Marine ecosystem services: Linking indicators to their classification

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A B S T R A C T

There is a multitude of ecosystem service classifications available within the literature, each with its own advantages and drawbacks. Elements of them have been used to tailor a generic ecosystem service classification for the marine environment and then for a case study site within the North Sea: the Dogger Bank. Indicators for each of the ecosystem services, deemed relevant to the case study site, were identified. Each indicator was then assessed against a set of agreed criteria to ensure its relevance and applicability to environmental management. This paper identifies the need to distinguish between indicators of ecosystem services that are entirely ecological in nature (and largely reveal the potential of an ecosystem to provide ecosystem services), indicators for the ecological processes contributing to the delivery of these services, and indicators of benefits that reveal the realized human use or enjoyment of an ecosystem service. It highlights some of the difficulties faced in selecting meaningful indicators, such as problems of specificity, spatial disconnect and the considerable uncertainty about marine species, habitats and the processes, functions and services they contribute to.

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1. Introduction

Human activities in the marine environment are extensive and few areas are now untouched by them. Competition between these activities for space and resources is increasing, especially in coastal zones, leading to growing calls for more effective management of marine ecosystems. Since the 1990s, there has been a shift in marine management thinking from a single activity (‘sectoral’) approach toward management focused on ecosystems, acknowledg- edging the interactions between components of ecosystems and the position of humans within these systems (Atkins et al., 2011). This ecosystem approach to management necessitates a deeper understanding of the linkages and dynamic relationships between ecological, social and economic systems (Borja et al., 2010).

Central to the ecosystem approach is an understanding of ecosystem services, the direct and indirect contributions that ecosystems make to human well-being (de Groot et al., 2010a). By assessing the impacts of human activities on ecosystem services, a clearer understanding can be gained of the trade-offs between these activities and ecosystem services. The overall effect of human activities on human well-being, as well as on the environment, can be explored (Millennium Ecosystem Assessment, 2005). The more detailed understanding that arises can contribute to the development of more informed management plans and a more transparent decision-making process.

The interactions between natural systems and human society are complex and their analysis calls for the establishment of a systematic assessment framework (Atkins et al., 2011). This requires a clear understanding of what is meant by ecosystem services along with a comprehensive approach for their categori- zation. Many ecosystem service classifications have been defined and support the identification of aspects of ecosystems that require further exploration in an ecosystem service assessment. Little
guidance is offered, however, in how to undertake this assessment. The identification and quantification of indicators of changes in ecosystem services and the benefits they provide for humans is one way of bridging this gap. What is considered an ecosystem service, and hence what makes a relevant and useful ecosystem service indicator is likely to be context specific.

This paper first reviews the state of the art of ecosystem service classifications and in the selection of their associated indicators. From this a series of research questions are derived. Building on this literature an ecosystem service classification for marine systems is proposed and distinct indicators are selected for each service. As a part of the VECTORS project (www.marine-vectors.eu), this classification is then applied and relevant indicators are specified for a case study site in the North Sea the Dogger Bank. Indicators of ecosystem functions and ecosystem benefits are also identified. The process leading to the identification of the indicators is then discussed.

2. State of the art

2.1. Ecosystem service classifications

The Millennium Ecosystem Assessment (MA) classification of ecosystem services is perhaps the most cited. It defined ecosystem services as "the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2005, p.v), and divided them into four ecosystem service categories: supporting, provisioning, regulating and cultural services. Although it has been widely applied, it is not without criticism. The loose definition of ecosystem services by the MA undermines the application of accounting systems to ecosystem services (Boyd and Banzhaf, 2007). As the value of supporting services is considered inherent in the value of all other services (Fisher et al., 2009), the absence of hierarchy within the classification makes it inappropriate for use with ecosystem service valuation (Wallace, 2007; Fisher and Turner, 2008) as it leads to considerable double counting (Boyd and Banzhaf, 2007). This makes it problematic to apply in a decision-making context (Fig. 1).

A number of ecosystem service classifications have subsequently been developed (e.g., Fisher et al., 2009; de Groot et al., 2010a; Balmford et al., 2011; Mace et al., 2011; EEA, 2013), some of which have been tailored specifically for the marine environment (e.g., Atkins et al., 2011; Böhnke-Henrichs et al., 2013; Liquete et al., 2013; Turner et al., 2014). Each strives for a clear distinction between ecosystem services (also known as final services), the functions that generate those services (also called intermediate services) and the benefits derived from the services. Where the boundaries are placed between services, functions and benefits varies with classification.

The inclusion of abiotic components of ecosystems into ecosystem services classifications has been disputed. Abiotic components are integral to ecosystems, determining ecological functions, and hence ecosystem services. Some classifications explicitly include water and abiotic raw materials, as well as human activities such as aggregates, energy generation, and shipping (e.g., Atkins et al., 2011; Cooper et al., 2013). Their inclusion, however, is problematic. Ecosystem services are considered to be ecological in nature (Fisher et al., 2009) and delivered by the living components of the ecosystem. The quantity and quality of abiotic components (e.g., aggregates, oil and gas) is not generally determined by the living parts of the ecosystem. Where they are (e.g., water quality), this is already captured by

![Fig. 1. Location of the Dogger Bank (the white area) in the North Sea.](image)
other services (e.g., waste treatment and assimilation). To overcome this difference, the Common International Classification of Ecosystem Services (CICES) consultation recommends the development of a complementary classification for abiotic outputs from ecosystems (Haines-Young and Potschin 2013).

de Groot et al. (2010a) suggest that "perhaps we should accept that no final classification can capture the myriad of ways in which ecosystems support human life and contribute to human well-being" and “that no fundamental categories or completely unambiguous definitions exist for such complex systems” (p. 17). Classification systems need to be suited to the policy and management problem at hand, and different interpretations may be needed depending on the context (Fisher et al., 2009; de Groot et al., 2010a).

To assess the ecosystem services identified by a classification system, the capacity of the ecosystem to deliver ecosystem services in biophysical terms and their ability to maintain this over time must be determined (TEEB, 2010). Ecosystem services result from a bundle of ecosystem functions (e.g., the provision of seafood results from a combination of primary and secondary production, biogeochemical cycling, food web dynamics etc.) and may contribute to a range of ecosystem benefits (e.g., the regulation of climate helps provide a habitable environment, allows the production of food and facilitates multiple ecosystem functions important for other services) (Austen et al., 2011). Assessing and quantifying every aspect of ecosystem services is a challenging task, especially when the relationship between services, functions and underlying biodiversity remains poorly understood (Kremen, 2005; Barbier, 2007). The use of indicators can facilitate this process.

2.2. Ecosystem service indicators

Indicators are proxies for complex phenomena and can be used to reflect the provision of a service and how it is changing over time. Indicators, where measurable, are useful for supporting management activities as well as contributing to studies aiming to model and value changes in ecosystem service provision (Nie-mejier and de Groot, 2008). Practical guidelines for selecting indicators relevant to ecosystem services, however, are still missing (van Oudenhoven et al., 2012; UNEP-WCMC, 2011), especially for the marine environment. There is no unified approach to indicator selection or agreed indicators for each ecosystem service. Consequently, indicator selection is often inconsistent with a focus on arbitrary categorical indicators and monetary values (Seppelt et al., 2011). Without a coherent approach there is a danger that the information contained in the indicators cannot be validated and is not relevant to management (Dale and Beyeler, 2001).

Many of the indicators already developed within the literature are not specific to ecosystem services. They often focus on taxonomic identities of communities and species, or structural and functional aspects (Feld et al., 2009). They tend to be selected for a limited number of ecosystem services (e.g., Haines-Young et al., 2012) or for more wide ranging environmental features such as landscape structure (e.g., Syrbe and Walz, 2012). This is often due to insufficient data to characterize them (Reyers et al., 2010). Those that are supported by data tend to be associated with provisioning and regulating services (Feld et al., 2009; Layke, 2009; UNEP-WCMC, 2011; Egoh et al., 2012).

Food provision indicators are well established and relatively easy to quantify. Agricultural production per land area gives the production of food and facilitates multiple ecosystem functions (e.g., ICES stock assessment database) and fish catch is recorded globally (e.g., FAO, 2012).

Although indicators for regulating services are also numerous, they are not all measured equally. In a review of 78 terrestrial papers, Egoh et al. (2012) found that climate regulation (primarily focusing on carbon storage and sequestration) and water flow regulation were most commonly assessed. Feld et al. (2009) identified a bias toward indicators of water retention. In the marine and coastal environment, Lique et al. (2013) found that most studies focus on water purification, coastal protection and climate regulation.

Typically indicators for regulating services are used to track negative change or degradation of the service (e.g., changes in habitat area track loss of carbon storage capacity). They are often lagging indicators that demonstrate damage that has already occurred. They cannot anticipate change and provide little information about future degradation (Layke, 2009). How to use these indicators to demonstrate avoided change, such as the avoided impacts of a pollution incident as a result of bioremediation, remains a challenge.

Fewer indicators for cultural services have been identified and quantified, although this situation is changing. Hernández-Morciolo et al. (2013) found that most cultural ecosystem service studies focus on indicators of recreation and tourism (a bias also evident in studies of the marine environment, Lique et al., 2013). Furthermore, most indicators for cultural ecosystem services were unclear in their definitions, purpose and understanding of the processes to be measured. Similar findings were reported by Milcu et al. (2013). Both report that indicators of ecosystem benefits were most widely cited and the link to the state of the ecosystem was rarely mentioned. This is problematic as benefit indicators may not indicate what, if anything, in the ecosystem requires management or intervention if the indicator moves in a particular direction. Movement of the indicator may simply reflect changes in human preferences.

To generate a better understanding of the implications of ecosystem change, indicators need to be developed that describe not only ecosystem services, but also the ecological functions that deliver them, the benefits they provide and the interrelationships between them (Nicholson et al., 2009; de Groot et al., 2010b). Indicators of ecosystem functions and services should be ecological, reflecting their nature, while indicators of ecosystem benefits demonstrate the realized human use or enjoyment of an ecosystem service. Only when combining indicators of functions, services and benefits, can change (both positive and negative) be detected and appropriate management actions taken. No single indicator will be able to capture these multiple dimensions and composite indicators, or suites of indicators, will be needed for each ecosystem service.

The most appropriate spatial and temporal scale for indicator measurement is unclear and likely to be problem specific. Feld et al. (2009) found that most indicators are measured at regional or local scales, although functional indicators and indicators reflecting temporal differences are rarely measured at all, irrespective of scale. Many ecosystem services provided by the marine environment are global non-proximal (Costanza, 2008), meaning location does not matter, nor does the proximity of the location to the human beneficiaries. Furthermore, many marine species are mobile and different locations may be more or less important at different times of the year or during different stages in an organisms’ life-cycle, all affecting the provision of ecosystem services. Ideally, indicators need to reflect this dynamic nature of ecosystem services. The remoteness of many marine ecosystems to their beneficiaries also presents challenges for indicator selection. It may be difficult to attribute specific benefits to specific locations within the marine environment.

To ensure indicator usability, they need to be assessed against agreed criteria. For marine ecosystem indicators, Link et al. (2009)
recommend such criteria. These include measurability (are data available?), sensitivity (can they detect change?) and specificity (is the change in the indicator a response to the pressure of interest as opposed to natural variability?). Dale and Beyeler (2001), more generally, identify five additional criteria: that indicators (1) respond to stress in a predictable manner, (2) are anticipatory (i.e., signify impending change), (3) predict change that can be averted by management, (4) are integrative (i.e., can indicate change over key gradients across an ecological system) and (5) have low variability in response. van Oudenhoven et al. (2012) define 12 criteria. Many overlap with those described above, but useful additional criteria require the indicators to be scalable, portable (or transferable) to other locations and be clear and understandable.

The above discussion raises a number of questions that this paper aims to answer:

• What ecosystem services are provided by the marine environment and can a classification relevant to the whole marine environment capture those of an offshore marine site?
• What indicators can be developed for all the ecosystem services identified, for the ecosystem functions that deliver them and the ecosystem benefits they generate?
• How usable are these indicators for the Dogger Bank case study?

3. Methods
3.1. Description of the case study

The Dogger Bank is a large sandbank in the southern part of the North Sea covering approximately 18,700 km². It is located in the Exclusive Economic Zones of the UK, Denmark, Germany and the Netherlands. While the North Sea has an average depth of about 60 m, the Dogger Bank is only 20–50 m deep (Diesing et al., 2009). This alters local hydrodynamics and promotes primary production by phytoplankton, providing food for other species, including commercially targeted fish species (Sell and Kröncke, 2013). Consequently, the Dogger Bank is a historic fishing ground where large-scale, industrial trawlers, mostly from the Dutch and Danish fleets, target demersal fish (e.g., plaice, megrim and turbot) and sandeels. There is currently some use of fixed netting techniques as well. The Dogger Bank is also an important location for actual and potential production of energy. Besides five operational gas platforms in the area, the UK government is planning the world’s largest offshore wind farm to be installed on its section of the Dogger Bank. The Dogger Bank is vulnerable to the pressures created by the fishing industry and further development by the energy sector. Reflecting this, the UK, Dutch and German parts have recently been designated as candidate Special Areas of Conservation (cSACs) and management plans for the sites are being developed.

The Dogger Bank also delivers other ecosystem services. It acts as a nursery ground, providing suitable habitat for foraging and maturing fish species, such as plaice (Diesing et al., 2009; Hufnagl et al., 2013). It is of cultural importance as well, being a feeding ground for charismatic species such as the harbor porpoise, gray seals and many seabirds (Forewind, 2010). Fishers and archaeologists have found a number of prehistoric remains on the Dogger Bank, including teeth from sabre-toothed cats, mammoth skeletons, arrowheads and remnants from human settlements. A small number of recreational anglers and divers also visit the Dogger Bank every year.

Compared to many other offshore marine areas, the Dogger Bank is relatively well-studied. This is especially true for the UK sector. The consortium planning the wind farm construction has undertaken extensive surveys of the area (e.g., Forewind, 2013), as have the Joint Nature Conservation Committee (JNCC) in support of the application for SAC designation (Diesing et al., 2009). The bank has also been the subject of numerous scientific studies (e.g., Wiekking and Krönke, 2003; Kröncke, 2011; Sell and Kröncke, 2013; Hufnagl et al., 2013). It makes an ideal location to explore the applicability of an ecosystem services classification and its corresponding indicators.

3.2. Selecting an ecosystem service classification

Given the number of ecosystem service classifications already in existence, the objective was not to develop a new classification, but to modify and amend an existing framework. The aim was also to find a classification that is sufficiently generic to be applicable to different marine sites, while being sufficiently flexible to ensure site differences can be explored in detail. This would facilitate its application to any marine ecosystem.

Definitions were also clearly distinguished at the outset, to ensure ecosystem functions or benefits were not included in the ecosystem service classification:

• Ecosystem services are the direct and indirect contributions of ecosystems to human well-being (TEEB, 2010).
• Ecosystem functions are the ecological processes that control the fluxes of energy, nutrients and organic matter through an environment (Cardinale et al., 2012).
• Ecosystem benefits are the things that people create or derive from ecosystem services. Benefits are turned into products or experiences that are no longer functionally connected to the systems from which they were derived (Haines-Young and Potschin 2013).

As distinguishing between ecosystem functions, services and benefits is important, The Economics of Ecosystems and Biodiversity (TEEB) classification was used as a starting point (de Groot et al., 2010a), together with modifications suggested by Böhnke-Henrichs et al. (2013). Each ecosystem service and its definition were scrutinized for relevance at a general marine environment level (coastal, near- and off-shore) and the whole classification was reviewed for completeness. To ensure the classification is fit for purpose, the ability of the Dogger Bank to produce the ecosystem services identified was also examined. Using the expert judgement of the project team, relevance was determined by assessing whether the marine environment and the Dogger Bank could actually generate the ecosystem services identified. A number of alterations and additions were made through an iterative process.

3.3. Indicator selection

A two stage process was used for the selection of indicators. First, indicators for each marine ecosystem service in the classification were identified during an interdisciplinary expert workshop (henceforth, called ‘generic indicators’). Second, these indicators were tailored to fit the Dogger Bank case study (from here on, called ‘specific indicators’). This second step could then be repeated for other sites, if multiple sites were to be assessed.

During the workshop, the 63 participants were divided into six groups. Each group was allocated three ecosystem services and asked to (1) brainstorm indicators for each ecosystem service that could reflect the quantity and quality of the service, (2) suggest how each indicator could be measured (including units), and (3) identify potential data sources for each indicator.

Following the workshop, the project team assessed each generic indicator to ensure indicators of functions or benefits were not included. Once a list of generic ecosystem service indicators was compiled for each ecosystem service, the process was repeated
focusing on the Dogger Bank. The indicators identified were adapted and amended to make them specific to the case study. This required an exploration of data available for the Dogger Bank, additional evidence within the ecosystem service indicator literature, and in the absence of these, expert opinion. Dogger Bank specific indicators were then assessed against a set of applicability criteria:

- Measurability: are there data available for the measurement and quantification of the indicator?
- Sensitivity: does the indicator detect change in the ecosystem service over time?
- Specificity: can the indicator respond over time to changes in management as opposed to natural variability? Is this response predictable and does it have low variability?
- Scalability: can the indicator be aggregated or disaggregated to a different spatial scale and still retain its ability to indicate the change of interest?
- Transferability: is the indicator useful for other locations and hence studies?

For each indicator, the five criteria were answered on a yes/no basis. If the answer was no, the indicator was re-examined and

Table 1
Proposed classification of marine ecosystem services, their description and relevance to the Dogger Bank. Modified from de Groot et al. (2010a) and Böhne-Henrichs et al. (2013).

| Ecosystem service | Description | Relevance to the Dogger Bank |
|-------------------|-------------|------------------------------|
| **Provisioning services** | | |
| 1 Food provision: | | |
| a) Wild capture seafood | All available marine flora and fauna extracted from unmanaged marine environments for consumption by humans | ☑, extensive fishing (trawling) |
| b) Farmed seafood | Food from aquaculture for consumption by humans | X, no aquaculture in the area |
| 2 Biotic raw materials (non-food): | | |
| a) Genetic resources | The provision/extraction of genetic material from marine flora and fauna for use in non-medical contexts | ? , unknown |
| b) Medicinal resources | Any material that is extracted from or used in the marine environment for its ability to provide medicinal benefits | ? , unknown |
| c) Ornamental resources | Any material that is extracted for use in decoration, fashion, handicrafts, souvenirs, etc. | ☑, growing market for mammoth and other Mesolithic remains |
| d) Other biotic raw materials | Extraction of all other renewable biotic resources | ☑, harvesting of sandeels for animal feed and fertilisers |
| **Regulating services** | | |
| 3 Air purification | Influence of a marine ecosystem on concentration of pollutants from the atmosphere | ☑, extent unknown |
| 4 Climate regulation | The contribution of a marine ecosystem to the maintenance of a favorable climate through impacts on the hydrological cycle, temperature regulation, and the contribution to climate-influencing substances in the atmosphere | ☑, extent unknown |
| 5 Disturbance prevention or moderation | The contribution of marine ecosystem structures and functions to the dampening of the intensity of environmental disturbances such as storm floods, tsunamis, and hurricanes | X, area too far from the coast |
| 6 Regulation of water flows | The contribution of marine ecosystems to the maintenance of localized coastal current structures | ? , unknown |
| 7 Waste treatment and assimilation | The removal of contaminant and organic nutrient inputs to marine environments from humans | ☑, extent unknown |
| 8 Coastal erosion prevention | The contribution of marine ecosystems to coastal erosion prevention | X, area too far from the coast |
| 9 Biological control | The contribution of marine ecosystems to the maintenance of population dynamics, resilience through food web dynamics, disease and pest control | ☑, extent unknown |
| **Habitat services** | | |
| 10 Migratory and nursery habitat | The contribution of a particular marine habitat to migratory and resident species' populations | ☑, extent unknown |
| 11 Gene pool protection | The contribution of marine habitats to the maintenance of viable gene pools through natural selection/evolutionary processes which enhances adaptability of species to environmental changes, and the resilience of the ecosystem | ☑, extent unknown |
| **Cultural services** | | |
| 12 Leisure, recreation and tourism | The provision of opportunities for tourism, recreation and leisure that depend on a particular state of marine ecosystems | ☑, limited to some sailing, diving and recreational angling |
| 13 Aesthetic experience | The contribution that a marine ecosystem makes to the existence of a surface or subsurface landscape that generates a noticeable emotional response within the individual observer. This includes informal spiritual individual experiences but excludes that covered by service 17 | ☑, limited to those who go there |
| 14 Inspiration for culture, art and design | The contribution that a marine ecosystem makes to the existence of environmental features that inspire elements of culture, art, and/or design. This excludes that covered by services 2c, 13, and 16 | ☑, extent unknown |
| 15 Cultural heritage | The contribution of marine ecosystems to the maintenance of cultural heritage, and providing a ‘sense of place’ | ☑, extent unknown but links to Palaeolithic man |
| 16 Cultural diversity | The contribution of marine ecosystems to social and cultural values and adaptations that pertain to living at coasts and exploiting marine resources | ☑, extent unknown |
| 17 Spiritual experience | The contribution that a marine ecosystem makes to formal and informal collective religious experiences. This includes that covered by services 13 and 14 | ☑, extent unknown |
| 18 Information for cognitive development | The contribution that a marine ecosystem makes to education, research, and individual and collective cognitive development | ☑, extent unknown |

☑: relevant, X: not relevant, ?: relevance unknown.
Table 2

Indicators for each of the ecosystem services identified in Table 1 as relevant to the Dogger Bank. As stated in the text, it is expected that the indicators will be compared over time and space to denote change in the system.

| Ecosystem services | Generic marine ecosystem service indicators | Measurement (units) - measured over time | Dogger Bank specific indicators | Issues related to assessment criteria |
|--------------------|---------------------------------------------|------------------------------------------|---------------------------------|--------------------------------------|
| 1a: Food provision – wild capture sea food | Fish and shellfish populations, seaweed stock | Biomass (tonnes km\(^{-2}\)) or abundance (no. km\(^{-2}\)) of fish and shellfish; area (m\(^2\)) or biomass (tonnes km\(^{-2}\)) of seaweed | Population of nephrops and flatfish species such as plaice, turbot and lemon sole | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| | Quality of the fish, shellfish, seaweed stock | Species composition, age profile; length profile; percentage affected by disease; mortality rates | Quality of the populations of nephrops and flatfish species such as plaice, turbot and lemon sole | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| 1b: Food provision – farmed sea food | Fish and shellfish populations, seaweed stock | Biomass (tonnes km\(^{-2}\)) or abundance (no. km\(^{-2}\)) of fish and shellfish; area (km\(^2\)) or biomass (tonnes km\(^{-2}\)) of seaweed | N/A | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| | Quality of the fish, shellfish, seaweed stock | Percentage affected by disease; mortality rates | N/A | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| 2a: Biotic raw material – genetic resources | Presence and diversity of species with potential/actual useful genetic material | Presence/absence of desirable species; diversity of desirable species | Insufficient information to define indicators | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| | Quality of species with potential/actual useful genetic material | Endemism and uniqueness of species | Insufficient information to define indicators | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| 2b: Biotic raw material – medicinal resources | Quantity of available raw material | Total quantity available in a fixed area (g/rawn material) | Insufficient information to define indicators | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| | Quality of raw materials | Concentration of raw material (g l\(^{-1}\) seawater, g m\(^{-3}\) sediment) | Insufficient information to define indicators | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| 2c: Biotic raw material – ornamental resources | Quantity of raw material | Biomass available in a fixed area (tonnes km\(^{-2}\)) | Insufficient information to define indicators | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| | Quality of raw materials | Concentration (g l\(^{-1}\) seawater, tonnes km\(^{-2}\) sediment); purity | Insufficient information to define indicators | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| 2d: Other biotic raw material | Quantity of raw material | Biomass available in a fixed area (tonnes km\(^{-2}\)) | Population of sandeels (same measurement units as for food provision) | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| | Quality of raw materials | Concentration (g l\(^{-1}\) seawater, tonnes km\(^{-2}\) sediment); purity | Quality of the populations of sandeels (same measurement units as for food provision) | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| 3: Air purification | Air–sea flux of pollutants | Modeled or empirically determined pollutant air–sea flux rates and direction (μmol pollutant d\(^{-1}\) m\(^{-2}\), μg pollutant l\(^{-1}\) seawater d\(^{-1}\) m\(^{-2}\)) | Insufficient information to define indicators | Role of different components of the marine ecosystem involved in this service is unclear. Lack of knowledge prevents indicator identification |
| | Distribution of air–sea fluxes of pollutants | Modeled or empirically determined maps of pollutant concentrations (μmol1 l\(^{-1}\) m\(^{-2}\) d\(^{-1}\), μg air pollutant l\(^{-1}\) seawater m\(^{-2}\) d\(^{-1}\)) | Insufficient information to define indicators | |
| 4: Climate regulation | Air–sea and sediment–water fluxes of carbon and CO\(_2\) | Modeled or empirically determined (mg C m\(^{-2}\) d\(^{-1}\), mg CO\(_2\) m\(^{-2}\) d\(^{-1}\)) | As per generic indicators scaled to the area covered by the Dogger Bank | |
| | Air–sea fluxes of other greenhouse gases (e.g., dimethyl sulhide, methane, nitrous oxide) | Modeled or empirically determined (μg greenhouse gases m\(^{-2}\) d\(^{-1}\)) | As per generic indicators scaled to the area covered by the Dogger Bank | |
| | Levels of carbon in different components of the marine ecosystem | Modeled or empirically determined carbon levels: biomass of carbon (g m\(^{-2}\)); dissolved organic or inorganic carbon (mg C m\(^{-3}\)); suspended organic or inorganic carbon (mg C m\(^{-3}\)); buried particulate organic or inorganic carbon (mg C m\(^{-2}\)) | As per generic indicators scaled to the area covered by the Dogger Bank | |
| | Permanence of carbon sequestration | Percentage of annual carbon turnover from sediments | As per generic indicators scaled to the area covered by the Dogger Bank | |
| Ecosystem services | Generic marine ecosystem service indicators | Measurement (units) - measured over time | Dogger Bank specific indicators | Issues related to assessment criteria |
|--------------------|---------------------------------------------|---------------------------------------------|-------------------------------|---------------------------------------------|
| 5: Disturbance prevention and moderation | Capacity of water storage of habitat | Water storage capacity (m³/area) for different intertidal habitats (e.g., sediment, saltmarsh, mangrove) | N/A | |
| | Reduction of wave energy by near shore and intertidal habitats | Change in wave energy (J m⁻²) attributed to different intertidal and near shore habitats | N/A | |
| | Changing shoreline | Change in beach profile (slope (gradient) and width (m) and stability) over time determined empirically from photos, satellite, LiDAR, ARGUS camera and modeled | N/A | |
| 6: Regulation of water flows | Salinity/freshwater input | Change in salinity, tidal and freshwater flow rates (m³ s⁻¹) | Insufficient information to define indicators | |
| | Changing shoreline | Change in beach profile (slope (gradient) and width (m) and stability) over time determined empirically from photos, satellite, LiDAR, ARGUS camera and modeled | N/A | |
| | Rates of tidal and wind driven currents | Direct measures of flow and currents (m³ s⁻¹) and turbidity (mg m⁻³ or NTU) | Insufficient information to define indicators | |
| | Seabed morphology | Changes in seabed morphology using side-scan sonar | Insufficient information to define indicators | |
| 7: Waste treatment and assimilation | Absolute levels of waste in the water column | Chemical analysis (contaminant concentrations) and visual analysis | As per generic indicators scaled to the area covered by the Dogger Bank | Difficult to attribute to specific elements of the ecosystem structure and processes as knowledge is not available |
| | Presence of pathogens; outbreaks of E. coli infections; hospital admissions | Total coliforms or other pathogens (quantity per milliliter of water) | As per generic indicators scaled to the area covered by the Dogger Bank | Difficult to attribute to specific elements of the ecosystem structure and processes as knowledge is not available |
| | Benthic biodiversity levels/ratios/no. of sensitive species | Different biodiversity indices | As per generic indicators scaled to the area covered by the Dogger Bank | Indicates health of system which may indicate capacity for waste assimilation if waste inputs are known |
| | Toxicity levels within species | Chemical analysis (contaminant concentrations) | As per generic indicators scaled to the area covered by the Dogger Bank | |
| | Number of shellfish area closures | | As per generic indicators scaled to the area covered by the Dogger Bank | May not necessarily reflect change in ecosystem service; for example it could reflect changing risk appetite of consumers, producers or regulators |
| | Harmful algal bloom outbreaks | Remote sensing, water sampling to detect frequency and extent; modeling to determine future frequency and extent | As per generic indicators scaled to the area covered by the Dogger Bank | |
| 8: Coastal erosion prevention | Beach profile (slope and width); extent of maintenance and improvement required to provide protection | Change in beach profile (slope (gradient) and width (m) and stability) over time determined empirically from photos, satellite, LiDAR, ARGUS camera and modeled | N/A | Extent of maintenance/ improvement required may not necessarily reflect change in ecosystem service; for example it could reflect changing levels of risk aversion by consumers, producers or regulators |
| | Presence and elevation of biogenic habitat e.g., saltmarsh beds; seagrass beds; bivalve, coral and polychaete reefs | Volume (m³ or km³), or area covered (m² or km²), density (biomass or abundance m⁻³) and elevation of (height above mean seawater level) | N/A | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| | Presence of mitten crab | Presence of mitten crab (no. per unit area – could be estimated as number of burrows) | N/A | |
| 9: Biological control (checks and balances) | Presence/absence/ frequency of pests (e.g., algae blooms, foam, sea lice on farmed salmon) | Count data | As per generic indicators specifically applied to control of pests and HABs that affect fish species utilized by fisheries, mammals, seabirds and other marine organisms occurring in area | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| Ecosystem services | Generic marine ecosystem service indicators | Measurement (units)- measured over time | Dogger Bank specific indicators | Issues related to assessment criteria |
|--------------------|---------------------------------------------|----------------------------------------|-------------------------------|---------------------------------------|
| **10: Migratory and nursery habitat** | Area of habitat or density of biogenic habitat creating species “used” or identified as important for nursery or reproduction | Abundance m$^{-2}$ and species diversity | Spawning: abundance of cod, sandeels, plaice, nephrops; nurse: abundance of sprat, nephrops | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| | Number and diversity of species using the area for nursery or reproduction | Proximity to dependant populations or their migration routes; size (abundance) and health (viability) of off-site populations | As per generic indicators scaled to the area covered by the Dogger Bank | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| **11: Gene pool protection** | Genetic diversity | Diversity of species and subspecies, phylogenetic distance, Biodiversity Intactness Index (BII) | As per generic indicators scaled to the area covered by the Dogger Bank | Specificity problematic: difficult to distinguish impacts of climate change from other impacts |
| **12: Leisure, recreation and tourism** | Sea space available for recreation | Number of km$^2$ of sea with safe water quality available for recreational use | As per generic indicators scaled to the area covered by the Dogger Bank | May not necessarily reflect change in ecosystem service; for example it could reflect changing levels of risk aversion by consumers, producers or regulators |
| | Number and quality of beaches | Number and size of blue flag beaches | N/A | May not necessarily reflect change in ecosystem service; for example it could reflect changing levels of risk aversion by consumers, producers or regulators |
| **Water quality** | Chemical analysis (contaminant concentrations) and visual analysis; total coliforms or other pathogens (quantity per milliliter of water) Count data | Species of recreational interest e.g., harbour porpoise, grey seal, seabirds, fish | As per generic indicators scaled to the area covered by the Dogger Bank | |
| **Abundance and diversity of key species of recreational interest** | For example, extent of seagrass, maerl or h奖 beds (km$^2$) Count data | | As per generic indicators scaled to the area covered by the Dogger Bank | |
| **Area of biotopes of key interest to recreational users** | | | | |
| **13: Aesthetic experience** | Uniqueness of a site | 1/(number of sites with similar features) Count data | Insufficient information to define indicators | Uniqueness would increase if all other similar ecosystems degrade |
| | Abundance of key species of individual interest | | Species of individual interest e.g., harbour porpoise, grey seal, seabirds, fish | |
| | Area of biotopes of key interest to individuals | For example, extent of seagrass, maerl or h奖 beds (km$^2$) | As per generic indicators scaled to the area covered by the Dogger Bank | |
| **14: Inspiration for culture, art and design** | Species, habitat or ecosystems that have or can potentially inspire any piece of artwork | Insufficient information to define indicators | Insufficient information to define indicators | Generic indicators cannot be developed |
| | Species, habitats or ecosystems that can potentially form the core of contribute to a cultural custom, rite or way of life | | Insufficient information to define indicators | |
| **15: Cultural heritage** | Generic indicator cannot be developed | Insufficient information to define indicators | Insufficient information to define indicators. Some links to Palaeolithic people | Generic indicators cannot be developed |
| **16: Cultural diversity** | Species, habitats or ecosystems that are being or can potentially be studied to increase scientific knowledge | Insufficient information to define indicators | Insufficient information to define indicators |Generic indicators cannot be developed |
| **17: Spiritual experience** | Species, habitats or ecosystems that are being or can potentially be studied for educational purposes | Insufficient information to define indicators | Insufficient information to define indicators |Generic indicators cannot be developed |
| **18: Information for cognitive development** | Species, habitats or ecosystems that are being or can potentially be studied to increase scientific knowledge | Number of such species, habitats, ecosystems | Insufficient information to define indicators |Generic indicators cannot be developed |
| | Species, habitats or ecosystems that are being or can potentially be studied for educational purposes | Number of such species, habitats, ecosystems | Insufficient information to define indicators | |
amended where possible. Problems with this approach were noted.

Suggested indicators that were identified as being indicators of functions or benefits were also captured to allow a more complete ecosystem service assessment. As these indicators are not as well developed as those for their corresponding ecosystem service and were not fully assessed against the criteria, nor tailored for the Dogger Bank, they are presented differently.

4. Results

4.1. The classification adopted

The modified ecosystem service classification used to direct the indicator selection process is presented in Table 1. A number of amendments were made to the TEEB and Bohnke-Henrichs et al. (2013) classifications. Some irrelevant services were removed (e.g., the maintenance of soil fertility) and terms were clarified. For example, the definitions of cultural services in the TEEB framework can be considered as an expression of the preferences of an individual, rather than properties of the ecosystem (e.g., aesthetic experience, inspiration for culture art and design). There are some components of the ecosystem or natural environment, however, which make a contribution to culture. It is this contribution that should be considered the service.

Considerable discussion was given to the habitat services proposed by the TEEB typology. TEEB defines habitat services as “the importance of ecosystems to provide living space for resident and migratory species (thus, maintaining the gene pool and nursery service)” (TEEB, 2010; p. XXXV). These services can be considered important for safeguarding the future use of ecosystems; however, they can also be construed as “supporting services”. The availability of migratory and nursery habitats supports the provision of food, while the maintenance of the gene pool supports biodiversity as a whole. Nevertheless, each of these can be managed directly. Efforts can be devoted to the protection of areas that are important migratory and nursery grounds. For example, seasonal, spatial closures to fisheries (under EU regulations) of areas in the North Sea during cod spawning result in losses of food provision and income from these areas. Such losses imply that these areas have a value as nursery habitats and for gene pool protection, although the value of these habitat services is likely to be greater than just the change in income experienced. The position of habitat services is therefore likely to change, being services in some situations, but functions in others. This will vary according to the temporal and spatial boundaries given to the assessment.

Management plans for the Dogger Bank cSACs will likely include fisheries closures. This will allow the Dogger Bank to be managed in the future for its nursery habitat as well as for its gene pool protection. This suggests that habitat services should be retained in the classification (in keeping with TEEB, 2010; EEA, 2013; Liquete et al., 2013). However, these services will be future services provided by the Dogger Bank. As the Dogger Bank is open to fishing in 2014, an assessment and valuation of its ecosystem services would include the provision of wild capture sea food. As food provision is currently supported by these habitat services, an assessment of the migratory and nursery habitat and gene pool protection today would result in double counting. Nevertheless, such an assessment would become necessary in future following changes in management and if related changes in ecosystem services are to be explored. This highlights the temporal dimension of some ecosystem services and the difficulty in identifying clear boundaries between ecosystem functions and ecosystem services.

4.2. Indicator selection

The final selection of ecosystem service indicators is shown in Table 2. The first round of indicator selection from the expert workshop emphasized the importance of providing clear definitions. Not all experts were familiar with ecosystem service terminology, consequently the output generated indicators for ecosystem functions, services and benefits. For example, the amount (tonnes) of fish landed for human consumption was proposed as an indicator of the service “wild capture sea food” but this is an indicator of the benefit and not the service provided. The fishing activity used to land the fish will be highly selective and reflect quota allowances, thus, landings do not indicate the full potential of the ecosystem to provide the service. The indicator selection process also reiterated the need for multiple indicators for each ecosystem service, function and benefit. The agreed indicators of the “wild capture sea food” service were fish stock population size and quality of the fish stock, each of which are comprised of a number of measures.

Cultural service indicator selection also proved challenging. It is difficult to identify the specific contributory role of an ecosystem to many cultural services, and hence to identify indicators of these services. To illustrate, aesthetic experiences are inherent to an individual, but to identify indicators of the service of ‘aesthetic experiences’ the specific elements of a marine ecosystem that contribute to that experience must be known. These can then be used to indicate the state of the service. Many of the indicators suggested at the workshop were indicators of ecosystem benefits rather than of ecosystem services. This reemphasized the need for a suite of three indicator types for a complete ecosystem service assessment: indicators of functions, services and benefits.

Generic indicators of regulating and habitat services were relatively straightforward to select, but were more challenging at the specific level, mostly due to a lack of knowledge on how ecosystem functions generate corresponding services. Assessment against the applicability criteria also highlights quantification difficulties due to the lack of data. This is a problem for many provisioning and cultural services as well.

Indicator assessment suggested that the indicators selected will be sensitive to change over time. What change they will respond to, however, is unclear due to the current lack of evidence. In practice, many of the indicators identified are expected to lack specificity as signals from, for example, climate change become confounded with other sources of change (e.g., fishing). Nevertheless, they may indicate short-term changes (e.g., the cessation of demersal trawling) and therefore, support management decisions. Where the indicator selected for the Dogger Bank is the same as that for the generic indicator, scalability and transferability are assured across marine areas. However, modification is often required; for example, fish stock indicators need to be tailored to the stocks actually caught on the Dogger Bank.

Ecosystem function indicators for provisioning services are explored at the generic level (Table 3a), a result of data scarcity, but also because the functions are likely to be the same for all indicators. Among regulating services, some subdivision of the contributing functions can be made (Table 3b). Considerable overlap is evident between these functions and those contributing to provisioning services (and the same is likely true for cultural services). A one-to-one relationship does not occur between ecosystem functions and ecosystem services. Changes in ecosystem functions will likely indicate changes across multiple ecosystem services. Ecosystem function indicators were not assessed against the applicability criteria because of the difficulty in tailoring these indicators to the Dogger Bank and because of the known absence of data to characterize them. Indicators of the ecosystem functions that contribute to cultural ecosystem services...
were not explored. Evidence is only available for two of the Dogger Bank cultural ecosystem service indicators (abundance and diversity of key species of recreational interest and area of biotopes of key interest to recreational users) and the links between them and ecosystem functions are currently unclear.

Indicators of ecosystem benefits (Table 4) are also identified at the generic level and were not assessed against the applicability criteria. The indicators presented are exemplars, often high level and do not represent a comprehensive selection. Refining the indicators to the scale of the Dogger Bank proved demanding. Many of the benefits (and services that generate them) are not location specific and linking them to the Dogger Bank was not possible within the scope of this study. It is also clear that changes in the benefit indicators may result from shifts in individual or societal preferences, rather than from change in the ecosystem. More work is needed to identify relevant and applicable ecosystem benefit indicators.

5. Discussion

5.1. Applying an ecosystem service classification

There are several ecosystem service classifications available within the literature, many of which could potentially be applied to the marine environment. What is essential with a classification is clarity in definitions to ensure that only ecosystem services are captured and not a mixture of ecosystem services, functions and benefits. This led to many definitions being amended in the classification used in this study. Tailoring the classification to an offshore marine site was relatively straightforward requiring only minor modifications. When it was unknown whether the Dogger Bank contributed to a service (e.g., regulation of water flows), the service was retained for further investigation at the indicator stage, while irrelevant services were removed (e.g., disturbance prevention or moderation).

5.2. Distinguishing between indicators of functions, services and benefits

Identifying applicable function, service and benefit indicators remains a challenge. The greatest challenge is the lack of suitable data for the marine environment, as well as limited understanding of the links between ecosystem functions, services and benefits. Measuring indicators of functions, services or benefits in isolation may lead to incorrect conclusions. Potentially these indicators might point in different directions. For example, continued fishing activities and landings do not necessarily reflect any accompanying decline in fish stocks. When landings and stocks are measured together they can indicate where potential problems lie and where management and policy activity should focus. This reiterates the need for a suite of indicators that can more fully capture the effects of ecosystem change, both positive and negative.

Combining indicators of services and benefits to explore the impacts of management or policy options may be confounded by the spatial disconnect between the service providing area (e.g., the Dogger Bank) and the service benefiting area (e.g., coastal populations of the countries bordering the North Sea and beyond). Many of the benefit indicators presented in Table 4 are not specific to a particular location. Distinguishing the role of the Dogger Bank in these indicators has not been attempted, but is likely to be difficult, if not impossible. The direct beneficiaries of the Dogger Bank ecosystem services may be relatively few and mainly confined to the small number of people who go there (e.g., fishers, wind farm constructors, recreational sailors, divers and anglers). While service indicators may describe change as a result of human activities on the Dogger Bank, any corresponding change at the benefit level may be too difficult to detect. This raises questions about appropriate scales for the assessment of services and benefits, which is likely to be context specific.

Table 3a
Indicators of selected ecological functions contributing to the delivery of ecosystem services in Table 1. Provisioning services.

| Function | Primary production | Maintenance of food web dynamics | Nutrient cycling to maintain food web dynamics for target species | Supply of larvae and gametes of target species | Support breeding population of suitable size and quantity | Provision of suitable habitats |
|----------|--------------------|----------------------------------|---------------------------------------------------------------|-----------------------------------------------|--------------------------------------------------------|-------------------------------|
| Unit     |                    |                                  |                                                               |                                               |                                                        | Area of habitat (km² or m²); quality of habitat; Number of juveniles |
| 1a: Food provision – wild capture sea food | ✓                  |                                  |                                                              |                                               |                                                        |                               |
| 1b: Food provision – farmed sea food    |                    |                                  |                                                              |                                               |                                                        |                               |
| 2a: Biotic raw material – genetic resources |                    |                                  |                                                              |                                               |                                                        |                               |
| 2b: Biotic raw material – medicinal resources |                    |                                  |                                                              |                                               |                                                        |                               |
| 2c: Biotic raw material – ornamental resources |                    |                                  |                                                              |                                               |                                                        |                               |
| 2d: Other biotic raw materials          |                    |                                  |                                                              |                                               |                                                        |                               |

✓ indicates that the function is relevant to the ecosystem service
| Key ecosystem services | Examples of ecosystem functions that deliver the service | Indicators of functions and their measurement (Units) | Comments and issues related to assessment criteria |
|------------------------|--------------------------------------------------------|-----------------------------------------------------|--------------------------------------------------|
| 3: Air purification    | Absorption of atmospheric pollutants in seawater      | Micromoles or micrograms of pollutants per litre over time and space (µmol l⁻¹ m⁻², µg air pollutant l⁻¹ seawater m⁻²) | The role of different components of the marine ecosystem in this service is unclear |
| 4: Climate regulation  | Pelagic and benthic fixation of carbon through photosynthesis | Concentration of chlorophyll (mg m⁻² or mg m⁻³) primary productivity (mol C m⁻² d⁻¹) | Hydrodynamics determined through modeling |
|                        | Deposition and sequestration of carbon through hydrodynamic transport of advection and sinking | Carbon export as DOC and/or POC (mol C m⁻² d⁻¹) | |
|                        | Sedimentation and burial of carbon in sediments through bioturbation | Carbon storage (g C m⁻² time⁻¹) – carbon buried in sediments; depth of carbon in sediment | |
|                        | C storage in living biomass (seagrasses, salt marshes, fish, benthic organisms etc.) | Persistence of carbon in sediment (g C m⁻² y⁻¹) | |
|                        | Calcification by marine organisms | Production of greenhouse gases (µg greenhouse gases m⁻² d⁻¹) | Biogenic production of greenhouse gases is as yet poorly understood as is the role of these gases in climate regulation |
| 5: Disturbance prevention and moderation | Production and maintenance of healthy, living, biogenic physical structure that reduces and dampens extreme wave energy | Extent (km²) and health of seagrass/saltmarsh/oyster bed/biogenic reefs: density of living organisms, measures of growth and production, optimum ecophysiology | |
|                        | Production of biogenic physical structure that reduces and dampens extreme wave energy | Accumulation of mollusc shells: depth, volume and mass of biogenic structure per unit area over time | |
|                        | Bioturbation that increases sediment accumulation | Bioturbation measures such as burrow extent, turnover and stability per unit time, sediment accumulation and deposition due to the presence of bioturbating organisms | |
|                        | Production and maintenance of living saltmarsh beds that absorb excess water during extreme rainfall events or extreme high tides | Extent (km²) and health of saltmarsh: density of living organisms, measures of growth and production, optimum ecophysiology | |
| 6: Regulation of water flows | Hydrodynamic processes | Mass transport of water from advection flux (m³ m⁻² d⁻¹) determined, for example, from hydrodynamic modelling | The role of different components of the marine ecosystem in this service is unclear |
|                        | Deviation and entrainment of very localized flows through presence of epibenthic biogenic structures | Density (e.g., proportion of habitat occupied (%), volume (m³)), complexity (e.g., measured by species diversity, rugosity, fractal distance) of epibenthic structure | |
| 7: Waste treatment and assimilation | Microbial degradation, mineralization, transformation and conversion of toxicants to less toxic substances; burial of toxicants | Success of these processes can be suggested by the presence of resilient and healthy communities indicated by biodiversity levels/ ratios/so. of sensitive species | Healthy communities may exist due to lack of pollutants and waste to be treated or assimilated and may not necessarily indicate these processes are happening |
|                        | Degradation, mineralization, transformation and conversion of toxicants to less toxic substances | Degradation and mineralization rates measured as bacteria metabolism, concentrations of organic matter over time and space, chemical analysis for contaminants | There are a multitude of contaminants and toxicants and a multitude of degradation, mineralization, transformation and conversion pathways to be considered, many of which are poorly known |
|                        | Dilution and dispersal of toxicants through hydrodynamics | Diffusivity (mol toxicant) m⁻² s⁻¹ and advection (mol toxicant) m⁻² s⁻¹ flux determined, for example, from hydrodynamic modeling | |
|                        | Burial of toxicants through bioturbation | Chemical analysis in sediments and water; bioturbation measures such as: burrow extent, turnover and stability per unit time, sediment accumulation and deposition | |
|                        | Sequestration of toxicants by living organisms | Body biomass of toxicants | |
|                        | Storage of excess organic carbon in living biomass and burial in sediment | Carbon storage – carbon in living organisms; carbon buried in sediments; depth of carbon in sediment | |
|                        | Microbial reduction and cycling of excess nutrient facilitated through bioturbation | Nutrient levels and/or rates of nutrient cycling; bioturbation measures such as: burrow extent, turnover and stability per unit time, sediment accumulation and deposition | |
|                        | Food web facilitated organic carbon storage; reduction and cycling of excess nutrient | Production and biomass at different trophic levels | |
| 8: Coastal erosion protection | Presence of healthy seagrass/saltmarsh/oyster or mussel bed/biogenic reefs | Extent (km²) and health of seagrass/saltmarsh/oyster bed/biogenic reefs: density of living organisms, measures of growth and production, optimum ecophysiology | |
|                        | Accumulation of mollusc shells | Accumulation of mollusc shells: depth, volume and mass of biogenic structure per unit area over time | |
5.3. Indicator measurability and sensitivity

Indicators for many of the services delivered by the Dogger Bank, and at the more generic level, cannot be defined (e.g., biotic raw materials, regulation of water flows, and many cultural services), despite the relatively well-studied nature of the Dogger Bank. Existing data is inappropriate for the ecosystem service indicators selected. Ecological data largely relate to physical characteristics of the site, characterization of the biological communities present and commercial fisheries data (e.g., Diesing et al., 2009). Sampling is often sporadic and not necessarily repeated in the same location. Ecosystem service assessments require data that help explain the role of ecosystems in delivering ecosystem services (i.e., the links between ecosystem functions, services and benefits). This is problematic for future assessments and has been highlighted as one of the main challenges for the incorporation of ecosystem service assessments and valuation into marine planning (Börger et al., 2014). How the indicators selected may respond to human activity and natural events is largely unknown.

The uncertainty surrounding any indicator selected for ecosystem functions or services may therefore be substantial. An “honest declaration” of uncertainty is needed (Müller and Burkhard, 2012) and different decision contexts may need different degrees of precision. Scoring procedures could be employed to demonstrate how well indicators are supported by scientific evidence, to assess the quality of the indicators selected and their potential utility to management activities (Kershner et al., 2011).

5.4. Indicator specificity

Identifying indicators that respond to a specific change in the ecosystem is important if indicators are to support ecosystem management. Of the ecosystem service indicators identified in Table 2 that are measurable and sensitive to change, many are likely to change in response to multiple stressors (e.g., climate change and other human activities). Unless the indicators can indicate short-term change, their use in understanding the impact of, for example, invasive species or the construction of wind turbines on the Dogger Bank, becomes limited. Nevertheless, these indicators may highlight where to look when change occurs. If the indicator can show that a function or service is changing, the causes of this change and possible management actions can be explored. Identifying the exact cause of change, however, will always be challenging in such a complex environment.

Greater understanding is needed of the components of the ecosystem that are responsible for ecosystem service provision, be they components of populations, species, guilds, food webs or even habitats (Luck et al., 2003; Kremen, 2005). Indicators must be reliably linked to these components and the functions they carry out. There is still a considerable gap in this understanding, but improving the scientific basis behind the ecosystem services

| Key ecosystem services | Examples of ecosystem functions that deliver the service | Indicators of functions and their measurement (Units) | Comments and issues related to assessment criteria |
|------------------------|-------------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| 9: Biological control (checks and balances) | Production and maintenance of predators and competitors to control nuisance organisms; Maintenance of resilient and robust community structure | Bioturbation measures such as burrow extent, turnover and stability per unit time, sediment accumulation and deposition | |
| 10: Migratory and nursery habitat | Production and maintenance of suitable habitat | Area of suitable habitat (m²); quality of habitat; presence and abundance of target species for ecosystem service e.g., number of juveniles or spawning adults of target species utilizing habitat | |
| 11: Gene pool protection | Provision and maintenance of suitable habitat | Area of suitable habitat (m²); quality of habitat; presence and abundance of species/communities of concern for gene pool | |

### Table 3b (Continued)
## Table 4
Example indicators for some of the ecosystem benefits generated by the ecosystem services in Table 1.

| Ecosystem services | Examples of ecosystem benefits | Indicators of benefits and their measurement (units) |
|--------------------|--------------------------------|--------------------------------------------------|
| 1a: Food provision – wild capture sea food | Nutrition from wild catch seafood consumption | Grams protein/year/head or per household |
|                    | Wild catch seafood landed for human consumption | Landings data at particular times and places (tonnes) |
|                    | Fisheries revenues and contribution to Gross Value Added (GVA) | Monetary value (e.g., in £, $ or €) |
|                    | Employment in fisheries | Number of jobs |
| 1b: Food provision – farmed sea food | Nutrition from farmed seafood consumption | Grams protein/year/head or per household |
|                    | Farmed seafood landed for human consumption | Landings data at particular times and places (tonnes) |
|                    | Aquaculture revenues and contribution to GVA | Monetary value (e.g., in £, $ or €) |
|                    | Employment in aquaculture | Number of jobs |
| 2a: Biotic raw material – genetic resources | Quantity of genetic resources landed | Tonnes |
|                    | Knowledge of genetic material available for future use | Count of known existing genes of potential use (relating to option value) |
|                    | Revenues generated from the use of marine genetic resources and contribution to GVA | Monetary value (e.g., in £, $ or €) |
|                    | Employment in industries using marine genetic resources | Number of jobs |
| 2b: Biotic raw material – medicinal resources | Use of marine medical resources in medicines | Number of medicines, improvements in mortality rates and quality of life, etc. |
|                    | Revenues generated from businesses using marine medical resources (e.g., pharma- and neutra-ceuticals and their contribution to GVA | Monetary value (e.g., in £, $ or €) |
|                    | Employment in industries using marine medical resources | Number of jobs |
| 2c: Biotic raw material – ornamental resources | Contribution to ornamental uses | Tonnes |
|                    | Revenues generated by businesses using marine ornamental resources and their contribution to GVA | Monetary value (e.g., in £, $ or €) |
|                    | Employment in industries using marine ornamental resources | Number of jobs |
| 3: Air purification | Health (human, farm animals and pets) | Health costs avoided: monetary value (e.g., in £, $ or €) |
|                    | Crop productivity | Unit of measurement is unknown |
| 4: Climate regulation | Shadow price of carbon (Treasury Green Book, CO2 equivalent) | Monetary value (e.g., in £, $ or €) |
| 5: Disturbance prevention and moderation | Less prevention and control of erosion | Avoided costs of prevention and control of erosion: monetary value (e.g., in £, $ or €) |
|                    | Damages avoided loss of land | Avoided costs: monetary value (e.g., in £, $ or €) |
|                    | Damages avoided loss of production | Avoided costs: monetary value (e.g., in £, $ or €) |
|                    | Decrease in insurance costs (adverse selection) | Avoided costs: monetary value (e.g., in £, $ or €) |
| 6: Regulation of water flows | Avoided additional fuel consumption due to maintenance and/or enhancement of navigation channels | Avoided costs: monetary value (e.g., in £, $ or €) |
| 7: Waste treatment and assimilation | Avoided adverse health effects | Health costs avoided: hospital admissions (as long as accompanied by exposure information) |
|                    | Waste removal and burial | Costs of primary vs tertiary sewage treatment; replacement cost analysis: cost to change the system to comply with EU directives vs paying infraction costs: monetary value (e.g., in £, $ or €) |
|                    | Water filtration (reduction in turbidity). Clean status of beach and/or water quality, linked to tourism | Avoided costs of prevention and control of erosion: monetary value (e.g., in £, $ or €) |
| 8: Coastal erosion prevention | Natural protection for land/houses | Avoided costs of prevention and control of erosion: monetary value (e.g., in £, $ or €) |
|                    | Reduced cost of coastal protection measures | Cost of hard vs soft defence |
| 9: Biological control (checks and balances) | Biosecurity (through maintenance of ecosystem health) | Avoided outbreaks of human diseases related to change in environmental quality |
|                    | Avoided remediation | Avoided costs: monetary value (e.g., in £, $ or €) |
| 10: Migratory and nursery habitat | Dependence of off-site fisheries/catch percentage | Contribution to employment (no. of jobs) and revenue (monetary value e.g., in £, $ or €) |
|                    | Maintenance of fishing activity | Cost of hard vs soft defence |
| 11: Gene pool protection | Potential option of future use | Meta-analysis, choice experiments, analysis of option value: Monetary value (e.g., in £, $ or €) |
|                    | Protected species and habitats | Level of investment made in protection: Monetary value (e.g., in £, $ or €) |
|                    | Origin verification (w.r.t. culturally important species) | Price premium compared to other sources: Monetary value (e.g., in £, $ or €) |
| 12: Leisure, recreation and tourism | Number of rested people | Number of sick days avoided |
|                    | Coastline and seascape watching | Number of participants |
|                    | Wildlife watching | Number of wildlife watchers |
|                    | Beach usage | Number of beach visits |
|                    | Water usage | Number of swimmers, divers, surfers, boaters |
| 13: Aesthetic experience | Extent of a site to be watched and enjoyed | Number of tourist photos taken |
|                    | | Number of visits to a site |
concept will strengthen its political relevance and practical application (Seppelt et al., 2011).

5.5. Indicator scalability and transferability

Often it is only the generic indicators that are useful at larger scales and are transferable to some extent. To be meaningful for a particular site, indicators need to be made specific. For example, fish stocks are found across the North Sea and can be used as an indicator of the potential for food provision, but food provision from the Dogger Bank is contributed to by specific stocks such as plaice, turbot and lemon sole. The indicators selected in this work suggest that community structure of biota is a relevant indicator for a number of regulating ecosystem services, such as waste treatment and assimilation, climate regulation and air purification. To be useful to management, it needs to be specific to the location and context of interest, the service of interest and, in the case of waste treatment and assimilation, the waste of interest.

These examples suggest that the scalable and portable criteria may not be of primary concern for the identification of relevant indicators in all cases. They also highlight the need for additional contextual indicators, for example, the quantity of waste or contamination that is entering the system, the quantity that is removed by dilution alone and where is it removed to (e.g., locked up in sediments or within the bodies of organisms).

6. Conclusions

Exploring the application of an ecosystem service classification and related ecosystem service indicators to the Dogger Bank identified a number of issues. Ecosystem service classifications can capture the ecosystem services delivered by an offshore marine site, but generic level classifications, such as TEEB (2010) and EEA (2013) need to be tailored to each location. Irrelevant ecosystem services need to be removed and the definitions of each service fine-tuned to better reflect the case study site. Distinctions between ecosystem services, functions and benefits must also be made clear.

Using the classification developed, indicators for the full suite of ecosystem services were derived as well as for associated functions and benefits. This provides a novel contribution as studies typically focus on only a limited number of services, and rarely assess the full complement of ecosystem services, functions and benefits. The relevance and applicability of these indicators, however, cannot always be guaranteed. Data scarcity for the marine environment results in many indicators being unquantifiable. Indicator specificity is a particular problem. Indicators of functions, services and benefits will likely respond to a number of different causes of change. Understanding how a specific location contributes to ecosystem service provision and the benefits they generate, and how they will respond to change remains a challenge.

Tailoring generic level indicators to a specific case study can be achieved with meaningful results for ecosystem services, functions and benefits. All of these indicators should be assessed in conjunction to obtain a more complete understanding of the implications of ecosystem change. Focusing on just ecosystem service or function or benefit indicators may misrepresent a situation and lead to counterproductive management interventions.

Despite these challenges, there is potential to apply ecosystem service indicators to positive effect. With increasing emphasis on marine management, the EU Marine Strategy Framework Directive, the EU Biodiversity Strategy, and the Intergovernmental Platform on Biodiversity and Ecosystem Services are all currently developing indicators to help monitor their implementation and progress. By identifying what indicators can best describe ecosystem services, functions and benefits, effort can be made to ensure that they become applicable through focused monitoring and evaluation programs.

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