al., 2018).

When considering natural capital and ecosystem services in relation to deep-sea ecosystems, the premise is that deep-sea ecosystems perform functions that are linked to the provision of numerous services from which society benefits, including nutrient cycling, climate-regulation, and food provision (see Armstrong et al., 2012 and Thurber et al., 2014 for a full review of deep-sea ecosystem services). Although less tangible, educational and research services, aesthetic services, and the sense of 'awe' towards the deep sea (cultural and spiritual services) are also of importance. Armstrong et al. (2012) claim that there is little prospect of ever being able to comprehensively value deep-sea ecosystem services. However, they also argue that not being able to measure or estimate the value of an ecosystem service does not infer that a value does not exist.

Efforts have been made towards the valuation of ecosystem services for deep-sea environments. For example, willingness to pay for deep-sea species protection and the option to harvest medicine in the future has been estimated at £70–77 per person in Scotland (Jobstvogt, Hanley, Hynes, Kenter, & Whitte, 2015). A study by Wattage et al. (2011) aimed to understand the economic value put on the conservation of deep-water corals damaged by fishing activity by the Irish public. Interestingly, there was a willingness to pay a ring-fenced personal tax of €1 per annum to support the protection of cold-water corals in Irish waters. Valuation studies encompassing the whole of the deep sea have also been undertaken, but with wide ranging estimated values: between 0.01 I$/km^2/year to 6 billion I$/km^2/year, with most observations <5000 I$ (Vinde Folkersen et al., 2018).

Whilst valuing (*sensu* assigning a monetary value to) deep-sea natural capital and associated ecosystem services can increase awareness of their importance and the need for conservation action, it is crucial to keep in mind that economic valuation might not solely hold positive outcomes. Indeed, it is still debated whether economic valuation and payments for environmental services can deliver equitable conservation outcomes (Muradian et al., 2013; Wunder, 2013). In some contexts, natural capital/ecosystem services valuation may lead to perverse or unforeseen outcomes. For instance, it could bring to light the monetary use-value (such as market value) of a resource leading to unintended consequences, such as intensification of resource extraction, or even the start of its exploitation if the resource is not yet exploited. This is particularly important in instances where the resources' use-values exceed non-use or intrinsic values (e.g. value from hydrothermal vent mineral mining vs. value from other non-mining services from hydrothermal vents such as marine genetic resources [used for pharmaceutical, biofuel, biomimetic purposes]; Van Dover et al., 2018). Another important point is that, at any given point in time, current values may differ significantly from future values, as factors such as overexploitation of resources (diminishing value) and the discovery or start of exploitation of another (adding value) come into play.

The value that society associates with the deep sea ultimately depends on how societal and economic aspects interact with deep-sea resources (Vinde Folkersen et al., 2018). Nevertheless, attempts at evaluating the deep sea will perhaps help understand the costs and benefits associated with specific human–environment interactions and assist in making informed conservation management decisions (Thurber et al., 2014). Indeed, describing and valuing natural capital and ecosystem services can be a useful tool in supporting conservation dialogue, given that these concepts can be easily understood by non-scientists, whilst using financial, monetary terms can provide incentives for decision-makers to take actions towards effective conservation of the environment (Jobstvogt et al., 2015).

In the future, it may be essential to incorporate these emerging concepts into deep-sea conservation and management strategies, and discussions with stakeholders and decision-makers. Continued efforts should therefore aim to estimate the monetary and non-monetary values of the deep sea and promote their application and use as incentives and rationale for conservation. The UK Government's "25-Year Plan to Improve the Environment" recognizes the need to take a natural capital approach to understand the full value of the marine environment and incorporate it within decision-making (Defra, 2018b). Whilst progress has been made in considering this concept from a deep-sea perspective, not just in the UK but internationally, there is much to be learnt and challenges to be acted upon if this concept is to play a role in marine environmental decision-making processes.

5 | CONCLUSION

Since the early days of deep-sea exploration, significant strides have been made to improve knowledge of the UK deep sea, aided by technological and analytical advances within the context of numerous successful collaborations between academics, industry and conservation practitioners. This knowledge, applied within the development of legal frameworks and initiatives, has supported the establishment of fisheries measures and marine protected areas, which in combination are intended to conserve and safeguard the UK deep-sea environment for generations to come. The Darwin Mounds SAC, the first deep-sea MPA established in UK waters, is a prime example of how advancing scientific understanding of the UK deep-sea environment, enabling understanding of existing anthropogenic damage to the area and thus implementation of management measures, can be applied in a conservation context. However, the effectiveness of such spatial conservation measures in achieving their conservation aims is yet to be fully determined, and in some cases is premature, as the implementation of appropriate management measures is ongoing.

Despite progress in conservation actions being undertaken on a precautionary basis as advocated, e.g. by Dunn et al. (2018) and O'Leary et al. (2012), there are still extensive gaps in fundamental knowledge of deep-sea biodiversity and ecosystems, and in the implementation of appropriate designs and strategies for spatial protection, particularly in relation to the connectedness of deep-sea marine ecosystems; a finding not unique to the UK but apparent at a global scale. Whilst continued exploration efforts, collaborations, and development of innovative analytical techniques and artificial intelligence will probably provide means and opportunities to develop further MPA and fisheries management options, adopting emerging alternative or complimentary conservation options could also be considered for the UK, such as habitat restoration techniques. Applying emergent concepts, such as natural capital and ecosystem services, to the deep sea to help frame its value, may also promote conservation by embedding these concepts into decision-making processes—as well as exploring the application of more direct interventions such as that of deep-sea biodiversity restoration techniques. Nevertheless, multiple challenges will continue to arise when it comes to the protection and conservation of the deep sea, due to its complex nature and the multiple stakeholders involved from environmental, political, social and (growing) economic spheres.

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