Healthy & Biologically Diverse Seas Evidence Group
Technical Report Series:

Evaluation and gap analysis of current and potential indicators for Deep Sea Habitats

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Preface

The UK Marine Monitoring and Assessment Strategy (UKMMAS) aims to provide coordinated and integrated marine monitoring programmes which support periodic assessments of the state of the UK marine environment. The strategy aims to provide vital data and information necessary to help assess progress towards achieving the UK's vision of clean, healthy, safe, productive and biologically diverse seas. The overarching strategy is supported and delivered by four evidence groups; Clean and Safe Seas Evidence Group (CSSEG); Productive Seas Evidence Group (PSEG); Healthy and Biologically Diverse Seas Evidence Group (HBDSEG) and Ocean Processes Evidence Group (OPEG). These groups are responsible for implementing monitoring and observations programmes to contribute to ecosystem-based assessments of marine environmental status.

As part of the HBDSEG programme of work, a series of reviews of environmental indicators was undertaken for the following marine ecosystem components:

1. Rock and biogenic reef habitats
2. Sediment habitats
3. Deep sea habitats
4. Seabirds and waterbirds
5. Cetaceans
6. Seals
7. Plankton
8. Microbes

The aim of the reviews was to evaluate a wide range of currently available and potential indicators for marine biodiversity monitoring and assessment. This task was undertaken particularly to inform future needs of the EU Marine Strategy Framework Directive (MSFD). The work was carried out by a group of consultants and contributors and was managed by JNCC.

Each review included a process to evaluate indicator effectiveness against a set of specified scientific and economic criteria. This process identified those indicators of activity, pressure, state change/impact and ecosystem structure and function that were considered to be scientifically robust and cost effective. The indicators which met these criteria were then assessed for inclusion within an overall indicator suite that the reviewers considered would collectively provide the best assessment of their ecosystem component's status. Within the review, authors also identified important gaps in indicator availability and suggested areas for future development in order to fill these gaps.

This report covers one of the ecosystem components listed above. It will be considered by HBDSEG, together with the other indicator reviews, in the further development of monitoring and assessment requirements under the MSFD and to meet other UK policy needs. Further steps in the process of identifying suitable indicators will be required to refine currently available indicators. Additional indicators may also need to be developed where significant gaps occur. Furthermore, as the framework within which these indicators will be used develops, there will be increasing focus and effort directed towards identifying those indicators which are able to address specific management objectives. There is no obligation for HBDSEG or UKMMAS to adopt any particular indicators at this stage, based on the content of this or any of the reports in this series.

This report has been through a scientific peer review and sign-off process by JNCC and HBDSEG. At this time it is considered to constitute a comprehensive review of a wide range of currently available and potential indicators for this marine ecosystem component.

Summary

A range of national and international legislation, obligations and commitments aim to promote and maintain a healthy and biologically diverse marine environment from intertidal waters to the deep sea. These require sustained and routine observations to achieve their objectives. This report evaluates the applicability of twenty seven potential environmental indicators, identifies gaps, and suggests indicators that could be used to monitor and assess the state of UK deep-sea habitats. These indicators are reviewed against potential anthropogenic pressures, together with ecosystem structure and function. Of these twenty seven indicators, eighteen were assessed as “recommended”, and can be mapped to the assessment framework and may be used within an integrated monitoring programme. Of the eighteen recommended, twelve are indicators of ecosystem structure/function, three of pressure, two of state change/impact and one is an indicator of activity.

The deep sea is the largest ecosystem on earth, and is thought to contain more species than any other habitat. While attaching a monetary value to the deep sea is difficult, it provides a number of important ecosystem functions which may alter in response to anthropogenic pressures. The deep sea also provides a range of ecosystem goods and services (i.e. human benefits directly or indirectly derived from ecosystem functions). In particular, maintenance of biodiversity is thought to be essential to ecosystem stability, so that loss of species may detrimentally influence ecosystem function, and therefore the provision of goods and services. The principal anthropogenic pressures that may have an impact on UK deep-sea habitats are identified as demersal fisheries, oil and gas industry activities, land-based/shipping pollution and climate change. At present, there are no routine UK deep-sea environment monitoring programmes and the only protected area in UK deep waters is the *Darwin Mounds* region. Regional and international statutory obligations are therefore not being fully addressed or fulfilled.

While a number of indicators address aspects of ecosystem structure of deep-sea benthic ecosystems, there are major gaps in indicators of ecosystem function, underpinned by our lack of knowledge of deep-sea ecosystems in general. While this lack of knowledge is being addressed by researchers, it is unlikely that ongoing research efforts will lead to the development of relevant indicators in the near future. The development of an effective monitoring programme will require improved knowledge of deep-sea habitats in UK waters, together with more research on the impacts of different pressures. Also, monitoring should not focus only on ‘charismatic’ species (e.g. corals and sponges); while these may act as “umbrella species”, a huge number of small, poorly known species live in the deep sea, forming the major component of the biodiversity and playing an important role in ecosystem functioning. Less charismatic species should not be overlooked from either a monitoring or conservation perspective.

The critical evaluation of the indicators highlighted significant gaps in their development and implementation:

- The extent, abundance and diversity of specific UK deep-sea habitats are poorly understood, or remain unknown. Surveys still recover many species which are new to science and there is a paucity of knowledge of deep-sea ecological processes. This restricts accurate assessments of the biodiversity of deep-sea benthic ecosystems, which is thought to be directly linked to ecosystem function.

- We have very limited data on the temporal variability of benthic ecosystems at bathyal depths, which may act as a baseline against which anthropogenically induced changes may be measured.
- The UK does not currently monitor bioaccumulation of contaminants of any kind in deep-sea organisms.
- There is no ecotoxicological information for deep-sea organisms.
- Molecular and biochemical indicators are potentially useful in revealing contaminant exposure and the health of species, but such techniques remain under development.
- While current fisheries VMS data can allow an assessment of fishing activity the data can be unreliable and is difficult to analyse.

The review of the anthropogenic pressures with regard to relevant indicators highlighted gaps in current deep-sea habitat monitoring efforts. Gaps that could be covered or addressed by the suggested indicators are:

- The impact of demersal fishing on UK deep-water habitats. This activity is not monitored and its impact is unknown in the vast majority of UK deep-sea habitats, although it is thought to be the principle pressure. This could be routinely monitored by photographic transects to measure extent, abundance and diversity of habitats, together with satellite-based vessel monitoring data to identify the location, extent and intensity of demersal fishing activity.
- No routine monitoring programmes on the sustained impact of oil and gas industry activity on deep-sea habitats are in place, although the industry is required to perform pre-operational baseline studies. Indicators for this include changes in faunal diversity around drill sites, which may be monitored by a variety of techniques. For deep-sea environments, photographic surveys are the most straightforward and cost-effective method.
- The extent and impact of litter/debris (shipping, fishing and land-based) is unknown in the deep sea. Photographic transects will show the extent and potential impact of litter.

We recommend two main methodologies which focus on the environmental impact of fisheries and the offshore oil and gas industry: Satellite based vessel monitoring system (VMS) and photographic surveys of benthic megafauna. VMS employs equipment already in place and may prove to be a cost-effective method for monitoring fishing activity. This is tightly linked to fishing activity, and can be used in fisheries monitoring and management to reduce the negative effects of demersal fishing. Monitoring of Potentially Vulnerable Marine Ecosystems and other habitat types (e.g. background mud, sand and rocky biotopes) can be carried out by photographic surveys which are cost effective and relatively quick. Photographic surveys would also produce data on litter abundance and distribution. In addition, benthic macrofauna may act as a useful indicator under certain circumstances (e.g. around oil and gas industry infrastructure), while existing long-term time-series studies provide unique information on the long-term effects of global warming.

Contents

1 Introduction

1.1 Aims and objectives of this report

This report aims to identify the most effective indicators of deep-sea ecosystem state, pressures and impacts. The work comprises five elements:

i a review of existing indicators for deep-sea habitats;

ii a review of the indicators against relevant pressures and ecosystem structure and function;

iii the identification of significant gaps and indicators which may be able to fill them;

iv an evaluation of the effectiveness of the indicators against standardised scientific and economic criteria;

v the recommendation of a set of indicators for deep-sea habitats that are effective scientifically and economically and could be used in future within an integrated monitoring and assessment programme.

1.2 Work undertaken in this report

This report builds on the work carried out for the initial Deep Seas Indicator Report (Smith and Hughes, 2008). It reviews indicators proposed in the earlier report and identifies further potential indicators against the OSPAR/UKMMAS assessment matrix. Current gaps in our knowledge are highlighted and additional/ alternative indicators are suggested and critically reviewed. This was carried out in a standardised manner using an online database developed by JNCC. A brief résumé of the pressures and impacts on the UK deep-sea floor is given to clarify the indicator needs of this habitat.

1.3 Deep-sea habitats

1.3.1 The ecosystem

Deep-sea sediments cover over 65% of the Earth’s surface. Microbial processes occurring there drive nutrient regeneration and global biogeochemical cycles essential to sustain primary and secondary production in the oceans (Gage and Tyler, 1991). We define the ‘deep-sea floor’ as that portion of the seafloor beyond the continental shelf break, which is situated at about 200m water depth in the NE Atlantic (Gage and Tyler, 1991). The deep sea is not the tranquil, monotonous environment it was once considered to be, and may experience phenomena such as elevated currents (“benthic storms”) as well as distinct seasonality in food inputs. There are a number of distinct deep-sea habitats in UK waters: abyssal plains, seamounts (rising >1000m above the sea-floor), carbonate mounds and continental slopes. Continental slopes, which form the majority of the UK deep-sea area, in turn contain a range of important habitats, such as coral mounds, sand contourites, terraces, and submarine canyons. Exposed hard rock is uncommon in the deep sea, being confined to steep continental slopes and seamounts in UK waters (Gage and Tyler, 1991). Each of these deep-sea habitats has its own distinct associated fauna. The European Nature Information System (http://eunis.eea.europa.eu/) lists the deep-sea habitat types in Europe, but this is generally considered to be incomplete and in need of development; some UK deep-sea habitat types are missing from the list.

The most extensive benthic surveys of deep UK waters (initiated by Atlantic Frontier Environmental Network) were carried out in the UK Atlantic Margin (North and Northwest of Scotland) for the Department for Business, Enterprise and Regulatory Reform (BERR) (formerly DTI) (Bett, 2001; Hughes *et al*, 2003). These Strategic Environmental Assessment (SEA) surveys have revealed distinct faunal habitats related both to topographic and hydrographic regimes (Bett, 2001; Hughes *et al* 2003). Such surveys still recover many species that have not been formally named and there is little knowledge of the detailed ecological processes that occur in these habitats.

The vast majority of the deep-sea fauna derive their energy from a ‘rain’ of detritus from the surface waters. The main exceptions to this rule are chemosynthetic environments (hydrothermal vents and colds seeps), which are fuelled by chemicals released from the seafloor. These systems have not yet been definitively identified in deep UK waters, although there have been reports of fluid flow (pockmark) sites in the SEA7 area to the north west of Scotland (Bett, 2001; Connor *et al* 2006). Most pockmarks are small (10s of metres across) and do not show up on conventional surface mounted multibeamed systems. These sites are potentially important because they have very distinct associated fauna (Hovland and Judd, 1988; Dando *et al* 1991). Because little research has been carried out on chemosynthetic environments in UK deep waters, it is difficult to predict how they will be impacted by demersal fishing activity and the oil and gas industry (Rogers *et al* 2008). The limited number of extensive UK deep-water surveys, coupled with the lack of suitable technology needed to see such features in the deep sea, has led to mainly anecdotal evidence on their distribution in deep UK waters. Limited TOBI (deep-towed sidescan sonar) data in deep UK waters has revealed a large pock-mark field adjacent to the *Darwin Mounds* in the northern Rockall Trough (Bett, 2001). A large area of polygonal faults has been observed in the Hatton-Rockall Basin (Weaver *et al* 2000), with traces of bacterial mats that have presumably resulted from waters being expelled along the fault planes (Colin Jacobs, pers. comm.). Further survey work is required to map these sites. More research on these chemosynthetic habitats is required before efficient assessment and monitoring can be carried out in accordance with statutory obligations and before they are irreversibly impacted by human activity, as has been observed at cold-seep sites in New Zealand waters (Baco *et al* 2008).

In the deep sea, low temperatures and a limited supply of food typically results in relatively low rates of growth, respiration, reproduction, recruitment and bioturbation in comparison to shallow-water ecosystems (Gage and Tyler, 1991; Smith and Demopoulos, 2003). The biomass of deep-benthic communities is less than that of shallow-water or terrestrial communities because of the reduced food availability (Smith and Demopoulos, 2003). Seamounts, carbonate mounds, sand volcanoes (e.g. the *Darwin Mounds*, NW Scotland) and submarine canyons (e.g. Whittard canyon, off the coast of Ireland) are exceptions, yielding relatively high biomass communities by focusing water flow and hence organic matter.

Some deep-sea species are known to live for several decades or even hundreds of years, and some species are adapted to seasonal changes in food supply (Gage and Tyler, 1991;

Gooday, 2002). Recently, evidence has emerged from time-series studies conducted over a period of a decade or more that long-term faunal changes occur in the deep sea. It has been suggested that these shifts may reflect changes in the quality of the food delivered to the seafloor, perhaps related to climatic oscillations (Billett *et al* 2001; Billett *et al* in press; Wigham *et al* 2003). It is important to understand these natural fluctuations in deep-sea communities in order to distinguish them from those arising as a result of human impact.

In the past the remoteness and vast extent of the deep sea has protected it to a large extent from human impacts. However, the low productivity and biomass of deep-sea ecosystems, coupled with the low physical energy of the environment increases sensitivity to such pressures (Glover and Smith, 2003; Davis *et al* 2007). Well-publicised habitats, such as the deep-water coral reefs off the Scottish coast, are likely to get protection from human pressures and impacts. There is the danger, however, that the much more extensive areas of soft sediment, which are also characterised by high biodiversity (Snelgrove and Smith, 2002) but are not so charismatic, may be overlooked. The high species diversity of soft sediment communities, believed to be maintained by small-scale environmental heterogeneity, can easily be disturbed. A multiscale spatial model synthesising information about anthropogenic drivers of ecological change has shown deep waters around the UK are highly impacted (Halpern *et al* 2008). At present, there are no deep-sea monitoring programmes in UK waters. Regulations require that the oil and gas industry perform an environment description at the beginning of a project (i.e. baseline survey to feed into the Environmental Impact Assessments (EIAs)), however, this does not have to be carried out if there is sufficient existing data available (e.g. SEA surveys have been performed in the drilling area). For monitoring, management and protection programmes to work successfully, we need to increase our knowledge concerning the location and ecology of the different deep-sea habitats in UK waters (Davis *et al* 2007).

1.3.2 Pressures and impacts on UK deep-sea habitats

Demersal fisheries. A shift from shelf fisheries to the deep sea has already led to the removal of late-maturing fish species that recover slowly (Devine *et al* 2006). Deep-sea fisheries concentrate in productive areas, such as seamounts and canyon walls, where levels of biodiversity and endemism in the benthic fauna can be high (De Forges *et al* 2000) although the degree of endemism can be low on north Atlantic seamounts (Hall-Spencer *et al* 2007). The fishing activities cause considerable ‘collateral damage’ to the benthic ecosystem by physically destroying habitat and removing key species (Roberts, 2002; Gage *et al* 2005; Davis *et al* 2007). In particular, trawling eliminates the larger, sessile organisms such as corals and sponges that create the spatial and structural habitat favoured by other species (Tissot *et al* 2004). It is likely that in its current form, deep-sea fishing is unsustainable (Davis *et al* 2007).

Benthic surveys are revealing the increasing extent to which bottom-trawling is altering deep-sea coral habitats (Hall-Spencer *et al* 2002). This is a particular concern because these reefs take centuries to millennia to develop (Hall-Spencer *et al* 2002). A comparison of fished and unfished seamounts has revealed much lower biodiversity and biomass at fished sites (Koslow *et al* 2001). In UK waters, colonies of the deep-sea coral *Lophelia pertusa* are at risk from trawling activities (Rogers, 1999; Roberts, 2002; Davis *et al* 2007; Rogers *et al* 2008) and some have already been impacted (Bett, 2000; Wheeler *et al* 2004; Clark and Koslow, 2007; Davis *et al* 2007; Hall-Spencer *et al* 2007). *Lophelia* has been reported along the continental shelf, on offshore seamounts, banks and attached to carbonate mounds and sand volcanoes (e.g. *Darwin mounds*) in UK waters. The species has also been reported growing on active oil platforms and on the decommissioned Brent Spar platform (Bell and Smith, 1999). An inshore reef complex has recently been mapped in the entrance to the Sea of Hebrides and there are many records of *Lophelia* on the Rockall Bank. In January 2008, the North East Atlantic Fisheries Commission prohibited bottom trawling and fishing with static gear from a number of large areas in the Rockall and Hatton banks (www.neafc.org), with the aim to protect deep-water corals. The other deep-water area to receive protection (trawling ban) is the *Darwin Mounds* region, inhabited by deep-water corals as well as very delicate giant protists (xenophyophores), which can grow to sizes of 20cm or more (Hughes and Gooday, 2004; Masson *et al* 2003).

Although not as picturesque or as widely reported as deep-water corals, sponge aggregations are also at risk from trawling (Hughes *et al* 2003). A photographic study on the impact of trawling on deep-sea sponges has revealed that no evidence of repair of tissues was evident after a year and many individuals died of tissue necrosis (Freese, 2001). They are described as ‘being of substantial ecological significance within the UK Atlantic Margin’ (Bett, 2001). Demosponge aggregations, or ‘*osterbund*’ as they are more commonly known, have been observed at mid-slope depths (~500m) north and west of Shetland, coinciding with iceberg ploughmark terrain (Bett, 2001) in regions where the currents are elevated and resuspension and transport of particles are enhanced (Klitgaard *et al* 1995). Demosponges have been impacted by trawling (Bett, 2001). The morphology of the sponges influences the occurrence and composition of the associated fauna, the majority of which use them as a substratum (Klitgaard, 1995). Unlike demosponges, hexactinellid sponges form aggregations in areas of open sediment. The HMS ‘*Lightning*’ and ‘*Porcupine*’ research cruises in the late 1800s first observed hexactinellid sponge aggregations in the northern Rockall Trough (Thompson, 1873). More recent surveys have found hexactinellids to be a principle component of the megafaunal community at 1000-1400 m in the SEA7 survey area NW Scotland (Hughes and Gage, 2004; Davies *et al* 2006). They also occur in the Porcupine Seabight (southwest of Ireland) (Rice *et al* 1990). Hexactinellid sponge aggregations create a very distinct habitat. Analysis of the abundance and taxonomic composition of the macrobenthos suggests the presence of sponge spicule mats at the sediment surface substantially modifies the fauna by increasing the numerical abundance of macrobenthos with increasing spicule abundance (Bett and Rice, 1992).

The OSPAR list of threatened and/or declining species and habitats includes seamounts, carbonate mounds, *Lophelia pertusa* reefs and deep-sea sponge aggregations. Octocorals (sea-pens, sea-fans and soft-corals), which are known by the habitat name of ‘coral gardens’ by OSPAR, also are included in this list, form part of the by-catch of demersal trawls (Edinger *et al* 2007). In the deeper SEA7 survey area, between 2000-3500 m, the soft coral *Acanella arbuscula* is highly abundant (Duineveld *et al* 1997b; Hughes and Gage, 2004; Davies *et al* 2006). This species has also been found at shallower depths (~1300m), where it is associated with fine sediments (Davies *et al* 2006). *Acanella arbuscula* is almost always seen in association with the ophiuroid *Ophiomuseum lymani* (a deposit feeding brittlestar) (Hughes and Gage, 2004). Therefore, if the octocoral is impacted through demersal trawling then it is likely that *O. lymani* will be adversely affected too.

Oil and Gas Industry. Initially, exploration for oil and gas resources was confined to shallow shelf seas. However, increased energy demands and the advancement of technology have meant that oil and gas exploration is moving into increasingly deeper waters, for example, the Faeroe-Shetland Channel. The expansion of the industry has provoked concerns regarding its impact on benthic communities in the deep sea. While the impact of drilling will mainly be confined to the area around the drilling structures, the impact may be significant. The major source of disturbance results from drill cutting spoil which may smother organisms, organic enrichment and the release of toxic chemicals (Kröncke *et al* 1992; Daan and Mulder, 1996; Currie and Isaac, 2005; Jones *et al* 2006; Jones *et al* 2007). Thirty years of North Sea drilling have left between 1 and 1.5 million tonnes of drill cuttings on the seafloor (UKOOA, 2002). It is possible that drill cuttings will pose a greater local environmental hazard in the deep sea than in shallow water because recovery rates will be lower (Glover and Smith, 2003). Only the drill cuttings produced by excavating the initial top-hole of the well are discharged directly onto the seafloor in UK deep waters (Hyne, 2001), however, drill sediment (cuttings separated from the mud, which is recycled) and the cuttings discharged at the sea surface can settle from the upper ocean to the deep seafloor around drilling platforms (UKOOA, 1998).

The content of drilling muds (used to prevent ‘blow outs’ and to lubricate the drill bit) is controlled by statutory and EU regulations. In the mid 1990s oil-based muds were replaced with light synthetic muds, but research showed these synthetic muds were not broken down naturally in seawater and so were phased out in the early 2000s (UKOOA, 1998). New regulations stipulate the use of water-based muds, although in some areas synthetic muds are still allowed. The toxicity of water-based drill muds is thought to be minimal; it is quickly diluted if released into the environment. Nevertheless, ecotoxicological research on the mud has shown some degree of toxicity in marine organisms, although this depends on the species involved and the contaminant (Terzaghi *et al* 1998). The effects of these water-based muds are currently being tested on deep-sea echinoderms (Sarah Murty Hughes, pers. comm.). Chemical contaminant effects in the deep sea have not been monitored and the impact of a complex mix of contaminants when influenced by a suite of environmental variables is difficult, if not impossible to predict from laboratory studies.

Many of the common effects on the fauna from drilling activity have been attributed to the discharge of cuttings contaminated with oil-based drilling mud (Olsgard and Gray, 1995). The most recent research into the impact of drilling on the deep-sea environment has assessed the physical disturbance caused by the discharge of cuttings (Jones *et al* 2006; Jones *et al* 2007; Gates and Pullen, 2008).

Changes in faunal composition have been used to assess the impact of drilling on the local environment (Olsgard and Gray, 1995; Jones *et al* 2006; Mojtahid *et al* 2006; Jones *et al* 2007; Gates and Pullen, 2008). Physical disturbance (i.e. sedimentation/smothering from drill cuttings) results in a reduced number of species, dominated by a few opportunistic species resulting in greatly reduced values of diversity indices (Olsgard and Gray, 1995; Jones *et al* 2006; Jones *et al* 2007). Effects attributed to toxicity and sediment disturbance/ smothering associated with drilling activities are evident in the benthos to distances of 50 to 250 m from deep-water platforms (Peterson *et al* 1996; Jones *et al* 2006; Jones *et al* 2007), although this can vary with current regime and nature of the drilling activity (Jones *et al* 2007). While there is some research modelling the dispersion of sea-surface discharged drill sediment (Khondaker, 2000; Hannah and Drozdowski, 2005), little is known about the potential extent and affect on deep-sea ecosystems. Factors other than the simple volume of drill cuttings, such as their particle size, hydrographic conditions, depth and the type of mud used are important variables in determining the extent of the impact on the community (Olsgard and Gray, 1995).

The oil and gas industry recognise their environmental impact and regulations have been put in place for companies to perform environmental impact assessments. An extensive survey of the deep benthic ecosystem west of Scotland was carried out in response to this requirement (Bett, 2001). This extensive survey also had a wider remit: to assess the potential impact of deep-water fisheries and provide a regional setting, enabling an assessment of larger-scale environmental processes that may not be evident at a local scale (Bett, 2001). Scientists are working with oil and gas companies to use their technology to further research in the deep sea (e.g. www.serpentproject.com). This has included determining the localised impacts of deep-sea drilling (Jones *et al* 2006; Jones *et al* 2007; Gates and Pullen, 2008). There is little or no information on contaminant exposure and its effect on deep-sea species. The Norwegian Deepwater Programme (NDP) is currently examining if exposure, dose and effect responses in shallow water organisms can be extrapolated to deep-sea species. This programme is also developing methods to examine uptake and effects in deep-sea species and examine hydrocarbon uptake and biomarker responses in selected invertebrates (Skadsheim *et al* 2005). There is currently little or no monitoring of environmental impacts by the oil and gas industry. Therefore, aspects of the national and international legislation, obligations and commitments related to healthy, productive and biodiverse seas are not being fulfilled.

Climate change. The deep sea is often considered as an ‘extreme’ environment. However, this is from a human perspective. Deep-sea organisms experience far more stability in terms of water temperature, salinity and currents than do their shallow-water counterparts and may not tolerate even small changes in these environmental parameters. Individuals, populations and communities will be affected by local and regional changes in upper ocean primary productivity, organic-carbon flux and thermohaline circulation driven by climate change (Glover and Smith, 2003). Given the uncertain influence of climate change on upper ocean processes, predicting the specific impacts on deep-sea ecosystems is difficult. Some predicted broad-scale changes certainly would have catastrophic consequences on deep-sea life. Possible changes in the global thermohaline circulation caused by climate change (Schmittner and Stocker, 1999; Bryden *et al* 2005) would have considerable impact on deep-sea fauna. These effects could be similar to the diversity fluctuations during the Cenozoic and Quaternary revealed by the microfossil (foraminifera and ostracod) record preserved in deep-sea sediments (Thomas and Gooday, 1996; Hunt *et al* 2005). At least in some cases, reductions in diversity were caused by changes in thermohaline circulation and must have had a substantial impact on ecosystem functioning (Danovaro *et al* 2008). In addition, climate-driven changes in upper-ocean biogeochemistry (Richardson and Schoeman, 2004; Orr *et al* 2005) will alter the quantity and quality of food arriving at the sea-floor, driving changes in deep-sea floor community composition (Billett *et al* 2001; Ruhl and Smith, 2004). Benthic biomass and abundance, bioturbation depth and rates have all been shown to be affected by food supply (Smith *et al* 1998; Smith and Rabouille, 2002; Smith and Demopoulos, 2003). Therefore, changes in the rates of these processes (ecosystem function) will in turn affect the sequestration and burial of carbon.

High atmospheric carbon dioxide concentrations caused by emissions from burning fossil fuels are recognised as a primary driver of global warming, but these emissions are also acidifying the oceans (IPCC, 2007). Deep-water masses in the NE Atlantic are relatively “young” because they originate in the Greenland-Norwegian Sea by the cooling and sinking of surface water. These acidified surface waters may be transported quickly (less than 5 years) to deep-water habitats around the UK. Decreases in pH will have a particular impact on organisms that secrete carbonate (aragonite or calcite) structures (Orr *et al* 2005). This is particularly applicable to the deep-water scleractinian corals that secrete aragonite skeletons because this form of carbonate is more soluble than calcite (Turley *et al* 2007). It is predicted that 70% of deep-water corals will be under the aragonite saturation limit by 2099 (Guinotte *et al* 2006). There have been no published experimental results on the impact of higher seawater CO_2 concentrations on deep-water corals. However, if deep-water corals respond in the same way as warm-water species, a substantial decrease in calcification would occur as a result of acidification (Kleypas *et al* 2006). Coccolithophores (a group of phytoplankton that secrete carbonate scales, or liths) will also be affected detrimentally by a decrease in pH (Orr *et al* 2005), and this will have implications on bentho-pelagic coupling. Changes in the phytoplankton community and the resultant biochemical composition of organic matter flux to the deep-sea floor has been shown to influence the biochemistry of deep-sea organisms, depending on their feeding adaptations and selectivity (Neto *et al* 2006; Smith *et al* in press). This in turn may give some species a reproductive advantage, leading to community change, as observed at the NE Atlantic Porcupine Abyssal Plain (PAP) time-series station (Billett *et al* 2001).

Land-based pollution. Pollutants may enter the deep-sea system if they are associated with particulate organic matter sinking from the upper ocean, as well as through long-range and long-term transportation by deep-ocean currents (Thiel, 2003). Submarine canyons along the continental shelf and slope play an important role in the transport of sediments and organic matter to deep basins and may also serve as a ‘fast-track’ for contaminants into the abyss (Ahnert and Borowski, 2000). A body of evidence shows persistent pollutants such as heavy metals, organochlorines, butyltins, polychlorinated biphenyls (PCBs) and dichloro-diphenyl-trichloroethanes (DDTs) are bioaccumulated by deep-sea fauna (Lee *et al* 1997; Moore *et al* 1997; Takahashi *et al* 1997; De Brito *et al* 2002; Harino *et al* 2005). There have been few ecotoxicological studies involving deep-sea organisms because of the remoteness of the ecosystems and the difficulty of carrying out experiments either *in situ* or at the ambient pressures. Differences in the physical environment, as well as differences in the physiology, behaviour and ecology of the organisms make it potentially misleading to apply with confidence the results of toxicological research on shallow-water organisms to their deep-water counterparts (Childress, 1995; Siebenaller and Garret, 2002). Ecotoxicological studies are required to assess the effects of pollutants on the deep-sea fauna at all levels of biological organisation.

Litter. Both marine and terrestrially derived litter has been recorded in the deep-sea environment (Galgani *et al* 2000; Gjerde, 2006; Weaver and Masson, 2007). The distribution and concentration of such debris appears to be affected by hydrodynamics, submarine geomorphology and human factors (Galgani *et al* 2000). Litter found in the deep sea includes fishing gear, clinker, plastic, glass bottles, metallic objects and plastic bags (Galgani *et al* 2000; Weaver and Masson, 2007). Accumulation trends of plastics and the presence of micro-plastics in the deep sea are of concern. The estimated longevity of plastics varies but, depending on the physical and chemical properties of the polymer, is thought to be in the range of hundreds or possibly thousands of years. In the deep sea this is likely to be greatly increased where light is absent and oxygen concentrations are low (Barnes *et al* 2009). In seawater plastics are known to sorb and concentrate contaminants. A range of additives used in the manufacture of plastics are potentially harmful and have been linked to endocrine disrupting effects (Teuten *et al* 2009). A likely transfer route for these chemicals is by ingestion of small and microscopic plastic fragments by benthic organisms (Teuten, 2007). Apart from the provision of an attachment substratum for sessile organisms, the impact of human debris on deep-sea benthic ecosystems is unknown.

1.4 Policy Background

National and international policy obligations

The UK depends on its seas to help meet a range of economic and social needs, for example, fisheries, recreation and natural resources. At the same time, they contain a range of important habitats and diverse forms of life, which are essential for the healthy functioning of the marine environment and ultimately contribute to its sustainability. For sustainable development, the resources and opportunities offered by our oceans and seas should only be utilised if we also protect their ecological processes and ecosystems (Defra, 2002, 2005). In response to this, Defra (Department for Environment, Food and Rural Affairs) embarked on the development of the UK Marine Monitoring and Assessment Strategy (UKMMAS, 2007). Within the UKMMAS, evidence groups have been established that are responsible for coordinating the work needed to achieve the goal of a sustainable marine environment. The Healthy and Biologically Diverse Seas Evidence Group (HBDSEG) is responsible for implementing monitoring and observation programmes covering ecosystem health, biodiversity and oceanographic processes. HBDSEG complements the other evidence groups for Clean and Safe Seas (CSSEG), Productive Seas (PSEG) and Ocean Processes (OPEG). These three groups all report to the Marine Assessment and Reporting Group (MARG), which in turn is governed by the Marine Assessment Policy Committee (MAPC). The MAPC oversees the UKMMAS structure, identifying the requirements for marine monitoring and assessment in order to meet national and international obligations and commitments.

There are a range of drivers in the UK (expressed as formal national and international legislation, obligations and commitments), which have been collated into a comprehensive list by the United Nations Environment Programme World Conservation Monitoring Centre (UNEP WCMC, 2006) to provide support for the further development of formal UK marine objectives. A set of Contributory Marine Objectives (CMOs) has been developed by the UKMMAS three evidence groups to compliment the Government’s overall vision for clean, safe, healthy and biologically diverse and productive seas. These objectives provide the overall policy framework to guide the UKMMAS. The CMOs are grouped under themes (Human Use, Healthy and Functioning Ecosystems, Optimising economic returns and Infrastructure and Social Integration) that will provide a body of work on which further development of High Level Objectives across Government and Devolved Administrations can build.

The UK is one of sixteen contracting parties to the Oslo Paris (OSPAR) Convention for the Protection of the Marine Environment of the North East Atlantic. The goals of the convention are to 1) maintain the structure and function of marine ecosystems, 2) protect its biodiversity, and 3) reduce levels of pollution, contamination and physical damage to acceptable levels (Defra, 2002). In order to meet its objectives, the OSPAR Convention has adopted several long-term strategies. The Commission’s Biodiversity Committee (BDC) is delivering OSPAR’s biodiversity strategy through a number of work streams to include: Ecological Quality Objectives (EcoQOs), assessment of threatened and declining species and habitats, designation of Marine Protected Areas (MPAs) and the assessment of human activities. A framework set out for assessing monitoring needs has been created by the UK and recommended for further development by OSPAR's Environmental Assessment and Monitoring Committee and the ICES (International Council for Exploration of the Sea) working group on Ecosystem Effects of Fishing Activities.

The European Union also recognises the need for the monitoring and assessment of the marine environment. The Marine Strategy Framework Directive (MSFD) was adopted in June 2008, which will require periodic assessments of the marine environment. The MSFD establishes European Marine Regions on the basis of geographical and environmental criteria. Each Member State - cooperating with other Member States and non-EU countries within a marine region - are required to develop strategies for their marine waters. The marine strategies to be developed by each Member State must contain a detailed assessment of the state of the environment, a definition of “good environmental status” at regional level and the establishment of clear environmental targets and monitoring programmes. This will include assessments on biodiversity and pressure (anthropogenic), with the aim of achieving a good environmental status for the marine environment.

1.5 OSPAR/UKMASS Assessment framework background

The assessment framework developed by JNCC was first presented to the OSPAR Convention’s Biodiversity Committee in February 2007 and has since gained wide support across OSPAR as a tool to guide the development of a strategic approach to biodiversity monitoring. It has been particularly welcomed for its potential benefit in meeting the needs of the Marine Strategy Framework Directive (MSFD).

The framework takes the form of a matrix which relates ecosystem components (e.g. deep-seabed habitats) to the main pressures acting upon them (e.g. physical disturbance to the seabed). The ecosystem components have been correlated with components used by OSPAR and the MSFD. The columns of the matrix are a generic set of pressures on the marine environment, which are based on those used by OSPAR, MSFD and the Water Framework Directive (WFD). A 3-point scale of impact (low, moderate, high) reflects the degree of impact each pressure has on an ecosystem component. Each cell of the matrix has additionally been populated with a set of known indicators[1], derived from statutory and non-statutory sources, which are used to monitor and assess the state of that ecosystem component. The assessment matrix helps to highlight priorities for indicator development and monitoring programmes, based on the likely degree of each impact on the ecosystem component in question.

Since 2007 this approach has also been introduced to the UK’s Marine Monitoring and Assessment Strategy (UKMMAS) and is being further developed by the Healthy and Biologically Diverse Seas Evidence Group (HBDSEG). The intention has been to have parallel development at UK and OSPAR levels which will help ensure similar biodiversity strategies are developed at national and international levels. It is also envisaged that the development process will benefit from wide input across OSPAR Contracting Parties.

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[1] Note: cells of the matrix where impacts have been identified currently contain a number of species and habitats on protected lists (OSPAR, Habitats Directive), which could potentially be used as indicators of the wider status of the ecosystem component which they are listed against. Should this be appropriate, certain aspect of the species or habitat (e.g. its range, extent or condition) would need to be identified to monitor/assess.

The overall goal of the UKMMAS is to implement a single monitoring framework that meets all national and international multiple policy commitments (UKMMAS, 2007). This will identify if there are any significant gaps in the current monitoring effort and aim to minimise costs by consolidating monitoring programmes. To help meet this goal, the assessment matrix has been developed with HBDSEG to provide a useful framework that analyses components of an ecosystem and their relationships to anthropogenic pressures. The framework aims to encompass three key issues: an assessment of the state of the ecosystem and how it is changing over space and time, an assessment of the anthropogenic pressures on the ecosystem and how they are changing over space and time, and an assessment of the management and regulatory mechanisms established to deal with the impacts.

The further development of the assessment framework has been divided into five shorter work packages: 1) assessment of pressures, 2) mapping existing indicators to the framework, 3) review of indicators and identification of gaps, 4) modifying or developing indicators and 5) review of current monitoring programmes. The following work will contribute to work package 3 and will critically review indicators, identify gaps and recommend an overall suite of the most effective indicators for the ecosystem component in question.

1.6 Definitions used in the report and analysis

Definitions of activity, pressure, state change/ecological impact and ecosystem structure and function are used within this report as follows (adapted from the 2008 CP2 methodology[2]):

***Activity* –** Human social or economic actions or endeavours that may have an effect on the marine environment e.g. fishing, energy production.

***Pressure* -** the mechanism (physical, chemical or biological) through which an activity has an effect on any part of the ecosystem e.g. physical disturbance to the seabed.

***State change/ecological impact* –** physical, chemical or biological condition change at any level of organisation within the system. This change may be due to natural variability or occurs as a consequence of a human pressure e.g. benthic invertebrate mortality.

***Ecosystem structure and function* –** ecosystem level aspects of the marine environment (i.e. structural properties, functional processes or functional surrogate aspects) which are measured to detect change at higher levels of organisation within the system (i.e. changes at ecosystem scales), that is not attributable to any pressure or impact from human activity e.g. natural changes in species' population sizes. Please see Annex 4.

Defined pressures list

The standard list of pressures against which indicators for this ecosystem component are reviewed is taken from the generic pressures list in the latest version (v11) of the UKMMAS / OSPAR assessment framework. Those pressures which are relevant to the ecosystem component (i.e. those that cause any impact on it) are used within the critical indicators review, gap analysis and this report.

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[2] Robinson, L.A., Rogers, S., & Frid, C.L.J. 2008. *A marine assessment and monitoring framework for application by UKMMAS and OSPAR – Assessment of Pressures and impacts* (Contract No: C-08-0007-0027 for the Joint Nature Conservation Committee). University of Liverpool, Liverpool and Centre for the Environment, Fisheries and Aquaculture Science, Lowestoft.

2 Methods and data sources

Indicators were identified in the initial indicator report, submitted to JNCC in 2008 (Smith and Hughes, 2008). Recent literature (post 2007) was reviewed to identify additional indicators and, where necessary, update existing indicators. Additional advice was sought, where necessary, from experts in specific fields relating to the indicators under consideration.

Information relating to each indicator was entered onto an on-line summary database, developed by JNCC, through which assessments were made of the scientific and economic value of individual indicators. The results of the assessment determined whether an indicator would be ‘recommended’ (see section 5.2).

The OSPAR/UKMMAS assessment framework identified pressures on deep-sea habitats for which no indicator was reported. Possible indicators to fill these gaps where identified from the Pressure Gap Report (Annex 1) generated by the on-line database.

Aspects of ecosystem structure and function for the deep sea not currently addressed by indicators were identified by reference to Structure and Function Report (Annex 2) generated by the on-line database.

3 Review of the existing indicators and critical evaluation

3.1 Current indicators summary

Twenty seven indicators were evaluated. Of these, eighteen were recommended and nine were not recommended (see Annex 3 and Table 3). The recommendation process comprises an evaluation based on a scientific and economic assessment of each indicator. As deep-sea research requires at least "moderate" platform requirements (e.g. ocean-going vessels) and equipment (e.g. deep-water cameras), together with lengthy planning of cruises, the score for the economic evaluation for all indicators assessed in this report is low.

3.1.1 Photographic analysis of habitat extent of potentially vulnerable ecosystems (ID: 1217)

Pressures: Atmospheric climate change, pH changes, Temperature changes - regional/national, Physical change (to another seabed type), Physical damage (abrasion and other physical damage), Removal of non-target species, No specific pressure

Activities: Extraction - non-living resources - oil and gas, bioprospecting, fishing – benthic trawling

Recommended

Potentially vulnerable ecosystems in the deep sea include deep-water coral reefs, seamounts, carbonate mounds, octocorals, demosponges and hexactinellid aggregations.

According to the EC Interpretation Manual of European Union Habitats (European Commission, 2007), reefs "can be either biogenic concretions or of geogenic origin. They are hard compact substrata on solid and soft bottoms, which arise from the sea floor in the sublittoral and littoral zone". The deep-water genus *Lophelia* is included in the list of reef-forming species.

The Marine Monitoring Handbook (Davies *et al*, 2001) presents a summary of general attributes that can be used as indicators of the health of reefs and to monitor the impacts from pressures. The extent (or shape) of a reef is unlikely to change significantly over time unless it has been physically impacted by a human pressure such as deep-sea fishing. The extent of deep-sea reefs can be traced using side scan sonar, although this method does not distinguish between live and dead coral. Photographic transects are therefore more beneficial, and can also be used to determine the biotic composition of the ecosystem, which provides another indicator of the health of a reef.

Although not as picturesque and as widely reported as deep-water corals, deep-sea sponge aggregations are also at risk from trawling (Hughes *et al* 2003; Shepard, 2006), and are also classified as "potentially vulnerable ecosystems".

The scientific literature on the effects of fishing on seamount habitats is summarised by Clark and Koslow (2007). The impact of demersal fisheries on reefs, seamounts and the associated deep-water coral, *Lophelia pertusa*, in NE Atlantic waters is discussed in papers by Roberts *et al* (2000), Fossa *et al* (2002), Hall-Spencer *et al* (2002), Wheeler *et al* (2004) and Shepard (2006). Using side-scan sonar, ROV (Remotely Operated Vehicle) footage and photographic transects these reports illustrate the mechanical damage to coral, and the trawl marks, caused by demersal trawling.

The extent of the impacts of the fishing industry is not fully known, and is not monitored. At present there is no routine monitoring of the impact of demersal trawling on *Lophelia* reefs or other deep-water habitats. Therefore, the UK is not meeting its statutory obligations. Repeated photographic surveys provide the most straightforward and cost effective method of monitoring the health of reefs and other deep-sea habitats as indicated by their extent.

3.1.2 Photographic analysis of habitat distribution of potentially vulnerable ecosystems (ID: 1332)

Pressures: Atmospheric climate change, pH changes, Physical change (to another seabed type), Physical damage (abrasion and other physical damage), Removal of non-target species.

Activities: Extraction - non-living resources - oil and gas, bioprospecting, fishing – benthic trawling.

Recommended

The known distribution of deep-sea corals on seamounts, oceanic islands and continental slopes in the Northeast Atlantic is detailed in Rogers (1999) and Hall-Spencer *et al* (2007). These records of deep-water corals records are concentrated around the Faroes shelf, Rockall Bank, Anton Dohrn Seamount, Rosemary Bank, Hatton Bank and Bill Bailey’s Bank and reflect the intensity of sampling/survey efforts (Rogers, 1999). The emerging picture is that *Lophelia* is widespread on UK continental margins.

The distribution of large demosponges in the deeper waters around the Faroe Islands and Faroe Bank is described by Klitgaard (1995). Bett (2001) reported the occurrence of demosponge dominated communities at mid-slope depths (c. 500m) north and west of Shetland and well developed sponge communities in the north and mid SEA 4 area although they are only poorly developed in the south of the area (Hughes *et al* 2003). Hexactinellid sponges were found during the HMS *Porcupine* Expedition to the northern Rockall Trough (Thompson, 1873). More recently they were observed at depths between 1000 and 1400m NW of Scotland in the Rockall-Hatton Basin (SEA 7 survey area) (Hughes and Gage, 2004; Davies *et al* 2006) and in dense aggregations in the Porcupine Seabight (Rice *et al* 1990). At present, however, we do not have a full understanding of the distribution of these organisms. Baseline information on the distribution and density of sponge aggregations, and the diversity of the species associated with them, are currently needed.

Repeated photographic surveys provide the most straightforward and cost effective method of monitoring the health of reefs and other deep-sea habitats as indicated by their distribution.

3.1.3 Structure of habitat-forming species (ID: 1218)

Pressures: Physical change (to another seabed type), Physical damage (abrasion and other physical damage), Litter, Removal of non-target species

Activities: Extraction - non-living resources - oil and gas, fishing - benthic trawling

Recommended

Habitat-forming species in the deep sea include deep-water corals, soft corals (octocorals), demosponges and hexactinellid sponges, and xenophyophores.

Despite our knowledge of the existence of cold-water corals since the time of Linnaeus (1707-1778), it is only in recent years that we have begun to unravel the geological and ecological complexities of the biogenic reefs formed by deep-water corals at high latitudes (Davis *et al* 2007). Cold-water reefs harbour a rich and distinct ecosystem and provide nursery grounds for species, including commercial fish species (Freiwald *et al* 2004).

Studies of octocoral forests around the British Isles show that a number of interactions occur between species in these habitats, increasing concern that unregulated trawling poses a threat (Myers and Hall-Spencer, 2004). The gorgonian soft coral *Acanella arbuscula* is abundant between 2000-3500m, in the deeper SEA7 survey area (Duineveld *et al* 1997a; Hughes and Gage, 2004; Davies *et al* 2006). This species has also been found at shallower depths (~1300m), where it is associated with fine sediment and strong current regimes (Davies *et al* 2006). Extensive octocoral forests have recently been described along the continental shelf break off Ireland at 1km depth (Hall-Spencer and Brennan, 2004).

Hexactinellid aggregations are linked to increased macrofaunal abundance and richness, in particular where they are surrounded by large deposits of sponge spicules (Rice *et al* 1990; Bett and Rice, 1992; Davies *et al* 2006). The sponges themselves are keystone species, which provide a habitat for many other invertebrates. The extent, structure and density of the sponge aggregations therefore may indicate the health of the ecosystem. Detailed analysis of the fauna associated with hexactinellid and demosponge aggregations will be more time consuming and expensive than photographic surveys.

More work is needed to describe the extent and abundance/density of octocorals and deep-sea sponges in UK deep waters. The main pressure on octocorals aggregations is demersal fishing. This activity is not monitored and its impact therefore unknown. As a result, the UK is not meeting its statutory obligations.

Xenophyophores, giant protozoans (up to 20cm diameter) are a dominant and conspicuous component of many deep-sea assemblages. One species, *Syringammina fragilissima*, has been shown to be abundant off the UK, for example at 1000m water depth in the Northern Rockall Trough in the vicinity of the *Darwin Mounds* (Hughes and Gooday, 2004). Due to their delicate nature, xenophophores are not recovered in benthic trawls (and are likely to be destroyed by trawling), although in recent years, photographic surveys have shown them to be common. In particular, they are often found in areas with enhanced organic carbon fluxes, such as beneath highly productive surface waters, on sloped topography, or near certain topographic features such as cauldera walls, basalt outcrops or on the sides of sediment mounds (Levin and Gooday, 1992). The tests of xenophyophores provide microhabitats for a range of other species, and are thought to act as hotspots of biological activity on the seafloor which enhance local habitat heterogeneity, and hence biodiversity (Hughes and Gooday, 2004)

Repeated photographic surveys provide the most straightforward and cost effective method of monitoring the health of deep-sea habitats as indicated by their structure and density.

3.1.4 Density of habitat-forming species (ID: 1333)

Pressures: Physical change (to another seabed type), Physical damage (abrasion and other physical damage), Litter, Removal of non-target species

Activities: Extraction - non-living resources - oil and gas, fishing - benthic trawling

Recommended

Habitat-forming species in the deep sea include deep-water corals, soft corals (octocorals), demosponges and hexactinellid sponges.

As sponges are keystone species, providing habitats for many other invertebrates the density of sponge aggregations may indicate the health of the ecosystem.

Repeated photographic surveys provide the most straightforward and cost effective method of monitoring the health of deep-sea habitats as indicated by their density.

3.1.5 Species diversity of potentially vulnerable ecosystems (ID: 1219)

Pressures: Atmospheric climate change, pH changes, Temperature changes - regional/national, Physical change (to another seabed type), Litter, Removal of non-target species, No specific pressure

Activities: Extraction - non-living resources - oil and gas, bioprospecting**,** fishing - benthic trawling

Recommended

Potentially vulnerable ecosystems in the deep sea include reefs, seamounts, carbonate mounds, demosponges, hexactinellid aggregations and octocorals.

Deep-water coral reefs support an abundant, distinct and diverse faunal community, creating ‘biological hotspots’ and can be an important habitat for commercially valuable fish species (Clark *et al* 2006).

Deep-sea sponge aggregations also harbour a wide diversity of invertebrates and constitute, next to coral reefs, one of the richest and most interesting biotopes (Bacescu, 1971). A distinction must be made between demosponges and hexactinellid sponges because they are associated with different substrata, and have their own distinct fauna (Bett and Rice, 1992; Klitgaard *et al* 1995). Demosponges are found on reef/rocky substrata and hexactinellid sponges are found in open sediment. Demosponges harbour species that use them as a substratum, so that the sponge morphology influences the occurrence and composition of the associated fauna. Hexactinellid aggregations are linked to increased macrofaunal abundance and richness, in particular where they are surrounded by large deposits of sponge spicules (Rice *et al* 1990; Bett and Rice, 1992; Davies *et al* 2006). The sponges themselves are keystone species, which provide a habitat for many other invertebrates.

The main pressure on potentially vulnerable deep-sea ecosystems is demersal fishing. This activity is not monitored and its impact therefore unknown. As a result, the UK is not meeting its statutory obligations The extraction of oil and gas from the seafloor produces localised affects (community change) around the drilling area, up to 250m from the drill head (Jones *et al* 2006), which may also impact on sponge aggregations.

3.1.6 Water quality parameters (ID: 1220)

Pressure: Atmospheric climate change, pH changes, Temperature changes - regional/national, Salinity changes - regional/national, Water flow changes (tidal and ocean currents) - regional/national, No specific pressure

Activities: None.

Not recommended

The effects of changes in water quality parameters has not been demonstrated for deep-sea assemblages, but any changes in deep-water thermohaline circulation are likely to affect benthic communities at all scales of organisation.

Given the great uncertainty regarding climatic influences on the surface ocean, predicting specific impacts in the deep sea is very difficult (Glover and Smith, 2003). Researchers are only just beginning to understand the potential impacts of climate change on global thermohaline circulation (Schmittner and Stocker, 1999; Bryden *et al* 2005; Scott *et al* 2008), which would have a catastrophic effect on deep water ecosystems.

Acidification arising from the increased flux of anthropogenic carbon dioxide to the ocean is thought likely to have significant ecological effects by the mid to late 21st century (Orr *et al* 2005, IPCC, 2007). Ocean pH has already fallen by 0.1 units since pre-industrial times and is set to fall another 0.3-0.4 units by the year 2100 if fossil fuel burning continues at its current rate. Acidification will trigger significant changes in oceanic carbonate chemistry with major adverse effects on calcifying organisms. In the deep sea, attention has so far been focused on reef-forming corals (Turley *et al* 2007), which may be particularly affected by the shoaling of the aragonite saturation horizon (the depth separating saturated and under-saturated waters). It is estimated that 70% of known scleractinian cold-water coral ecosystems will be in under-saturated water by 2100 (Guinotte *et al* 2006). There have been no published experimental results on the impact of higher seawater CO_2 concentrations on deep-water corals. However, if deep-water corals respond in the same way as warm-water species, a substantial decrease in calcification would occur as a result of acidification (Kleypas *et al* 2006). Other deep-sea calcifying organisms such as molluscs, crustaceans and many benthic Foraminifera will also be sensitive to ocean acidification but the full extent of future impacts is still uncertain.

Although the effects of changes in water quality parameters have not been demonstrated for deep-sea assemblages, changes in temperature, salinity and pH may influence the presence, distribution, recruitment processes and spawning behaviour of species.

Monitoring of water quality parameters is carried by academic researchers, e.g. NOCS and SAMS, Elliot Line Surveys (Allen, 2007) and the Faeroe-Shetland Channel is monitored by Marine Scotland - Science in Aberdeen.

3.1.7 Persistent anthropogenic compounds (ID: 1222)

Pressures: Non-synthetic compound contamination (inc. heavy metals, hydrocarbons, produced water), Synthetic compound contamination (inc. pesticides, antifoulants, pharmaceuticals)

Activities: Extraction - non-living resources - oil and gas, waste disposal - liquid - industrial and agricultural liquid discharges.

Recommended

Persistent anthropogenic compounds reach the deep sea. The presence of these compounds in the environment is a clear indication of anthropogenic pollution; these include organochlorines e.g. DDT, HCB and PCBs found in pesticides, fungicides and coolants/ paints, organotins e.g. TBT, used in antifouling paint), polycyclicaromatic hydrocarbons (oil and Gas industry water soluble contaminants and PCBs, by-products of combustion) and heavy metals e.g. Cu and Cd.

Measuring contaminant levels and comparing them against baseline levels will determine if contamination is increasing. If baseline levels are known, it is suggested deep-sea organisms can be used as biomonitors of contaminants (Moore *et al* 1997; Roberts *et al* 2000). However, often no distinction is made between contamination (raised levels of contaminant in comparison with the background level) and the impacts of the contamination (Olsgard and Gray, 1995). The effect of anthropogenic contaminants on freshwater and coastal marine organisms has been the subject of intense scientific investigation for many years. The USEPA Ecotox database (http://cfpub.epa.gov/ecotox/) includes over 220,000 records on aquatic species from tests on >4000 species and >7000 chemicals. None of these tests was performed on deep-sea organisms. It would be misleading to apply the results of shallow water toxicological research to deep-sea species, because their physiology, behaviour and ecology differ from their shallow-water counterparts (Sarah Murty-Hughes, pers. comm.). Some studies have shown that the bioavailability of contaminants may be modified at high pressure, leading to alteration in the toxicity of a compound (Skadsheim *et al* 2005). Although the deep-sea amphipod *Eurythenes gryllus* has been suggested as a sentinel species for monitoring levels and biological effects of contaminants in the deep sea (Camus *et al* 2006), it may not be a good biomonitor of contaminant levels from a direct source (i.e. oil and gas drilling activity), as this is a highly mobile scavenging species so that variable pollutant concentrations in specimens may result from feeding from spatially remote resources, i.e. distant from high contaminant levels (Koschinsky *et al* 2003).

The UK is not currently monitoring bioaccumulation of contaminants of any kind in its deep waters, in contravention of statutory obligations.

3.1.8 Megafauna

Megafaunal diversity (ID: 1303) Recommended.
Megafaunal abundance (ID: 1338) Recommended.
Megafaunal biomass (ID: 1339) Not recommended.
Megafaunal distribution (ID: 1340) Recommended.

Pressures: Atmospheric climate change, Non-synthetic compound contamination (inc. heavy metals, hydrocarbons, produced water), Siltation rate changes, Physical damage (abrasion and other physical damage), Litter, Removal of non-target species, No specific pressure.

Activities: Extraction - non-living resources - oil and gas, fishing - benthic trawling, infrastructure – cables, infrastructure – pipelines, infrastructure - offshore (oil and gas platforms).

Megafaunal community change comprises four separate indicators: abundance, biomass diversity and distribution. However these can not be considered in isolation. For example, a measure of faunal abundance has very limited value if considered in isolation. Evenness and Diversity Indices (e.g. Pielou's Index, Simpson's Index, Shannon-Weiner Index, Hurlbert Rarefaction) which are often used to assess the impact of anthropogenic inputs, require abundance data as well as data on species diversity for their calculation.

Megafaunal organisms are defined as those large enough (typically > 5cm) to be identified in photographs or caught in a trawl, and generally contain taxa such as echinoderms and decapods (Gage and Tyler, 1991; Gray and Elliott, 2009). Conventional environmental assessments do not generally address the megafauna. Monitoring of megafauna is effective for evaluating the impacts of disturbance on the seafloor. Photographic studies allow a fine-scale survey of megabenthic abundance, diversity and distribution. This allows a greater spatial extent to be covered than conventional macrofaunal sampling techniques; analysis of photographs and video is also relatively quick, and generally requires less taxonomic expertise.

Remotely Operated Vehicles (ROVs) have been successfully used to assess the impact of the oil and gas industry on the ecosystems surrounding drilling platforms in the deep sea (Jones *et al* 2006; Jones *et al* 2007; Gates and Pullen, 2008). Since ROVs are already in place and are primarily used to monitor the drill well and drilling platform, they offer a cost effective method of monitoring the impact of drill cuttings on megafauna. ROVs can also be used to take push cores for macro- and meiofaunal analysis and the data generated used in conjunction with the megafaunal data to obtain a detailed picture of the effects of drilling on the benthic environment (Gates and Pullen, 2008).

There are taxonomic limitations in using any of the indices that involve benthic fauna. This is most acute in the smallest size class, the meiofauana, where many of the species present may be poorly known, and undescribed. Macrofauna are the most common size class used as indicators in shallow waters. Faunal assemblages in the upper bathyal region (200-800m water depth) may contain many macrofaunal species also found on the continental shelf which are relatively well known. With increasing depth, however, the proportion of undescribed species will increase, making their use as an indicator more difficult. With all size classes, only a limited number of taxonomists have expertise in working with deep-sea species, particularly in the commercial sector.

3.1.9 Macrofauna

Macrofaunal diversity (ID: 1231) Recommended.
Macrofaunal abundance (ID: 1335) Recommended.
Macrofaunal biomass (ID: 1337) Not recommended.
Macrofaunal distribution (ID: 1336) Recommended.

Pressures: Non-synthetic compound contamination (including heavy metals, hydrocarbons, produced water), Siltation rate changes, Litter, No specific pressure.

Activities: Extraction - non-living resources - oil and gas, fishing - benthic trawling, infrastructure - cables, infrastructure - pipelines, infrastructure - offshore (oil and gas platforms).

As with the megafauna, assessing macrofaunal community change comprises four separate indicators: abundance, biomass diversity and distribution. However these can not be considered in isolation. For example, a measure of faunal abundance has very limited value if considered in isolation. Evenness and Diversity Indices (e.g. Pielou's Index, Simpson's Index, Shannon-Weiner Index, Hurlbert Rarefaction) which are often used to assess the impact of anthropogenic inputs, require abundance data as well as data on species diversity for their calculation.

The macrofauna is composed of animals that are retained on a 500 µm sieve (although some workers occasionally use other sieve sizes). The most abundant animals in the macrofauna are polycheate worms, bivalve molluscs, and crustaceans (Gray and Elliott, 2009). Individual macrofaunal species are affected by and in turn influence the structure of the sediment, facilitating an intimate link between the water column and sediment. The sedimentary fauna in general, and the macrofauna in particular, support higher trophic levels, especially the mobile hyperbenthic crustaceans and fish (Gray and Elliott, 2009). Monitoring of macrofaunal community change around oil and gas installations by seabed sampling has been carried out in shallow waters in conjunction with chemical sampling (e.g. the North Sea), but has not been carried out routinely in the deep sea. The AFEN study was carried out as a baseline for UK deep-water regions (Bett, 2001) and Hughes *et al*. (2003) synthesised the results of five surveys of deep sea macrofauna in the SEA4 area.

Changes in faunal abundance and biodiversity indicate impacts through organic enrichment, physical disturbance, toxicity or habitat change. Changes in ecosystem structure (species abundance and diversity) can be extrapolated to indicate the health of the ecosystem.

Box corers are the most commonly used sampling devise for macrofauna in the deep sea. However, in recent years hydraulically damped corers such as megacorers have been shown to be superior. It has been demonstrated that box corers underestimate macrofaunal abundances due to a bow wave effect (Gage and Bett, 2005).

3.1.10 Meiofauna

Meiofaunal diversity (ID: 1224) Recommended.
Meiofaunal abundance (ID: 1341) Recommended.
Meiofaunal biomass (ID: 1343) Not recommended.
Meiofaunal distribution (ID: 1342) Recommended.

Pressures: Atmospheric climate change, Non-synthetic compound contamination (inc. heavy metals, hydrocarbons, produced water), Physical damage (abrasion and other physical damage), No specific pressure.

Activities: Extraction - non-living resources - oil and gas, fishing - benthic trawling.

As with the other faunal size classes, four separate indicators address the meiofauna: abundance, biomass diversity and distribution. However these can not be considered in isolation. For example, a measure of faunal abundance has very limited value if considered in isolation. Evenness and Diversity Indices (e.g. Pielou's Index, Simpson's Index, Shannon-Weiner Index, Hurlbert Rarefaction) which are often used to assess the impact of anthropogenic inputs, require abundance data as well as data on species diversity for their calculation.

Meiofaunal organisms are those that will pass through a 0.5mm sieve, but that are retained on a 63 µm sieve (Gray and Elliott, 2009). The meiofauna is dominated by nematode worms and harpacticoid crustaceans, turbellarians and the Gastrotricha. The meiofauna may also include juvenile members of the macrofauna.

In pollution studies Giere (2009) suggests that meiofauna are preferable to macrofauna as, *inter alia*, they are widespread, even in small sites are usually abundant, have high species richness, short generation cycles and low sensitivity to mechanical disturbance of the sediment. A reduction in biodiversity has been related to a reduction in ecosystem functioning for benthic nematodes, but may be relevant for other faunal groups (Naeem *et al* 1994). A recent study of the relationship between ecosystem functioning and biodiversity in the deep sea has shown that higher biodiversity supports increased efficiency and higher rates of ecosystem processes (Danovaro *et al* 2008).

3.1.11 Biomarkers

A number of molecular, biochemical, histological, immunological, physiological and behavioural indicators can potentially serve as biomarkers of exposure, stress and adverse effects (Anderson and Lee, 2006; Sarkar *et al* 2006). Biomarkers have been used to indicate the exposure of shallow-water organisms to pollutants. Although the study of biomarkers in deep-sea animals is in its infancy, they may be a potentially powerful tool in future monitoring programmes (Kropp, 2004). Research on using biomarkers in deep-sea animals is currently under development at the National Oceanography Centre, Southampton through the SERPENT project (Sarah Murty Hughes, pers. comm.), at IRIS and Akvamiljø through the Norwegian Deepwater Programme (http://www.iris.no/Internet/akva.nsf), and at the Norwegian College of Fishery Science (Camus and Gulliksen, 2005; Camus *et al* 2006; Pampanin *et al* 2006).

i. Molecular biomarkers (ID: 1225)

Pressures: pH changes, Temperature changes - regional/national, Salinity changes - regional/national, Non-synthetic compound contamination (including heavy metals, hydrocarbons, produced water,) Synthetic compound contamination (inc. pesticides, antifoulants, pharmaceuticals), De-oxygenation

Activities: Extraction - non-living resources - oil and gas, infrastructure - offshore (oil and gas platforms), shipping

Not recommended

Up-regulated gene expression and the activities of stress-inducible defensive proteins and metabolic enzymes (citrate synthase, ubiquitin and 70kDA heat shock protein) can be used as biomarkers of environmental and pollutant induced stress. The number of mRNA transcripts from toxicant induced genes are an indication of the level of an organism's stress response.

Cytochrome P450 plays a key role in the biotransformation of contaminants that include dioxins, PCBs and PAHs (Sarkar *et al* 2006). It is expressed during exposure to contaminants and has been used as a biomarker of pollution in the North Sea in the sea star *Asterias rubens* (Den Besten *et al* 2001). Deep-sea studies have focused on cytochrome expression in fish (Kropp, 2004) and further research is needed if Cytochrome P450 is to be used in deep-sea invertebrates. DNA integrity can also be used as a biomarker of pollution; the integrity of DNA can be greatly affected by genotoxic agents, causing DNA strand breaks, loss of methylation and formation of DNA adducts (Ericson *et al* 2002). DNA adducts are sensitive biomarkers of exposure to genotoxic contaminants and are considered to be a cumulative index of current and past exposure (Ericson *et al* 2002). DNA integrity studies have been carried out on deep-sea fish and hydrothermal vent invertebrates (Pruski and Dixon, 2003; Kropp, 2004), but have so far not been used as a biomarker of pollution.

ii. Oxidative stress biomarkers (ID: 1227)

Pressures: Non-synthetic compound contamination (including heavy metals, hydrocarbons, produced water), Synthetic compound contamination (inc. pesticides, antifoulants, pharmaceuticals), Physical change (to another seabed type).

Activities: Extraction - non-living resources - oil and gas, shipping.

Not recommended

Immunological biomarker responses provide evidence of the deleterious effects of anthropogenic contaminants. Responses include changes in lysosome (digestive organelles) composition, integrity and morphometric parameters, and coelomocytes (cells that respond to injuries, host invasion and cytoxic agents). The antioxidant defence properties of deep-sea invertebrates is under development in Norway and includes three biomarkers for oxidative stress: Glutathione (metabolic detoxification), Total Oxygen Scavenging Capacity (capability of tissue to neutralise reactive oxygen species) and Catalase (an enzyme that catalyses H_2O_2 to $2H_2O + O_2$) (Larsen *et al* 2002; Camus and Gulliksen, 2005; Camus *et al* 2006). Oxidative stress is caused by an imbalance between the production of reactive oxygen and a biological systems ability to readily detoxify the reactive intermediates or easily repair the resulting damage. Antioxidant studies on mussels have shown that it is necessary to record baseline levels of these biomarkers at specific sites, before monitoring work commences, as relatively large differences among sites may occur naturally (Larsen *et al* 2002).

Further work needs to be undertaken to determine if deep-sea species found in UK waters can be used for this type of study. Firstly, a suitable sentinel species (or range of species) must be found; the deep-water coral *Lophelia pertusa* and "*Pogonophora*" tube worms (Siboglinid polychaetes) have been deemed unsuitable for such a study because the enzyme activity/ antioxidant levels were found to be below detection limits (Larsen *et al* 2002). The giant deep-sea amphipod *Eurythenes gryllus* has been suggested as a sentinel species for monitoring levels and biological effects of contaminants (Camus *et al* 2006). This species is widespread and abundant in the deep ocean (it has been recorded at depths of 7500m; Thurston *et al* 2002) and baseline data on its antioxidant capabilities has been determined (Camus and Gulliksen, 2004). *Eurythenes gryllus* is a highly mobile scavenging species, however, and sessile or slow moving species may be more suitable for assessing impacts from discrete contaminant sources (i.e. drill sites). Echinoderms are widespread and diverse in the deep sea and a number of reasons have been proposed for their use in ecotoxicological studies in shallow waters, which are also applicable to deep-water studies (Sarah Murty Hughes, pers. comm.):

a Benthic and infaunal echinoderms have direct contact with sediment-bound contaminants;
b They can be of reasonable size, giving sufficient tissue quantities for analysis;
c They have a key phylogenetic position, and the closest known relatives of the chordates;
d An extensive body of ecotoxicological work has been carried out on shallow-water echinoderms from eggs to adults, so that deleterious effects caused by various toxicants are well documented;
e They are relatively sedentary and therefore representative of a study area.

Ecotoxicological studies on echinoderms are under-development at the National Oceanography Centre, Southampton. The aim is to assess the gene expression of a metabolic enzyme (Citric Synthase) and two molecular chaperones (Ubiquitin and 70kDA Heat Shock Protein) in an analog deep-sea echinoid. It is important to note that stress experienced by deep-sea species during recovery may affect the gene expression of stress response biomarkers; this needs to be addressed before molecular biomarkers can be used in deep-sea species with confidence (Chris Hauton pers. comm.). Future work may aim to characterise patterns of stress-induced gene expression and correlate them to different stressors. This could be especially valuable in multiple stressor environments where toxicity may result from the cumulative effects of many stressors, each with many interactions (Snell *et al* 2003). It is also important to correlate gene expression with adverse effects on the animal, so that inferences can be made on organism and ecosystem health (Snell *et al* 2003).

Caution must be applied when using biological responses to identify exposure to contaminants, to monitor changes in contamination levels and to provide an early warning system of environmental deterioration. Six hypothetical time-integrated responses of biomarkers have been recognised and clearly demonstrate that the use of biomarkers without a thorough understanding of their initial induction, maximum induction, adaptation and recovery periods can lead to erroneous conclusions. Precise times for these processes (which will differ between animal groups and stressor type) must be understood so that sampling intervals are designed to avoid under or over estimation of pollution levels (see Wu *et al* 2005, for more details). Temporal variation in antioxidant enzyme activity has been observed in shallow-water species and deep-sea hydrothermal vent mussels (Company *et al* 2006). This has been related to temporal variations of reproductive status (Company *et al* 2006) and highlights the need for understanding temporal changes in baseline levels. A mixture of contaminants can make it difficult to relate biomarker responses to a particular contaminant class (Anderson and Lee, 2006) and certain types of chemicals may elicit a response much more rapidly than others (Wu *et al* 2005). Some biomarkers respond well to contaminant exposure but are not useful in the field because of high natural response variability (Huggett *et al* 2003).

The use of these biomarkers to monitor contaminants in the deep sea is being developed. They offer potential advantages for future monitoring by helping to achieve statutory obligations.

iii. Biochemical biomarkers (ID: 1228)

Pressures: Non-synthetic compound contamination (including heavy metals, hydrocarbons, produced water), Synthetic compound contamination (including pesticides, antifoulants, pharmaceuticals), Physical change (to another seabed type)

Activities: Extraction - non-living resources - oil and gas, shipping

Not recommended

Biochemical biomarkers, which have been used in shallow-water ecotoxicology studies, are potentially applicable to deep-sea organisms. Sewage sludge is known to contain high concentrations of metals (Forstner and Wittman, 1983) and deep-sea industrial activities are possible sources of heavy metal contamination (Koschinsky *et al* 2003). The concentration of heavy metals in deep-sea holothurians has been suggested as a proxy for sediment heavy metal concentration (Moore *et al* 1997), although, bioaccumulation provides no information on the health of the animal. Metallothioneins are non-enzymatic proteins that protect against metal toxicity. They have the potential to be used as biomarkers of exposure and therefore function as early warning signals of the presence of heavy metals (Sarkar *et al* 2006). Invertebrate metallothionein studies have mainly focused on molluscs, with some work on deep-sea hydrothermal mussels (Company *et al* 2006). Metallothionein induction can be estimated by different analytical methods (differential pulse polarography, radioimmunoassay, spectrophotometry, ELISA), by molecular approaches (protein expression) or as a function of the metals bound to the metallothioneins (Sarkar *et al* 2006).

These potential biomarkers will be subject to the same limitations as detailed for oxidative stress and molecular biomarkers. The use of biomarkers in the deep sea to monitor contaminants is in its infancy. The stress experienced by the organism during retrieval from the seafloor may affect the biomarkers being targeted; this problem needs to be addressed before such biomarkers can be used with confidence. Nevertheless, this approach may provide powerful tools in future monitoring programmes and offer the potential to help achieve statutory obligations.

3.1.12 Litter

Litter – abundance (ID: 1229).
Litter – distribution (ID: 1334).

Pressures: Physical damage (abrasion and other physical damage), Litter

Activities: Shipping

Recommended

A variety of anthropogenic litter (or debris) finds its way into the deep ocean, although plastics account for the major part because of their poor degradability. Glass or metal objects, clinker, as well as fishing gear debris can also occur in appreciable quantities (Galgani *et al* 1996; Galgani *et al* 2000). The presence of litter is both a pressure and an indicator. Little information is currently available concerning anthropogenic debris in the deep sea because considerable resources are required to undertake such a study. One survey on the French continental slope found that plastic bags accounted for a very high percentage of total debris and most debris was concentrated in canyons descending from the slope onto the abyssal plain (Galgani *et al* 1996). Photographic transect surveys could be amalgamated with monitoring of the UK deep-water benthos. A recent research cruise to the Whittard Canyon, SW Ireland (Weaver and Masson, 2007), revealed no evidence of litter accumulation (Paul Tyler, pers comm.). However, another recent (June 2007) study coordinated by MESH (Mapping European Seabed Habitats) in the SW Approaches (320km southwest of Lands End) revealed extensive fishing gear debris and plastic bags concentrated in the canyons in the survey area (www.searchmesh.net). Spatial variation in the concentration of debris may be related to the hydrographic regimes, geomorphological factors, anthropogenic activities and river inputs (Galgani *et al* 1996; Galgani *et al* 2000). More work is required in UK deep waters to assess the distribution and abundance of litter.

Smaller items such as plastic pellets (or nurdles/mermaids tears, the raw material of plastic products) and microscopic fragments of plastic from biodegradable composites and abrasive substances are also polluting the oceans. These fragments are widespread in the ocean and may persist for centuries (Thompson *et al* 2004, Barnes *et al* 2009). They can contain high concentrations of hydrophobic organic contaminants and have been shown to be important agents in the transfer of contaminants to organisms that ingest them (Teuten *et al* 2007). Some of these contaminants are potentially harmful and have been associated with carcinogenic and endocrine disrupting effects (Teuten *et al* 2009). Research on these small contaminants has so far focused on shallow water and coastal benthic environments. The impact of these pellets and fragments on the deep-sea environment is unknown. Advice from shallow-water plastic pellet/debris specialists may assist the design of a sampling protocol for monitoring the impact of plastic pellet debris on the benthos in deep UK waters. The impact of litter in UK deep-waters is not currently addressed; therefore statutory obligations are not being achieved at present.

3.1.13 Long term change in the deep sea benthos (ID: 1230)

Pressures: Atmospheric climate change, pH changes, Temperature changes - regional/national, No specific pressure

Activities: bioprospecting, fishing - pelagic trawling, biological, oceanographic survey (research, education), waste disposal - solid - munitions (chemical and conventional)

Not recommended

Deep sea fauna depend on organic matter created in surface waters by photosynthesis for food. The products of this primary production fall to the seabed as phytodetritus during the summer months. The flux of organic matter varies greatly from year to year owing to changes in climate and its effects on the upper ocean community. In the food limited environment of the deep sea changes in the flux have a profound and immediate effect on the structure of the benthic community providing a useful and powerful indicator of climate change.

A benthic sampling time-series established by John Gage and co-workers at two stations in the Rockall Trough (Gage *et al* 1980) ran from the mid-1970s to the early 1990s. This focused on growth rates and reproductive cycles of selected benthic invertebrate species rather than analysis of change at the community level, and the material collected has not so far been used to address this issue. The archive of data and unprocessed samples held at the Scottish Association for Marine Science is potentially a valuable source of historical information and efforts are underway to mobilize this with a view to re-starting the Rockall Trough time-series in the future.

The Porcupine Abyssal Plain Sustained Observatory site (PAP-SO) is situated 270km southwest of Ireland at a depth of c. 4850m. The site, remote from the continental slope to the east and the Mid-Atlantic Ridge to the west, is not subject to the other factors such as strong currents, temperature changes that effect many other time series especially in shallow water. The PAP has been studied since 1989, with the aim of determining how the seabed community and geochemistry of the sediments change in response to a highly seasonal input of organic matter from the overlying waters (Billett and Rice, 2001). The site was chosen for its distance from the continental slope and Mid-Atlantic Ridge, making it relatively free of any downslope sediment transport. Long-term change has been observed in the invertebrate megafauna at the PAP over a period of 10 years (Billett *et al* 2001). This change has been termed the '*Amperima* Event', characterised by an increase in abundance of the holothurians *Amperima rosea*, and *Ellipinion molle* by more than two orders of magnitude (Billett *et al* 2001; Billett *et al* in press). The community change seems to be linked to a change in the quality rather than the quantity of the organic matter reaching the seafloor (Billett *et al* 2001; Wigham *et al* 2003). Recent studies have shown that changes in the resources available to the animals can influence their reproductive biochemistry, depending on the feeding mode and selectivity of the species (Neto *et al* 2006; Smith *et al* in press).

Although the PAP-SO is not located directly in UK waters, the time-series provides a unique data set on deep-sea community change in the NE Atlantic, which may help us to understand faunal shifts that occur directly in UK deep waters. This time-series also helps to meet a statutory obligation and the CMO that is not adequately covered by the other indicators suggested so far: 1) 40 - United Nations Framework Convention on Climate Change, 2) 8b – characterise ocean and atmospheric processes to contribute to the overall UK understanding of environmental interactions.

Based on scientific sensitivity and accuracy, the evaluation process failed to recommend this indicator as being effective. However, the value of this long-term time series cannot be underestimated as a baseline for decadal time-scale change in faunal communities in the deep waters of the North East Atlantic.

3.1.14 Satellite based vessel monitoring system (VMS) (ID: 1315)

Pressures: Physical change (to another seabed type), Physical damage (abrasion and other physical damage), Siltation rate changes, Removal of non-target species.

Activities: Fishing - benthic trawling, fishing - pelagic trawling.

Recommended

From 1 January 2005 all vessels exceeding 15m overall length operating in European waters (EC, 2003) were required to install and operate satellite-based tracking devices. The data, transmitted to Fishing Monitoring Centres (FMCs) in the States to which the vessel is registered, include date, time, speed and position. In the UK these data are held by the Marine and Fisheries Agency. Transmissions are required at not more than two hourly intervals. Analysis of these data based on vessel speed and direction can allow identification of vessels engaged in demersal trawling. Limitations to this indicator are that it is often unclear what type of fishing is taking place and anecdotal evidence suggests that there may be misreporting of VMS data (ICES, 2007).

While VMS data may be suitable for managing and policing the activities of fishing vessels they do not indicate how the deep-sea ecosystem has been affected and may therefore not reflect the impact of this pressure on the deep-sea environment. Nevertheless, they may be useful in estimating the potential environmental impact. This indicator employs equipment already in place and so may prove to be a cost-effective method for monitoring fishing activity. However, in order to be an effective indicator of activity, these data and their analyses need to be available within a short time-frame if real-time management is to be achieved.

3.1.15 *Arrhis phyllonyx* (ID: 1205)

Pressure: No specific pressure

Activities: None listed.

Not recommended

Arrhis phyllonyx is a cold-water deep-sea amphipod crustacean (not shrimp, as detailed on the OSPAR matrix, as this term is attributed only to decapod crustaceans) that has its southernmost distribution limit at the Orkney Isles in the NE Atlantic (Lincoln, 1979). Its distribution is limited to cold waters, and it is abundant in areas such as deep Norwegian fjords (Thurston, pers. com). It has only been found in UK waters on a few occasions. This species is included in the UK's Biodiversity Action Plan (UKBAP), which was drafted in response to the Convention on Biological Diversity signed in 1992. As it is at the limit of its distribution, making it liable to considerable physiological stress, and is only found occasionally and in low abundances, *A. phyllonyx* is not a good indicator species for UK deep waters.

3.2 Evaluation of the effectiveness of indicator against standard scientific and economic criteria

3.2.1 Criteria used to evaluate indicators

In order to achieve a consistent critical appraisal of all indicators, the indicators for this ecosystem component have been reviewed and scored against the following set of criteria. These criteria have been built into the online indicators database application and the data has been stored electronically.

A Scientific criteria:

The criteria to assess the scientific 'effectiveness' of indicators are based on the ICES EcoQO criteria for 'good' indicators. The scoring system is based on that employed within the Netherlands assessment of indicators for GES (2008)[3]. A confidence score of 3 – High, 2 – Medium, 1 – Low is assigned for each question. A comment is given on the reasons for any low confidence ratings in the comment box provided within the database. All efforts have been made to seek the necessary information to answer criteria questions to a confidence level of medium or high.

Indicator Evaluation:

1. **Sensitivity: Does the indicator allow detection of any type of change against background variation or noise:**

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

2. **Accuracy: Is the indicator measured with a low error rate:**

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

If the indicator scores 1 or 2 for question 1 or 2, conclude that it is ineffective and do not continue with the evaluation –the indicator will still be stored within the database as considered but will be flagged as 'insensitive, no further evaluation required'

3. **Specificity: Does the indicator respond primarily to a particular human pressure, with low responsiveness to other causes of change:**

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

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[3] Langenberg. V.T. & Troost T.A. (2008). Overview of indicators for Good Environmental Status, National evaluation of the Netherlands.

4. Performance:

For questions 4a-f, if a score of 1 is given, please consider if the indicator is of real use. Please justify (within the report) continuing if a score of 1 is given. The following criteria are arranged with descending importance:

a Simplicity: Is the indicator easily measured?

Score	**3**	**2**	**1**	**Confidence**
Options	Usually	Occasionally	Rarely	

b Responsiveness: Is the indicator able to act as an early warning signal?

Score	**3**	**2**	**1**	**Confidence**
Options	Usually	Occasionally	Rarely	

c Spatial applicability: Is the indicator measurable over a large proportion of the geographical to which the indicator metric it to apply to e.g. if the indicator is used at a UK level, is it possible to measure the required parameter(s) across this entire range or is it localised to one small scale area?

Score	**3**	**2**	**1**	**Confidence**
Options	Usually	Occasionally	Rarely	

d Management link: Is the indicator tightly linked to an activity which can be managed to reduce its negative effects on the indicator i.e. are the quantitative trends in cause and effect of change well known?

Score	**3**	**2**	**1**	**Confidence**
Options	Usually	Occasionally	Rarely	

e Validity: Is the indicator based on an existing body or time series of data (either continuous or interrupted) to allow a realistic setting of objectives:

Score	**3**	**2**	**1**	**Confidence**
Options	Usually	Occasionally	Rarely	

f Relatively easy to understand by non-scientists and those who will decide on their use:

Score	**3**	**2**	**1**	**Confidence**
Options	Usually	Occasionally	Rarely	

***Thresholds for scientifically poor, moderate and good indicators*:**

Combine indicator evaluation scores for:

1. Sensitivity
2. Accuracy
3. Specificity
4. Performance

Evaluation Score	Indicator 'Effectiveness' Category
22-27	**Good**
16-21	**Moderate**
9-15 OR not all questions completed due to expert judgement not to continue	Poor

Further economic evaluation required - see section B below

B Economic criteria:

Having identified the most scientifically robust indicators using the above stated criteria, a further economic evaluation of those most effective indicators (i.e. those falling in the good or moderate categories) is carried out using the criteria stated below.

1. Platform requirements

Score	4	3	2	1
Options	None e.g. intertidal sampling	Limited e.g. coastal vessel	Moderate e.g. Ocean going vessel or light aircraft	Large e.g. satellite or several ocean going vessels

2. Equipment requirements for sample collection

Score	4	3	2	1
Options	Simple equipment requirements e.g. counting number of organisms	Limited equipment requirements e.g. using quadrats on the shoreline	Moderate equipment requirements e.g. measuring physiological parameters	Highly complex method e.g. technical equipment operation

3. Amount of staff time required to plan collection of a single sample

Score	4	3	2	1
Options	Hours	Days	Weeks	Months

4. Amount of staff time required to collect a single sample

Score	4	3	2	1
Options	Hours	Days	Weeks	Months

5. Amount of staff time required to process a single sample

Score	**4**	**3**	**2**	**1**
Options	Hours	Days	Weeks	Months

6. Amount of staff time required to analyse and interpret a single sample

Score	**4**	**3**	**2**	**1**
Options	Hours	Days	Weeks	Months

7. Amount of staff time required to QA / QC data from a single sample

Score	**4**	**3**	**2**	**1**
Options	Hours	Days	Weeks	Months

***Thresholds for economically poor, moderate and good indicators*:**

Evaluation Score	**Indicator 'Effectiveness' Category**
24-28	**Good**
19-23	**Moderate**
7-18	Poor

Those indicators which fall within the **'Good'** or **'Moderate'** economic category will then be tagged within the summary database as '**Recommended**' indicators. Indicators can also be 'recommended' via expert judgement even if the evaluation of the indicator does not score well enough to be automatically recommended. This judgement will be justified within the report text.

3.2.2 Additional information on the critical analysis of indicators

As there is currently no routine monitoring in UK deep-water habitats there is no body of literature upon which to draw. Owing to the lack of background data, responses to the scientific evaluation questions were frequently 'occasionally' and 'rarely' and confidence levels often 'medium' or 'low'.

For an indicator to be recommended scientifically, the sensitivity must be scored as "usually" for sensitivity. This is defined as "Does the indicator allow detection of any type of change against background variation or noise?" As the indicators assessed here are not in regular use in the deep sea, there is a degree of subjectivity in this assessment.

We know very little about ecosystem function in deep-sea habitats. This is not apparent from Appendix 2, because of the way indicator "associations" are tabulated. The on-line summary database allows the addition of ecosystem functions "associated with" each indicator.

Although the biological indicators (i.e. mega-, macro-, and meiofaunal indicators) change in response to a number of pressures, it is impossible to link these to specific pressures, especially when the pressure is general (e.g. climate change). However, the application and interpretation of the indicator must be understood within a particular context (e.g. the impact of oil industry infrastructure on benthic fauna).

The presence of litter in the deep sea is both a pressure and an indicator, and disentangling these two aspects is impossible. The OSPAR/UKMMAS assessment matrix identifies the impact of litter as ‘unlikely or negligible’ in deep sea habitats. There is wide geographic variation in the distribution and concentration of litter in the deep sea due to geomorphological and hydrological factors and monitoring is problematic. However the persistence of plastics in the environment, hundreds to thousands of years – possibly greater in the deep sea (Barnes *et al* 2009) and the degradation of plastic debris into micro plastics together with the, as yet, little known effects on organisms suggest that monitoring of marine litter is essential.

4 Gap analysis – Review of indicators against relevant pressures and important aspects of ecosystem structure and function

4.1 Review of indicators against pressures and identification of gaps

Please refer to the associated spreadsheet 'Deep sea Annex 1.xls'. This gap matrix was produced as a tool to aid authors in identifying significant gaps in current or potential indicators i.e. where important pressures on the ecosystem component have no suitable indicators associated with them. All recommended indicators have been prefixed with [R] and the cells containing them are coloured green.

It should be noted that if a single indicator is associated with more than one pressure within the pressures gap matrix, it may mean that this indicator responds to a range of pressures or the synergistic effects of a combination of pressures. Such an indicator would not necessarily be able to detect change which can be attributed to each individual pressure. Although the biological indicators (i.e. mega-, macro-, and meiofaunal indicators) change in response to a number of pressures, it is impossible to link these to specific pressures, especially when the pressure is general (e.g. climate change). However, the application and interpretation of the indicator must be understood within a particular context (e.g. the impact of oil industry infrastructure on benthic fauna).

Monitoring the deep sea is complex, time consuming and, relative to shallow water monitoring, expensive. There is currently no routine monitoring of deep sea habitats in UK waters so the long-term scientific effectiveness of potential indicators is unproven.

Annex 1 shows ecosystem components against pressures. This indicates that there is a suite of indicators available that address the impacts of all main pressures which are likely to affect deep-sea benthic ecosystems.; i.e. climate change, pollution and chemical changes (which in the deep-sea are likely to be as a result of activities of the oil and gas industry), and trawling (potentially leading to physical change to another seabed type as well as physical damage), with the indicators addressing specific aspects of these pressures. Only one indicator (1315; Satellite based vessel monitoring system) directly monitors the activity which may lead to the environmental pressure, in this case demersal trawling. Annex 1 also indicates that different indicators may be applicable over different deep-sea marine landscapes, as defined within the assessment. Areas of research which could be developed in the future to fill gaps are addressed in "section 7.3 Recommendations for areas of development to address significant gaps".

Table 1 shows ecosystem pressures, identified from the OSPAR/UKMMAS assessment matrix, not currently being addressed by recommended indicators contained within the summary database. The final column of the OSPAR/UKMMAS assessment matrix 'no specific or impacting activity' lists as indicators hydrothermal vents, deep-sea benthos biodiversity and morphology, benthic community structure and function (Porcupine), and *Arrhis phyllonyx.* These are all dealt with within the text of this report or incorporated within other indicators.

The impact of demersal fishing on UK deep-water habitats is not monitored and its impact is unknown in the vast majority of UK deep-sea habitats, although it is thought to be the principle pressure. This could be routinely monitored by photographic transects to measure extent, abundance and diversity of habitats, together with satellite-based vessel monitoring data to identify the location, extent and intensity of demersal fishing activity.

No routine monitoring programmes on the sustained impact of oil and gas industry activity on deep-sea habitats are in place, although the industry is required to perform pre-operational baseline studies. Indicators for this include changes in faunal diversity around drill sites, which may be monitored by a variety of techniques. For deep-sea environments, photographic surveys are the most straightforward and cost-effective method.

The extent and impact of litter/debris (shipping, fishing and land-based) is unknown in the deep sea. Photographic transects will show the extent and potential impact of litter.

Small-scale de-oxygenation arising from, for example, organic enrichment is not an issue affecting the deep sea (Table 1). Dissolved oxygen concentrations in marine waters resulting from increases in water temperature have been demonstrated for tropical deep-sea regions, and may be associated with increases in carbon dioxide concentrations in the water column (Stramma *et al* 2008; Brewer and Peltzer, 2009). However, this likely to exert only a negligible effect in the well oxygenated deep waters of the North Atlantic.

With regards to the “Introduction or spread of non-indigenous species and translocations” (Table 1), this is not considered an issue in the deep sea within UK deep waters. It should be noted, however, that the cold water species, *Paralithodes camtschaticus*, the red king crab, was introduced into Russian and northern Norwegian waters during 1960s and is present to depths of 300m. As this species is restricted to cold waters, it is thought extremely unlikely that this species will spread to UK waters.

Table 1. Pressures relating to deep-sea habitats, identified within the OSPAR/UKMMAS assessment matrix, not currently being addressed by recommended indicators contained within the summary database. (Impacts from the OSPAR/UKMMAS assessment matrix).

Pressure	Impact (taken from OSPAR assessment framework)	No indicator/ indicator not 'recommended' on JNCC Pressures Gap Matrix	Possible Indicator	Comment
Salinity changes - regional/national	Low	Not recommend: Water quality parameters (1220) Molecular biomarkers (1225) Long-term change in deep-sea benthos (1230)	None required	Can be measured directly
Water flow changes (tidal and ocean currents) - regional/national	Low	Not recommended: Water quality parameters (1220) Long-term change in deep-sea benthos (1230)	Changes in community structure (abundance, biomass, diversity and distribution) of mega, macro and meiofauna	Changes in the deep thermohaline circulation will potentially affect all levels of the ecosystem.
Emergence regime changes (sea level) - regional/national	Low	No indicator	None required	Not an issue in the deep sea
Wave exposure changes - regional/national	Low	No indicator	None required	Not an issue in the deep sea
De-oxygenation	Low	Molecular biomarkers (not a 'recommended' indicator)	Molecular biomarkers are under development	
Nitrogen and phosphorus enrichment	Low	No indicator	None required	Not an issue in the deep sea
Organic enrichment	Low	No indicator	None required	Not an issue in the deep sea
Physical loss (to land or freshwater habitat)	Low	No indicator	None required	Not an issue in the deep sea
Physical removal (extraction of substratum)	Moderate	No indicator	None required	Not an issue in the deep sea
Electromagnetic changes	Low	No indicator	None required	Not an issue in the deep sea
Introduction or spread of non-indigenous species and translocations	Low	No indicator	None required	
Removal of target species	Moderate	No indicator	None required	Not an issue in the deep sea. Species caught are as by-catch.

Table 2. Indicators, key pressures and indicator type.

Indicator	Primary Pressure	Indicator type
Satellite based vessel monitoring system	Physical damage (abrasion and other physical damage)	Activity
Photographic analysis of habitat extent of potentially vulnerable ecosystems	Physical damage (abrasion and other physical damage)	State change/Impact
Photographic analysis of habitat distribution of potentially vulnerable ecosystems	Physical damage (abrasion and other physical damage)	State change/Impact
Structure of habitat forming species	Physical damage (abrasion and other physical damage)	Ecosystem structure/function
Density of habitat forming species	Physical damage (abrasion and other physical damage)	Ecosystem structure/function
Litter - abundance	Litter	Pressure
Litter - distribution	Litter	Pressure
Persistent anthropogenic compounds	Non-synthetic compound contamination	Pressure
Species diversity of potentially vulnerable ecosystems	Physical change to another seabed type	Ecosystem structure/function
Megafaunal diversity	Non-synthetic compound contamination	Ecosystem structure/function
Megafaunal abundance	Non-synthetic compound contamination	Ecosystem structure/function
Megafaunal distribution	Non-synthetic compound contamination	Ecosystem structure/function
Meiofaunal abundance	Atmospheric climate change	Ecosystem structure/function
Macrofaunal diversity	Non-synthetic compound contamination	Ecosystem structure/function
Macrofaunal abundance	Non-synthetic compound contamination	Ecosystem structure/function
Macrofaunal distribution	Non-synthetic compound contamination	Ecosystem structure/function
Meiofaunal diversity	Non-synthetic compound contamination	Ecosystem structure/function
Meiofaunal distribution	Atmospheric climate change	Ecosystem structure/function
Oxidative stress biomarkers	Non-synthetic compound contamination	State change/Impact
Biochemical biomarkers	Non-synthetic compound contamination	State change/Impact
Molecular biomarkers	Temperature changes	State change/Impact
Water quality parameters	Atmospheric climate change	State change/Impact
Long-term change in deep-sea benthos	Atmospheric climate change	Ecosystem structure/function
Macrofaunal biomass	Non-synthetic compound contamination	Ecosystem structure/function
Megafaunal biomass	Non-synthetic compound contamination	Ecosystem structure/function
Meiofaunal biomass	No specific pressure	Ecosystem structure/function
Arrhis phyllonyx	No specific pressure	State change/impact

4.2 Review of indicators against ecosystem structure and function aspects and identification of gaps

Concepts of ecosystem structure and function may be useful in designing an overall framework for UK marine monitoring, as they are concepts that are inherent within the ecosystem approach and may help us to consider underlying processes rather than monitoring at small spatial scales or of small ecological scope (MRAG & UNEP-WCMC, 2007). Annex 2 identifies aspects of ecosystem structure and function associated with particular components. This shows that there are a number of indicators which may be used to examine various aspects of ecosystem structure. Ecosystem structure can be defined as “the taxonomic composition, biological diversity, or presence of specific habitats or species” (Bremner *et al* 2006), and this is relatively straightforward to measure using photographic techniques and benthic trawling for megafauna, together with core and grab sampling for meiofauna and macrofauna.

Annex 2 identifies only five indicators which provide information on ecosystem function: Photographic analysis of habitat extent of potentially vulnerable ecosystems (1217), Structure of habitat forming species (1218), Litter - abundance (1229), Photographic analysis of habitat distribution of potentially vulnerable ecosystems (1332), and Density of habitat forming species (1333). Between them, these only provide information on only two aspects of ecosystem function: delivery on recruiting organisms and trophic complexity. There are therefore major gaps in indicators of ecosystem function for deep-sea benthic ecosystems.

Ecosystem functioning involves a number of processes, which can be summarized as production, consumption and transfer of organic matter to higher trophic levels, organic matter decomposition, and nutrient regeneration. This can be assessed by measuring factors such as ingestion, absorption, respiration, defecation growth, and reproduction of individual organisms, populations and assemblages, and techniques are utilised in shallow-waters that could potentially be adapted for use in the deep sea. Ecosystem function is being investigated in the deep-sea by a number of scientific researchers; for example through “benthic landers” and *in-situ* experimentation (Gage and Bett, 2005; Witte *et al*, 2003). While this is an active area of research which is developing quickly, it is not yet at a stage where it can be used for the development of indicators which could be incorporated into a routine monitoring programme.

In recent years, the application of Biological Traits Analysis (BTA) has been successfully used to describe ecological functioning in marine benthic ecosystems (Frid *et al* 2008). Bremner *et al* 2006 suggest ten aspects of ecosystem function (physical and biological processes) which are considered as their key functions, and that could be used within a ‘pressure/function matrix”. In turn, 24 biological traits have been identified as indicators of key aspects of functioning. Unfortunately, for most of these traits we do not have data for deep-sea species (e.g. maximum growth rate, longevity, time to mature, fecundity, energy transfer efficiency, etc.) (Frid *et al* 2009). As yet, there is insufficient data available to apply the BTA method to deep-sea benthic assemblages, although this may prove a fruitful technique in the future.

A reduction in biodiversity has been related to a reduction in ecosystem functioning for benthic nematodes, but may be relevant for other faunal groups A recent study of the relationship between ecosystem functioning and biodiversity in the deep sea has suggested that a higher biodiversity supports increased efficiency and higher rates of ecosystem processes (Danovaro *et al* 2008). While biodiversity may therefore act as a proxy for ecosystem function, this is as yet unproven and requires further research.

5 Conclusions and recommendations

5.1 Database report tables

See attached Annexes:

Annex 1 contains the Gap Matrix Pressures report.
Annex 2 contains the Ecosystem Structure/function report.
Annex 3 contains the All indicators report.

5.2 Identification of an effective indicator set

Of the twenty seven indicators assessed eighteen are 'recommended' (See Annex 3, the "All indicators report"). Of these eighteen, twelve are indicators of ecosystem structure/function, three of pressure, two of state change/impact and one is an indicator of activity (Table 2 and Annex 3). The indicator which scored most highly (Table 3) in both the scientific and economic evaluation is Satellite Based Vessel Monitoring System, followed by Photographic Analysis of Habitat Extent of Potentially Vulnerable Ecosystems, Photographic Analysis of Habitat Distribution of Potentially Vulnerable Ecosystems, Structure of Habitat Forming Species and Density of Habitat Forming Species, followed by Litter Abundance and Distribution. We recommend that these are adopted as indicators within the context of a UK monitoring programme.

Due to its isolation, the deep-sea is subject to a limited range of anthropogenic pressures. However, it is increasingly subject to demersal fisheries and hydrocarbon extraction. Although there is a very real future threat from ocean acidification caused by climate change for species such as *Lophelia* the greatest current pressure to deep-sea habitats is from fishing. Here, we recommend two methodologies which therefore focus on the environmental impact of fisheries and the offshore oil and gas industry: VMS and photographic surveys.

5.2.1 VMS

This indicator employs equipment already in place and so may prove to be a cost-effective method for monitoring fishing activity. However, in order to be an effective indicator of activity, these data and their analyses need to be available within a short time-frame if real-time management is to be achieved. In addition, VMS is tightly linked to fishing activity, and can be used in fisheries monitoring and management to reduce the negative effects of demersal fishing.

5.2.2 Photographic surveys

Historically, studies of deep-sea benthic communities have relied upon sampling devices such as grabs, corers, trawls, etc. A number of indicators recommended here (i.e. Photographic analysis of habitat extent of potentially vulnerable ecosystems (1217), Photographic analysis of habitat distribution of potentially vulnerable ecosystems (1332), Structure of habitat forming species (1218), and Density of habitat forming species (1333)), are best addressed through photographic surveys of the seafloor, which can be accomplished using techniques such as epibenthic sleds and Remote Operated Vehicles

(ROVs). This has the advantage that it is non-destructive, while providing information on ecosystem structure, dynamics (e.g. bioturbation) and animal behaviour (Solan *et al* 2003). Monitoring of Potentially Vulnerable Marine Ecosystems, together with background habitats (i.e. those not considered “vulnerable”) can be carried out by photographic surveys. Given that the main pressure presently on deep-sea habitats is through demersal fishing activities, monitoring of extent, structure, diversity and distribution of potentially vulnerable ecosystems and habitat forming species should be carried out in areas where there is known fishing activity, with reference stations where there is none. These photographic surveys would also produce data on litter abundance and distribution (Litter abundance/distribution (Indicators 1229/1334)).

5.2.3 Macrofaunal studies

Specifically, these involve studying the distribution, abundance, biomass, and biodiversity of benthic macrofauna (i.e. indicators 1231, 1335, 1337 and 1342). While information on macrofauna provides highly relevant information on species distributions, biodiversity, ecosystem structure and potentially function the analysis of macrofaunal samples can be time consuming. While examining benthic macrofauna may be of use in small scale studies (e.g. monitoring around oil and gas platforms), as it has been used in shallow waters, it may be of more limited use in a routine, general monitoring programme. Developments in sample processing techniques, combined with increased knowledge of the taxonomy of deep-sea species, may allow this to become a more effective indicator in the future.

5.2.4 Long-term change in deep-sea benthos

The Porcupine Abyssal Plain Sustained Observatory (PAP-SO) has provided a unique data set on deep-sea community change in the NE Atlantic since 1989. This time-series helps us to meet a statutory obligation and Contributory Marine Objective (CMO) that is not adequately covered by other indicators. Based on scientific sensitivity and accuracy, the evaluation process failed to recommend this indicator as part of a routine monitoring programme. However, the value of this long-term time series cannot be overestimated as a baseline for decadal time-scale change in faunal communities in the deep waters of the North East Atlantic.

Table 3. Indicators addressed in this assessment, together with the pressures, scientific, economic and overall evaluation score and recommendation status. R = “Recommended”.

Pressures	Indicator	ID	Scientific Score	Economic Score	Total Score	R
Demersal fisheries	Satellite based vessel monitoring system	1315	Good	Moderate	46	Yes
Demersal fisheries /Oil and gas	Photographic analysis of habitat extent of potentially vulnerable ecosystems	1217	Good	Moderate	44	Yes
Demersal fisheries /Oil and gas	Photographic analysis of habitat distribution of potentially vulnerable ecosystems	1332	Good	Moderate	44	Yes
Demersal fisheries /Oil and gas	Structure of habitat forming species	1218	Good	Moderate	44	Yes
Demersal fisheries /Oil and gas	Density of habitat forming species	1333	Good	Moderate	44	Yes
Litter	Litter - abundance	1229	Good	Moderate	43	Yes
Litter	Litter - distribution	1334	Good	Moderate	43	Yes
Pollution	Persistent anthropogenic compounds	1222	Good	Moderate	43	Yes
Demersal fisheries /Oil and gas	Species diversity of potentially vulnerable ecosystems	1219	Moderate	Moderate	41	Yes
Demersal fisheries /Oil and gas	Megafaunal diversity	1303	Moderate	Moderate	41	Yes
Demersal fisheries /Oil and gas	Megafaunal abundance	1338	Moderate	Moderate	41	Yes
Demersal fisheries /Oil and gas	Megafaunal distribution	1340	Moderate	Moderate	39	Yes
Demersal fisheries /Oil and gas	Meiofaunal abundance	1341	Moderate	Moderate	39	Yes
Demersal fisheries /Oil and gas	Macrofaunal diversity	1231	Moderate	Moderate	39	Yes
Demersal fisheries /Oil and gas	Macrofaunal abundance	1335	Moderate	Moderate	39	Yes
Demersal fisheries /Oil and gas	Macrofaunal distribution	1342	Moderate	Moderate	38	Yes
Demersal fisheries /Oil and gas	Meiofaunal diversity	1224	Moderate	Moderate	38	Yes
Demersal fisheries /Oil and gas	Meiofaunal distribution	1336	Moderate	Moderate	38	Yes
Pollution	Oxidative stress biomarkers	1227	Moderate	Poor	35	No
Pollution	Biochemical biomarkers	1228	Moderate	Poor	34	No
Pollution	Molecular biomarkers	1225	Moderate	Poor	30	No
Climate change	Water quality parameters	1220	Poor		4	No
Climate change	Long-term change in deep-sea benthos	1230	Poor		4	No
Demersal fisheries /Oil and gas	Macrofaunal biomass	1337	Poor		4	No
Demersal fisheries /Oil and gas	Megafaunal biomass	1339	Poor		4	No
No specific pressure	Meiofaunal biomass	1343	Poor		4	No
No specific pressure	*Arrhis phyllonyx*	1205	Poor		2	No

5.3 Recommendations for areas of development to address significant gaps

1. The lack of knowledge concerning the location of deep-sea habitats and species, including potentially vulnerable ecosystems, hinders the development of indicators. Detailed mapping of UK deep-water habitats will be essential for the accurate implementation of indicators.

2. There is a lack of long-term baseline data to underpin the use of indicators, so little understanding of temporal changes within UK deep waters. This should be addressed by the establishment of regular long-term time series to produce baseline data.

3. The impacts of trawling are seen to be the main pressures on deep-sea habitats. Apart from the obvious effects of trawling on *Lophelia* reefs, however, there is little understanding of the effects of trawling on UK deep-water ecosystems, hindering the development and application of indicators of this activity and resulting pressure. In particular, further research is needed on the impacts of trawling on habitat forming species such as octocoral forests, hexactinellid and demosponge aggregations and xenophyophores.

4. Climate change is already thought to be exerting an influence on deep-sea habitats, as has been shown by changes at the Porcupine Abyssal Plain Sustained Observatory (PAP-SO). There are likely to be long-term changes associated with climate change, through changes in ocean productivity (and resulting export of food from the euphotic zone) and acidification. It is, however, unclear what the effects are likely to be on the deep-sea benthos, but it is likely to lead to a noticeable change in species distributions, and hence on ecosystem function. Indicators are needed that will directly address these changes. In addition, ocean acidification may have an impact on calcifying organisms, such as the cold-water coral *Lophelia pertusa*, although the greatest immediate pressure to this species is from demersal fishing. Indicators are required to assess the potential impacts of climate change, including a lowering of pH, on deep-sea organisms, assemblages and on ecosystem structure and function.

5. There have been few ecotoxicological studies involving deep-sea organisms because of the difficulty of carrying out experiments either *in situ* or at ambient pressures. Ecotoxicological studies are required to assess the effects of pollutants on the deep-sea fauna at all levels of biological organisation. Molecular, oxidative stress and biochemical biomarkers, currently in use in shallow waters, may be adapted for use in deep-sea habitats.

6. Our ability to understand, model, and predict the impacts of anthropogenic inputs is hindered by a lack ecological theories which adequately address deep sea ecosystems. This is particularly important for developing indicators of ecosystem function. A clearer understanding of concepts of disturbance, diversity-function relationships, top-down versus bottom-up control, facilitation and meta-dynamics may offer a framework for studying fundamental processes and understanding future change in deep-sea benthic ecosystems.

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