



**JNCC Report
No: #####**

Development of JNCC Marine Ecosystem Services Optimisation models

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Summary

Growing interest in marine natural capital has highlighted the need to better understand the provision and flow of marine ecosystem services from marine benthic habitats. There is increasing recognition of the benefits that humans derive from ecosystems through the provision of food and other goods, including opportunities for recreation. Human well-being is further supported by the processes and functions of ecosystems that regulate and maintain the natural environment, such as the absorption of flood waters by coastal saltmarshes and the provision of nursery habitats for commercially harvested species. Degradation and depletion of natural assets, beyond their ability to readily recover, reduces the benefits humans can derive from natural ecosystems. To ensure that uses and benefits are sustained, environmental managers and policy makers are seeking to develop decision support tools to manage human demands and pressures.

JNCC commissioned this project to further develop Marine Ecosystem Service Optimisation (MESO) models based on previously commissioned conceptual ecological models (CEMs) which represent broad marine, sublittoral habitats in the UK. The partially developed MESO models supplied to the project were Bayesian Belief Network (BBN) models made up of nodes and edges that represent the relationships between ecological components, pressures and ecosystem services within a habitat sub-model. This project built on these initial proof-of-concept MESO models to improve confidence in the model relationships as well as increase the usability of the models.

To our knowledge this is the first attempt to link ecosystem components in terms of the grouping of functionally similar species into functional groups (biological assemblages), with their capacity to provide ecosystem services. This takes the association between the ecological component down to a much more detailed level in terms of the functions being undertaken by the ecological assemblage that support the intermediate and final ecosystem services. The strength of the linkages is supported by information relating to the life history and biological traits of the species and thus a much more robust approach than expert opinion at the scale of biotopes comprised of many different functional groups.

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1 Introduction

Growing interest in marine natural capital has highlighted the need to better understand the provision and flow of marine ecosystem services from marine benthic habitats. There is increasing recognition of the benefits that humans derive from ecosystems through the provision of food and other goods, including opportunities for recreation. Human well-being is further supported by the processes and functions of ecosystems that regulate and maintain the natural environment, such as the absorption of flood waters by coastal saltmarshes and the provision of nursery habitats for commercially harvested species. Degradation and depletion of natural assets, beyond their ability to readily recover, reduces the benefits humans can derive from natural ecosystems. To ensure that uses and benefits are sustained, in the long term for future generations environmental managers and policy makers are seeking to develop decision support tools to manage human demands and pressures.

A key aim of this project was to link the elements of ecosystem structure and function (ecological components) that support the production of ecosystem services. Ecosystem services are defined as the contributions that ecosystems (i.e. living systems) make to human well-being. These services as defined in this project based on international typologies (see Section 2.3) are the outputs of ecosystems that most directly affect the well-being of people. Final ecosystem services are supported by ecosystem processes and functions. For example, native oysters harvested from a bay represent a final ecosystem service obtained by humans, the provision of this service is supported by the marine ecosystem through the presence and maintenance of suitable habitat for spat to settle and the quality and chemistry of the water column and the provision of suitable food (among other factors).

The purpose of this project was to advance understanding of the capacity of five broad marine habitat types (sand, coarse and mixed sediments mud, and rock) to supply ecosystem services and the sensitivity of this capacity to pressures caused by human activities, in order to develop management tools.

1.1 Project Aims and Objectives

JNCC commissioned this project to further develop decision support tools: Marine Ecosystem Service Optimisation (MESO) models based on previously commissioned conceptual ecological models (CEMs) which represent broad marine, sublittoral habitats in the UK (see section 2.1 for more information). The CEMs are diagrammatic representations of the influences and processes which occur within an ecosystem and consist of ecological components that represent parts of the marine ecosystem (including habitat factors, functional groups of species and ecological processes and functions).

The partially developed MESO models supplied to the project were Bayesian Belief Network (BBN) models made up of nodes and edges that represent the relationships between ecological components, pressures and ecosystem services within a habitat sub-model. The MESO models are used to simulate the probable effects of stressors (i.e. pressures) on the provision of ecosystem services, including intermediate (supporting services) and final ecosystem services supplied by the habitat.

To underpin further development of the MESO BBN, evidence was required on the effects of pressures caused by human activities on the components of marine ecosystems that support and provide ecosystem services. The response of the biological assemblages within the CEM to human pressures was identified as a particular evidence gap. The links between ecological components within the CEM and ecosystem services also required further

elucidation as most work to date has focussed on habitats that supply services not the individual parts.

Further work was also required to verify the existing models and add pressure and ecosystem service nodes and to optimise performance. JNCC also required development of a user-friendly interface so that the models became fully operational and accessible to decision makers. The objectives to deliver this work are set out below.

1.1.1 Ecological Objectives

1. Undertake a literature review to consolidate and summarise evidence of effects of anthropogenic pressures on the functioning of sublittoral sand, mixed sediments, mud, coarse sediments and rock.
2. Undertake literature review to consolidate and summarise evidence of effects of anthropogenic pressures on conservation objective attributes for sublittoral sand, mixed sediments, mud, coarse sediments and reef.
3. Undertake literature review to consolidate and summarise evidence of provision of ecosystem services (intermediate and final) from sublittoral sand, mixed sediments, mud, coarse sediments and reef.

1.1.2 Modelling Objectives

1. Create manually invoked mechanisms (e.g. scripts) to run BBN models in R (or another suitable programming language) based on JNCC's initial R script and the original VBA scripts in Excel. These must be able to run the existing four MESO models, ingest new data, test stressor scenarios and create outputs.
2. Create a user-friendly interface that consolidates all manually invoked mechanisms (e.g. scripts) and operational files (e.g. look up tables) into one place.
3. Create a package with 'functions' using the manually invoked mechanisms (e.g. scripts) from the primary objectives (e.g. R package if R scripting language used)
4. Expand the capabilities of the user-friendly interface from Objective 5 so that it operates with all MESO models (25 in total) from all five marine benthic habitats (sublittoral sand, sublittoral rock; sublittoral coarse sediment; sublittoral mixed sediment and sublittoral mud).

1.2 Project Report Outline

This report provides a comprehensive high-level description of the project findings and methodological approaches. More detailed technical evidence is presented in the report appendices and accompanying Excel spreadsheets.

Chapter 2 briefly describes the ecosystem service, pressure and conservation attribute frameworks adopted by this project and the literature review methodology and prioritisation. The evidence gathered from the review was used to assess the links between ecological components identified in the CEM models and links to ecosystem services, pressures and conservation attributes. Summary proformas for these are represented in this report.

Chapter 3 summarises the key findings and outputs.

Chapter 4 discusses the key evidence gaps and data limitations

Chapter 5 provides the final report summary and conclusions.

1.3 Project Outputs

The project outputs consist of this final report and the pressure, conservation attribute and ecosystem service proformas (Appendices 8, 9, and 10 respectively).

Outputs supplied separately include:

- Sediment ecosystem service review Excel spreadsheet;
- Rock ecosystem service review Excel spreadsheet;
- Pressure and conservation attribute review spreadsheet;
- Pressure scenario spreadsheet;
- Pressure- sensitivity assessment reviews for sand, coarse, mud, mixed and rock habitats; and
- BBN Model viewer and scripts.

2 Methodology

2.1 CEM Model Overview

The conceptual ecological models (CEMs) were developed for five broad habitats by previous projects (see Table 1 for references). The CEMs are diagrammatic representations of the influences and processes that occur within an ecosystem. The models are based on literature review and each model is accompanied by a report and technical appendices including details of the literature review and confidence assessments.

Each CEM consists of a number (approx. 50) of ecological components that represent different taxa, structural and / or functional aspects of the habitat, such as functional groups of taxa (e.g. burrowing fauna), abiotic factors (e.g. sediment type) or processes (e.g. sediment mobility). Characteristic species within habitats were assigned to functional groups based on species traits for representation within each CEM. These functional groups are referred to as biological assemblages within this project.

The CEMs contain habitat sub-models to represent the interactions between biological assemblages with a similar function (e.g. all predators and scavengers, or all filter-feeders etc), within a marine benthic habitat. Table 1 (below) shows the number of sub-models from each of the five JNCC CEMs of marine benthic habitats

Table 1 Summary of CEM models, number of submodels and references.

Model	No of Submodels	Reference
Shallow sublittoral sand	4	Coates <i>et al</i> 2016
Sublittoral rock	7	Alexander <i>et al</i> 2015
Shallow sublittoral coarse sediment	4	Alexander <i>et al</i> 2014
Shallow sublittoral mixed sediment	5	Alexander <i>et al</i> 2016
Shallow sublittoral mud	5	Coates <i>et al</i> 2015

The models are split into seven levels and take spatial and temporal scale into account through their design, as well as the magnitude and direction of influence between interacting ecological components. The seven levels include regional to global drivers, water column processes, local inputs/processes at the seabed, habitat and biological assemblage, output processes, local ecosystem functions, and regional to global ecosystem functions. Each sub-model is accompanied by an associated confidence model which presents confidence in the links between each model component.

1. Regional to Global Drivers – high level influencing inputs to the habitat which drive processes and shape the habitat at a large-scale, e.g. water currents, climate etc. These are largely physical drivers which impact on the water column profile. (Regional to Global Drivers are not included within BBN)

2. Water Column Processes – processes and inputs within the water column which feed into local seabed inputs and processes, e.g. suspended sediment, water chemistry and temperature etc.

3. Local Processes/Inputs at the Seabed – localised inputs and processes to the ecosystem which directly influence the characterising fauna of the habitat, e.g. food resources, recruitment etc.

4. Habitat and Biological Assemblage – the characterising fauna and sediment type(s) which typifies the habitat. For the sub-models, fauna are broken down into functional groups and sub-functional groups as necessary. Example taxa characterising each group are named in the models, however for the full list of fauna related to each grouping, please see the separate Excel spreadsheets for the pressure sensitivity information.

5. Output Processes – the specific environmental, chemical and physical processes performed by the biological components of the habitat, e.g. biodeposition, secondary production etc.

6. Local Ecosystem Functions – the functions resulting from the output processes of the habitat which are applicable on a local scale, whether close to the seabed or within the water column, e.g. nutrient cycling, habitat provision etc.

7. Regional to Global Ecosystem Functions – ecosystem functions which occur as a result of the local processes and functions performed by the biota of the habitat at a regional to global scale, e.g. biodiversity enhancement, export of organic material etc.

The models indicate that whilst the high level drivers which affect each functional group are largely similar, the output processes performed by the biota and the resulting ecosystem functions vary both in number and importance between groups (Coates *et al* 2016).

Confidence within the models as a whole was generally high, reflecting the level of information gathered during the literature review.

2.2 Ecological Components

The ecological components identified in the original CEM work were assessed by this project for feasibility of incorporation within BBN models as nodes. The ecological component nodes for each broad habitat were supplied by JNCC as an Excel spreadsheet. These nodes formed the basis of the literature review and the links with pressures, conservation attributes and sub-attributes and ecosystem services are presented in the summary tables (supplied separately). The biological assemblage nodes identified for each CEM underpin the pressure sensitivity assessments for the biota and were a key model input.

Some updates to taxonomy have taken place during the development of the CEMs and subsequently so that there may be differences in nomenclature between models. Largely we have not updated these but retained the original CEM names to prevent confusion when referring to the original reports. The changes identified are shown below in Table 2. Identifying name changes was important as searches were conducted for information both on currently accepted name and previous name where necessary.

Table 2 Changes in species nomenclature identified in this project

Current accepted name	Previous name or synonym
<i>Acrocnida brachiata</i>	<i>Amphiura brachiata</i> / <i>Ophiura brachiata</i> / <i>Ophiocoma brachiata</i>
<i>Apseudopsis latreilli</i>	<i>Apseudes latreilli</i>
<i>Crassikorophium crassicorne</i>	<i>Corophium crassicorne</i>
<i>Crisularia plumosa</i>	<i>Bugula plumosa</i>
<i>Ennucula tenuis</i>	<i>Nuculoma tenuis</i>

<i>Kurtiella bidentata</i>	<i>Mysella bidentata</i>
<i>Limecola balthica</i>	<i>Macoma balthica</i>
<i>Novocrania anomala</i>	<i>Neocrania anomala</i>
<i>Parexogone hebes</i>	<i>Exogone hebes</i>
<i>Philine quadripartita</i>	<i>Philine aperta</i>
<i>Phyllodoce maculata</i>	<i>Anaitides maculata</i>
<i>Saccharina latissima</i>	<i>Laminaria sachharina</i>
<i>Spiobranthus triqueter</i>	<i>Pomatoceros triqueter</i>
<i>Thracia phaseolina</i>	<i>Thracia papyracea</i>
<i>Venerupis corrugata</i>	<i>Venerupis senegalensis</i>

2.3 Ecosystem Service Framework

The ecosystem service frameworks used in this study were based on Potts *et al* (2014) and the Common International Classification of Ecosystem Services (CICES v5.1; Haines-Young & Potschin, 2018). The key difference between these two frameworks is that Potts *et al* (2014) includes both intermediate ecosystem services and final ecosystem services and goods and benefits while CICES only considers final ecosystem services.

The Potts *et al* framework is based on XXX and xxx. The framework specifically identified how xx and xx and xx.

CICES was developed from the work on environmental accounting undertaken by the European Environment Agency (EEA) CICES final ecosystem services were used rather than those identified in Potts *et al* (2014), as the CICES framework for marine relevant final ecosystem services is comprehensive and captures current understanding of the wide variety of services that can be delivered by ecosystems.

The CICES classification aims to support natural capital accounting and valuation and is designed to reduce double counting of ecosystem services by focussing **only** on final ecosystem services and excluding intermediate services (the ecosystem processes and functions that support delivery of the final services).

In the CICES classification ecosystem services are defined as the contributions that ecosystems make to human well-being, and distinct from the goods and benefits that people subsequently derive from them. The definition of each service identifies both the purposes or uses that people have for the different kinds of ecosystem service and the particular ecosystem attributes or behaviours that support them (Haines-Young & Potschin, 2018). It is important to note that an ecological component may be considered to provide an intermediate or final service depending on context (Haines-Young & Potschin, 2018). For example, crabs deliver an intermediate regulating service when they predate on nuisance species but represent a final ecosystem service when they are captured as food.

Within the Potts *et al* (2014) and CICES framework the intermediate and final ecosystem services are split into three major groups following international precedents in the Millennium Ecosystem Assessment (MEA, 2005) and The Economics of Ecosystems and Biodiversity (TEEB) (TEEB, 2010):

- Provisioning,
- Regulation and Maintenance and
- Cultural

The marine-relevant divisions within the CICES classification are given in Figure 1 (below).

The CICES hierarchy proceeds through Division, Group and Class, with the distinctions between individual services becoming more specific at each layer. Assessments can be made at any level within the nested structure depending on the context and data available (i.e. at the scale of Group or Division if more specific information for individual Classes is not available). This is intended to allow flexibility and take account of challenges presented for particular applications and different spatial scales. Within this project some services were assessed at the group level and others at the class.

Figure 1 Groupings of ecosystem services and main divisions for Abiotic factors (A); Biotic factors (B); see Appendix 3 for more information.

Provisioning	Regulating	Cultural
Division	Division	Division
Biomass (B)	Regulation of physical, chemical, biological conditions (A and B)	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting (A and B)
Genetic material from all biota (B)		Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting (A and B)
Water (A)	Maintenance	
	Division	
Non aqueous natural abiotic ecosystem outputs (A)	Transformation of biochemical or physical inputs to ecosystems (A and B)	

2.4 Ecosystem service selection

The selection of ecosystem services to scope into this work was based around those that are relevant to benthic marine systems. Not all ecosystem services can be related to marine ecosystems, as the concept was developed for terrestrial systems and thus some ecosystem services cannot be readily transposed from the terrestrial to the marine context (Hooper *et al* 2019). Examples of ecosystem service types that cannot be readily transposed are covered in more detail below.

The literature review prioritised ecosystem services that have clear evidence and linkages to the ecological components identified in the CEM and that could be feasibly incorporated in the MESO BBN. To incorporate the ecosystem service in the MESO model, evidence was required to link the ecological components in the CEM to the service and to parameterise the model edges, priors and posteriors (see section 3.3). Only ecosystem services with clear ecological component links and an associated evidence base were considered likely candidates for inclusion in the MESO BBN and were prioritised in the literature review (see Appendix 3 and Section 2.5). Where the first and second sifts identified information on other

ecosystem services unlikely to be incorporated in the BBNs (see Section 2.4.2) the information was still added to the review spreadsheets. Ecosystem service proformas for some of these services were created where at least some relevant information was found for the assessed habitats.

All the subtidal habitats were considered likely to provide the selected ecosystem services but the magnitude of contribution and the components providing the service may vary. For example, each of the assessed habitats provides different commercially fished species. The rates of ecosystem processes and services and the components that support these also vary between habitat types. For example in reef habitats macroalgae are the key primary producers while in mobile sediment habitats sediment diatoms support this service.'

2.4.1 Candidate sublittoral habitat relevant ecosystem services included in the MESO BBN

Ecosystem services with a clearly defined evidence base

Ecosystem services that met the criteria (linked to ecological components, candidate BBN model nodes and considered likely to be supported by a well-developed evidence base) were:

- Intermediate Services: Potts *et al* (2014): Primary production;
- Provisioning Service: CICES 1.1.5 Wild plants (terrestrial and aquatic) for nutrition, materials or energy;
- Provisioning Service: CICES 1.1.6 Wild animals (terrestrial and aquatic) for nutrition, materials or energy; and
- Provisioning Service (abiotic) CICES 4.3.1 Mineral substances used for nutrition, materials or energy.

For these ecosystem services the linkage between ecological components and the ecosystem service is direct, as the ecological component directly contributes to the ecosystem service. An example of this type of relationship is CICES 1.1.5 Wild plants (terrestrial and aquatic) for nutrition and materials that are clearly provided by the biological assemblage 'Macroalgae' in the rock CEM and for which information on species targeted is available in the grey and peer-reviewed literature.

Ecosystem services that are supported by ecosystem processes.

A number of ecosystem services are supported by ecological process and ecosystem functioning associated with the biota. In these examples the ecosystem service supply may be less quantifiable and be surrounded by higher levels of uncertainty but nevertheless links can be made between ecological components identified in the CEM and ecosystem services incorporated in the MESO BBN. These ecosystem services were also prioritised in the ecosystem service literature review (section 2.10).

Ecosystem services that met the criteria (linked to ecological components, candidate BBN model nodes and supported by evidence base) were:

- Intermediate Services: Potts *et al* (2014): Nutrient cycling;
- Intermediate Services: Potts *et al* (2014): Formation of physical barriers and Natural hazard regulation;
- Intermediate Services: Potts *et al* (2014); Formation of species barriers
- Intermediate Services: Potts *et al* (2014); Carbon sequestration;

- Regulating Service: CICES 2.1.1 Mediation of wastes or toxic substances of anthropogenic origin by living processes;
- Regulating Service: CICES 2.2.1 Regulation of baseline flows and extreme events;
- Regulating Service: CICES 2.2.6.1 Regulation of chemical composition of atmosphere and oceans (carbon sequestration) and
- Regulating Service: CICES 2.2.2.3. Maintaining nursery populations and habitats (Including gene pool protection).

2.4.2 Ecosystem services excluded from MESO BBN

For some ecosystem services the evidence base in the wider literature to identify and quantify linkages between ecological components and the delivery of the service is very limited. This may be because the link between the ecological components and ecosystem services is highly uncertain and the service is only present and/or provided under variable conditions. For example, larval supply is a highly stochastic process in marine systems (Siegel *et al* 2008) and for this reason larval supply was not included in the models.

Alternatively, the service may only be utilised under some circumstances so that the service supply fluctuates and is not readily associated with ecological components in the CEM. Examples of these services are the supply of genetic materials from organisms.

In other cases, there may be a link between ecological components within the CEM and the service, but the evidence base does not support consistent assessment, either because the service is difficult to quantify, under studied or the evidence is not collected. In contrast to managed human activities such as fisheries, for example, recreational activities are not licensed, and no systematic evidence is collected on them or the evidence base is extremely patchy. The link to ecological components may be tenuous, for example there may be high levels of recreational activity in the area, but the service is facilitated by infrastructure such as access roads and car parks and the link to ecological components is of less relevance in delivering the service. Similarly, the set-up, of aquaculture service is facilitated by site suitability, local demand and other factors (Saunders, 2010) and the CEM does not relate to the supply of the service.

- Intermediate Services: Potts *et al* (2014): Larval/gamete supply;
- Provisioning Service: CICES 1.2.1 Genetic material from plants, algae or fungi;
- Provisioning Service: CICES 1.2.2 Genetic material from animals;
- Provisioning Service: CICES 1.2.3 Genetic material from organisms;
- Provisioning service CICES 1.1.2: Cultivated aquatic plants for nutrition, materials or energy;
- Provisioning service: CICES 1.1.4: Reared aquatic animals for nutrition, materials or energy; and
- Regulating Service: CICES 2.2.2.1 Pollination (or 'gamete' dispersal in a marine context.

Where readily available the literature review captured information related to these services, but they were not prioritised.

2.4.3 Cultural services

The role that the ecosystem plays in supporting cultural ecosystem services is different from provisioning and regulating ecosystem services. This is for two reasons:

- 1) The distinction between cultural ecosystem services and benefits is not clear for cultural ecosystem services; many of the services categories used are best understood as benefits produced not only through cultural services, but also through provisioning and regulating services (Chan *et al* 2012).
- 2) The cultural ecosystem services are considered to be relational (i.e. the result of non-linear, multidirectional interactions between humans and ecosystems), comprising of environmental settings and cultural practices. Environmental settings both enable and are shaped by cultural practices (Fish *et al* 2016). The important difference is that for the most part, cultural ecosystem services are place based and the ecosystem provides that space.

These key differences mean it is harder to relate changes in cultural ecosystem services to changes in ecological components as they may be closer linked to landscape properties and thus vary widely in space and time. As such the majority of cultural ecosystem services have not been included in this work, primarily because subtidal habitats are not directly accessible to most of society.

Exceptions are where there are clear interactions:

- CICES 3.1.1 Physical and experiential interactions with natural environment and the parallel abiotic service
- CICES 6.1.1.1 Physical and experiential interactions with natural abiotic components of the environment.

In both cases these categories relate to divers (and anglers) and their experiential interactions with seabed components, as these societal groups experience the seabed or its assemblages first hand. Where readily available the literature review captured information related to cultural services, but they were not prioritised.

2.4.4 Services excluded as not marine or marine but not linked to sublittoral habitat

Ecosystem services that are not relevant to marine subtidal systems were not included in this project or that are not provided by sublittoral marine ecosystems in the UK. Examples include CICES 2.1.2.1 Smell reduction and CICES 2.1.2.3 Visual screening. Other examples include CICES 5.2.1.3 Gaseous flows which relate to the mediation of flows by natural abiotic structures but are not relevant to seabed habitats.

In some cases, excluded services may have marine relevance but for intertidal or coastal margins rather than subtidal; for example, there may be an argument for liquid flows being considered as a flow in some coastal habitats such as saltmarshes that function to regulate the volume of water running off from the land (Atkins *et al* 2015).

2.4.5 Abiotic ecosystem services

This project follows the convention in Tempera *et al* (2016) in generally excluding the CICES final ecosystem services that are delivered by abiotic components, although it is acknowledged that for some services the abiotic and biotic cannot be reasonably separated e.g. waste remediation. Abiotic raw materials and renewable abiotic energy whose availability, quantity or quality is not enhanced by living organisms or ecological processes (e.g. sand and gravel, salt, wind and wave energy) are natural resources but not ecosystem services (Liquete *et al* 2013a). The exceptions were the two ecosystem services where biota and the abiotic habitat influence the capacity to provide that service:

- Intermediate service: Carbon sequestration (Potts *et al* 2014) and

- Regulating service CICES 2.1.1. Mediation of wastes or toxic substances of anthropogenic origin by living processes, these were included in the literature review searches and prioritisation (see below)

2.4.6 Uncertainties in ecosystem service definition and interpretation

Some ecosystem services categories have been interpreted differently by different researchers: an example is that of genetic resources. CICES 5.1 defines it rather differently to the UKNEA ecosystem classification approach that Potts *et al* (2014) follows. Division 1.2 in CICES 5.1 defines 'Genetic material from all biota (including seed, spore or gamete production)' and this encompasses classes for plants and animals supplying the genetic material and classes to categorise what the genetic material is collected for e.g. establishing new populations or the design and construction of new biological entities. This is very much referring to genetic resources that are collected from the wild such as broodstock for aquaculture in the marine context. By contrast Potts *et al* 2014 have an intermediate service of 'Larval and gamete supply' that is defined in Atkins *et al* (2015), as 'Quantity of larvae/gametes supplied to a particular location (number per m³); Quality of larvae/gametes supplied to a particular location (% affected by disease; mortality rates). For the current study the CICES approach has been taken to genetic material.

It is important to note that reviews to date that link ecological features to components of ecosystems have worked at different scales to the current research;

- 1) Potts *et al* 2014 scored the importance of ecosystem services from broadscale habitats (EUNIS level 3) and some habitats of conservation importance (HOCl) which were generally EUNIS level 4 or 5 biotopes plus listed species;
- 2) Tempera *et al* 2016 mapped the spatial distribution of marine ecosystem service capacity for biotopes from EUNIS level 1 to 5;
- 3) Salomidi *et al* 2012 mapped the potential provision of ecosystem services from EUNIS level 4 biotopes based on expert judgement;
- 4) Galparsoro *et al* 2014 also mapped ecosystem services from benthic habitats (EUNIS level 2-4) for the European North Atlantic Ocean.

To our knowledge this is the first attempt to link ecosystem components in terms of the grouping of functionally similar species into functional groups (biological assemblages), with their capacity to provide ecosystem services. This takes the association between the ecological component down to a much more detailed level in terms of the functions being undertaken by the ecological assemblage that support the intermediate and final ecosystem services. The strength of the linkages is supported by information relating to the life history and biological traits of the species and thus a much more robust approach than expert opinion at the scale of biotopes comprised of many different functional groups.

2.5 Ecosystem services assessed in the MESO BBN

Table 3 below identifies the reviewed services that were incorporated in the MESO BBN models. A summary of the ecosystem services and their inclusion or rationale for exclusion is presented in Appendix 3. For marine relevant ecosystem services, evidence was gathered where available even if these could not be incorporated in the model (see Appendix 10 for proformas).

Table 3 The final list of ecosystem services assessed within this project and incorporated in the MESO BBN. Evidence for other services was collated where readily available. (See Appendix 3 for other services).

CICES Code or Potts <i>et al</i> (2014)	Final List of Ecosystem Services		Proforma No.
	Ecosystem service	Relevant CEM nodes	
Intermediate service	Primary production	Primary production	1
Intermediate service	Nutrient cycling	Nutrient cycling,	2
Intermediate service	Formation of species habitat	Habitat provision	4
Intermediate service	Formation of physical barriers	Sediment type	5
Intermediate service	Carbon sequestration	Carbon sequestration	7
C4ICES 1.1.5	Wild plants (terrestrial and aquatic) for nutrition and materials	Biological assemblage: Macroalgae	10
CICES 1.1.6	Wild animals (terrestrial and aquatic) for nutrition and materials	Biological assemblage	11
CICES 2.1.1	Mediation of wastes or toxic substances of anthropogenic origin by living processes	Nutrient cycling/carbon sequestration	13
CICES 2.2.1	Regulation of baseline flows and extreme events	Bioengineering/habitat provision/sediment stability	5
CICES 5.2.1.1	Regulation of baseline flows and extreme events (ABIOTIC)	Sediment type	5

2.6 Ecosystem service realisation and demand

In this study the ecosystem service potential from ecological assemblages is evaluated. This is different to the amount of ecosystem service actually realised because of the additional factor of societal or sectoral demand for that specific ecosystem service. Current understanding of demand is subject to different approaches (e.g. demand = actual consumption; demand = desires and preferences; demand = a mixture of actual consumption and desired and preferences). Each approach leads to different insights and to our knowledge there is no standardised way of assessing ecosystem service demand. Demand is based on understanding potential flows of ecosystem services but also includes demand metrics and proxies which are often values, preferences and benefits. Finally, ecosystem service providing and benefiting areas may be spatially and temporally disconnected making the understanding of flows of ecosystem services essential to understanding actual service delivery and the fulfilment of demand (Wolf *et al* 2015, Wei *et al* 2017).

2.7 Ecosystem service summary tables, confidence and level of contribution

The outputs of the ecosystem service review are presented in two literature review summary spreadsheets (rock and sediment). The evidence from these spreadsheets for the link between each ecological component and ecosystem service is summarised in draft proformas and the summary tables for each habitat. The type of link between each ecological component and ecosystem service, the confidence in the link and the relative magnitude of contribution is captured in each cell in the summary table and within the proformas.

The relative contribution assessment was used in the MESO BBN as input parameters for the models and the contribution categories are described in that section (Section 3.2.1). The link categories and confidence assessment criteria are outlined below in Table 4 and Table 5 respectively.

Table 4 Categories used to identify the link

Link Categories	Description
Provision	Direct link between the component and the provision of a service. Component directly provides the services, e.g. <i>Mytilus edulis</i> can be harvested and directly provide the service 'Wild animals (terrestrial and aquatic) used for nutritional purposes'.
Mediates	The component influences the flow (or rate) of the service, for example: climate mediates primary production; sediment mud content within a habitat mediates carbon sequestration,
Supports	The component supports a service but does not directly provide or mediate that service, for example, sand eels harvested for uses as an aquaculture feedstock support the provision of fish from aquaculture.
Not assessed	The link was not assessed or there was no evidence found to support assessment.
Not relevant	There is no link between the ecological component and the ecosystem service.

Table 5 Confidence scores for ecosystem service links. The asterisk notation was used in the summary tables to present the confidence assessment in the relevant ecological component x ecosystem service cell combinations.

Category	Description
High (***)	There is a good understanding of the component-ecosystem service relationship and/or the assessment is well supported by evidence. There is consensus amongst the experts.
Medium (**)	Whilst there is an understanding of the component-ecosystem service relationship, this may be based on limited evidence and/or proxy information. There is a majority agreement between experts; but conflicting evidence/opposing views exist.
Low (*)	There is limited or no understanding of the component-ecosystem service relationship and/or the assessment is not well supported by evidence. There is no clear agreement amongst experts.
Variable	The component-ecosystem service relationship is highly variable in space and/or time, for example geology influences the amenity value of a dive site but few places have an iconic status. Similarly, water currents influence

	larval transport, but the level is highly variable according to local conditions/tidal flushing and level of supply.
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2.8 Conservation Attribute Framework

In the context of this project, conservation objectives set out the broad management ecological aims to conserve a marine feature, such as sandbanks or moderate energy circalittoral rock for example. The attributes of each conservation objective are the ecological characteristics of the marine feature, and are 'Extent and Distribution', its 'Structure and Function' or its 'Supporting Processes', which together describe the desired condition or state of the feature. Table 6 below sets out the high-level Conservation Objective attributes and sub-attributes identified by JNCC.

Table 6 Conservation attributes and associated sub-attributes identified by JNCC.

Conservation Attribute	Sub-attribute
Extent and distribution	Sediment composition
Extent and distribution	Biological assemblages
Structure	Physical structure: finer scale topography
Structure	Physical structure: sediment composition
Structure	Biological structure: Key and Influential species
Structure	Biological Structure: Characteristic communities
Function	Ecological processes
Supporting processes	Hydrodynamic regime
Supporting processes	Water quality
Supporting processes	Sediment quality

2.9 Pressure Framework

Activities in the marine environment result in a number of pressures, which may result in an impact on environmental components that are sensitive to the pressure. A pressure is defined as 'the mechanism through which an activity has an effect on any part of the ecosystem' (Robinson *et al* 2008). Pressures can be physical (e.g. sub-surface abrasion), chemical (e.g. organic enrichment) or biological (e.g. introduction of non-native species).

An activity may give rise to more than one pressure. Therefore, rather than assessing the impact of activities as a single impact, the pressure-based approach supports clearer identification of the pathway(s) through which impacts on a feature may arise from the activity. Conversely, the same pressure can also be caused by a number of different activities. To be meaningful and consistent sensitivity to a pressure should be measured against a defined pressure benchmark.

The anthropogenic pressure framework used in this project is based on the list of marine pressures and their descriptions published within OSPAR agreement 2014-2021, 'OSPAR Joint Assessment and Monitoring Programme (JAMP) 2014-2021. Not all pressures within this framework are relevant to benthic habitats and the ecological components in the CEM. In addition, there are some issues assessing some pressures as the evidence base is limited. As a result, a number of pressures were excluded from the assessment at the

beginning of the review and these pressures were excluded on the basis of the rationale below (from Tillin & Tyler-Walters 2014):

- There is a paucity of research concerning the effects of underwater noise on marine invertebrates. While it is generally believed that invertebrates are relatively insensitive to these pressures, compared to other marine receptors such as marine mammals and fish, the evidence base for this is poor and currently, it is almost impossible to come to clear conclusions on the nature and levels of man-made sound that have potential to cause effects upon fish and invertebrates (Hawkins *et al* 2015).
- There is a lack of good quantitative data and an absence of studies concerning the effects of litter on marine invertebrates and Rochman *et al* (2016) came to the conclusion from a recent review that the quantity and quality of research requires improvement to allow the risk of ecological impacts of marine debris to be determined with precision.
- Potential effects from electromagnetic fields have been identified for a range of invertebrate species. However, threshold values are only available for a few species and it would be premature to treat these values as general thresholds. The significance of the response reactions on both individual and population level is uncertain if not unknown.
- There is very limited information on the effects of the introduction of light on marine invertebrates. Tasker *et al* (2010) excluded this pressure when developing indicators relating to the introduction of energy for the purposes of the Marine Strategy Framework Directive 'due partly to their relatively localised effects, partly to a lack of knowledge and partly to lack of time to cover these issues'.
- Radionuclide contamination is often detected, and bioaccumulation noted in some species (Cole *et al* 1999) but information on specific effects is limited.
- The effects of more recent pollutants such as nano-particulates on marine species continue to be studied, while novel endocrine disruptors have been shown to affect inshore shellfish through depressed reproduction (Langston *et al* 2007) but information on population effects is lacking.

The anthropogenic pressures included were selected based on relevance, with selection informed by previous reviews on pressures (Tillin & Tyler-Walters 2014). The final sub-set of pressures incorporated within the review and models was agreed with JNCC, the final decisions are outlined in Table 1(below).

We suggested that some pressures that are low priority or which are difficult to assess could potentially be addressed through a 'generic scenario'. This pressure scenario would assess a generic change in environmental quality and would be based on changes in the ecological functional groups based on the AMBI index that has been applied across a range of stressors (Muxica *et al* 2005).

Table 7 Final List of Pressures assessed and included in the MESO BBN, the pressure proformas are provided in Appendix 8

Pressure theme	Included in MESO BBN	Proforma
Physical change (reversible)	Habitat structure changes - removal of substratum (extraction)	1
	Abrasion/disturbance of the substratum on the surface of the seabed	2
	Penetration and/or disturbance of the substratum below the surface of the seabed, including abrasion	3
	Smothering and siltation changes (depth of vertical sediment overburden) (light and heavy)	4
	Changes in suspended solids (water clarity)	5
Physical loss (permanent change)	Physical change (to another seabed/sediment type)	6
Biological Pressures	Removal of non-target species	No proforma
	Removal of target species	No proforma
Hydrological changes (inshore/local)	Wave exposure changes - local	No proforma
Pollution and other chemical changes	Generic modelled scenario based on AMBI where impacts focus on changes in biological assemblage.	No proforma

2.10 Literature Review: Generic Method

The evidence review adopted a strategic approach to maximise efficiency and provide the best returns within the project resource allocation. The literature review methodology was rather generic for Objectives 1-3 with the outlined process followed for each of these objectives. The evidence review adopted a Rapid Evidence Assessment (REA) approach as described in Civil Service Guidance and described in Collins *et al* (2014). This approach uses a structured, step-wise methodology, following an *a priori* defined protocol to comprehensively collate, critically appraise and synthesise existing research evidence (traditional academic and grey literature) (Dicks *et al* 2017). Within the project time and resource constraints, the outline BBN model evidence requirements indicated where effort should be focussed in order to model ecosystem service delivery. Evidence for ecosystem services that were not in the model, most notably the cultural services, was collected where this was readily available (identified in the first literature sift) but extensive searches were not conducted. The review encompassed a wide range of literature, including government reports and peer-reviewed scientific literature.

2.11 First and second sift of literature

A first, rapid sift was undertaken of the available literature. The search used defined terms which were entered into Google and Google Scholar, the specialist indexing and abstracting service Aquatic Sciences and Fisheries Abstracts; Web of Science, the journal collections of Science Direct, Wiley On-line and the National Marine Biological Library catalogue. Relevant evidence was based on the title. All search terms, the date of search and the sources used

were recorded. All relevant references based on title were downloaded and added to reference libraries.

A second sift of the literature sorted references in the Endnote libraries into relevance for the pressure, conservation attribute and ecosystem service based on the title and abstract. Prioritisation categories are given in Table 8.

Table 8 Second sift prioritisation categories

Priority	Description
Priority 1	Peer reviewed papers on pressures on the marine environment from the UK
Priority 2	Papers based outside the UK (geographical extent)
Priority 3	Date restrictions, preference for most recent
Priority 4	Technical (by date)
NR	Not Relevant

The second sift for sand habitats captured relevant information for the study habitat types and general search terms e.g. marine offshore ecosystem service were not repeated for other broad habitats.

Additional literature was obtained by the following methods:

- Author's personal collections of papers and reports were searched;
- Further specific searches were undertaken on Google Scholar to address knowledge gaps;
- The first 1,000 references on the Plymsea archiving database (www.plymsea.ac.uk) were checked;
- Citations from papers and reports were sourced where relevant and reference lists were checked to identify new references;
- Statutory Nature Conservation Body on-line publications were searched;
- Where key reports were not available, authors or appropriate organisations were contacted;
- JNCC Pressures X Activity Database references were reviewed where relevant (weblink).

The search terms and databases searched are documented in Appendix 4.

2.12 Ecosystem services review

A wide range of literature on the environmental and ecological impacts on intermediate and final ecosystem services was reviewed and the evidence collated in Excel spreadsheets as follows:

- The ecological component and final and/or intermediate ecosystem services links;
- The description, magnitude and nature of the interaction between the ecological component and the final and/or intermediate ecosystem service, qualified based on the strength and quality of the evidence.

Ecosystem service information was assigned, where feasible, to the Potts *et al* 2014 intermediate services and/or the CICES final ecosystem service classification.

While ecological components within the conceptual ecosystem models may not directly provide an ecosystem service, they may modify delivery, for example the model components

of depth, suspended sediments, water chemistry and temperature, and light attenuation all influence the level of the intermediate ecosystem service, primary production. For each ecological component x ecosystem service interaction, a short summary of the key evidence and information is provided in the attached proformas (Appendix 10) and the summary Excel tables (provided separately), which also include an estimate of the confidence or reliability of the evidence using the confidence estimation guidelines provided in Appendix C from Defra Report ME5218¹.

A short knowledge gap analysis was also undertaken (section 4.5).

All literature search terms were recorded (Appendix 4) and search terms included both ecosystem service as key words as well as relevant functional group, species and component terms. Relevant literature was identified in the first literature sift. The prioritisation of literature was guided using the criteria outlined in the ecosystem service framework sections (Section 2.5 and 2.6). Ultimately, within time and budget constraints the MESO BBN model requirements identified where effort should be focussed.

2.13 Pressure Review

The pressures literature was reviewed in order of priority and key information extracted to an Excel spreadsheet. The literature was linked to activities from the Standard List of Human Activities in the Marine Environment (JNCC, 2018), and to pressures from the OSPAR framework. Activities that are not typically undertaken in sublittoral habitats or that do not produce pressures that may have direct, far-field effects on subtidal habitats (e.g. inshore recreational activities) were discounted from the review (see Appendix 2). The pressure review information was later collated in pressure proformas (Appendix 8) and associated confidence in the pressure x activity link identified (Table 9).

Where possible, information regarding the EUNIS broad habitat associated with the activity was assigned, and links to Ecosystem Components from the JNCC Conceptual Ecosystem Models were made. Additional information detailing the nature of interaction between the activity and the habitat, and the magnitude and duration of impact were also recorded, using standardised terms where possible.

A wide range of literature on the environmental and ecological impacts of anthropogenic pressures was reviewed and the evidence collated in Excel spreadsheets as follows:

- The ecological component on which the pressure acts;
- The magnitude and nature of the interaction between the anthropogenic pressure and the ecological component (qualified based on the strength and quality of the evidence);
- The relative duration of the pressure impact (the duration of the pressure); and
- Evidence for recovery of ecological components, recovery time and information on ecological thresholds.

Consideration in the review was given to activity and pressure pathway combinations to inform pressure scenarios to support the modelling objectives. Outline pressure scenarios for each activity were constructed using the JNCC Pressure – Activities Database, which provides direct links between pressure and activities within the marine environment, and the literature review, providing supporting evidence and breakdowns of the activities where applicable. Further aspects of each activity that were not captured in the PAD database were also added to the pressure scenarios. These pressure scenarios provide guidance to users

¹ Defra ME5218, URL: <http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19471>

of the MESO models as they indicate which pressures are associated with each activity phase.

Each pressure – activity link within the scenarios, was identified as Temporary or Permanent, using evidence from the literature review.

- A temporary pressure refers to an impact on the marine environment that ceases after the activity stops, such as noise from drilling. Temporary pressures also leave reversible impacts on the environment, such as the removal of substrate from dredging, where the residual layer of seabed is the same as the pre-dredge site, enabling biological communities to recolonise the area.
- A permanent pressure indicates damage to the sublittoral environment that remains after the pressure has ceased, where the environment cannot recover to the pre-pressure state. An example of this would be substratum change from soft sediments to hard rock, after rock dumping for cable protection.

Table 9. Confidence scores for pressure activity links based on evidence type, amount, quality and consistency and level of agreement / consensus.

Category	Description
High	There is a good understanding of the activity – pressure relationship and the link is well supported by evidence . There is consensus amongst the experts.
Medium.	Whilst there is an understanding of the activity-pressure relationship, this may be based on limited evidence and/or proxy information. There is a majority agreement between experts; but conflicting evidence/opposing views exist
Low.	There is limited or no understanding of the activity-pressure relationship and/or the assessment is not well supported by evidence. There is no clear agreement amongst experts

2.14 Sensitivity Assessment

The sensitivity assessment identified the impacts of anthropogenic pressures on the biological community following the established frameworks- MarLIN Marine Evidence based Sensitivity Assessment (MarESA)² and associated reports such as Tillin and Tyler-Walters (2014);

2.14.1 Definition of Sensitivity, Resistance and Resilience

The concepts of resistance and resilience introduced by Holling (1973) are widely used to assess sensitivity (Table 10). The UK Review of Marine Nature Conservation (Defra 2004) defined sensitivity as ‘dependent on the intolerance of a species or habitat to damage from an external factor [pressure] and the time taken for its subsequent recovery’.

Resistance is an estimate of an individual, a species population and/or habitat’s ability to resist damage or change as a result of an external pressure. It is assessed in either quantitative or qualitative terms, against a clearly defined scale. While the principle is consistent between approaches, the terms and scales vary. Resistance and tolerance are

² MarESA, URL: https://www.marlin.ac.uk/sensitivity/sensitivity_rationale

often used for the same concept, although other approaches assess 'intolerance' which is clearly the reverse of resistance.

A species is defined as very sensitive when it is easily adversely affected by human activity (low resistance) and/or it has low resilience (recovery is only achieved after a prolonged period, if at all). Highly sensitive species are those with both low resistance and resilience.

Table 10 Definition of sensitivity and associated terms.

Term	Definition	Sources
Sensitivity	A measure of susceptibility to changes in environmental conditions, disturbance or stress which incorporates both resistance and resilience (recovery).	Holt <i>et al</i> (1995), McLeod (1996), Tyler-Walters <i>et al</i> (2001), Zacharias and Gregr (2005)
Resistance (Intolerance/tolerance)	A measure of the degree to which an element can absorb disturbance or stress without changing in character.	Holling (1973)
Resilience (Recoverability)	The ability of a system to recover from disturbance or stress.	Holling (1973)
Pressure	The mechanism through which an activity has an effect on any part of the ecosystem. The nature of the pressure is determined by activity type, intensity and distribution.	Robinson <i>et al</i> (2008)

Resilience is an estimate of an individual, a species population and/or habitat's ability to return to its prior condition, or recover, after the pressure has passed, been mitigated or removed. The term resilience and recovery are often used for the same concept and are effectively synonymous³.

Sensitivity can, therefore, be understood as a measure of the likelihood of change when a pressure is applied to a feature (receptor) and is a function of the ability of the feature to tolerate or resist change (resistance) and its ability to recover from impact (resilience).

2.14.2 Sensitivity Assessment methodology

Tillin *et al* (2010) developed a method to assess the sensitivity of certain marine features, considered to be of conservation interest, against physical, chemical and biological pressures resulting from human activities. The sensitivity assessment methodology (Tillin *et al* 2010) bases the assessment on a theoretical population of the species in the middle of its environmental range. As Holt *et al* (1995) have pointed out, organisms near the limits of their range are more sensitive to change, so that sensitivity assessments should concentrate on sensitivities of populations in 'mid-range' or typical habitats.

The sensitivity assessment method used (after Tillin *et al* 2010) involves the following stages, which are explained in Appendix 5.

- A. Defining the key elements of the feature (addressed in this project by the CEM models that define the biological assemblage groups).
- B. Assessing feature resistance (tolerance) to a defined intensity of pressure (the benchmark).
- C. Assessing the resilience (recovery) of the feature to a defined intensity of pressure (the benchmark).

³ The terms 'resilience' and 'recoverability' are used to describe an ability or characteristic, while 'recovery' and or 'recovery rate' are used to denote the process.

- D. Combining resistance and resilience to derive an overall sensitivity score.
- E. Assessing the level of confidence in the sensitivity assessment.
- F. Providing a written audit trail.

The above steps ensure that the basis of the sensitivity assessment is transparent and repeatable and that the evidence base and justification for the sensitivity assessments is recorded.

2.15 Assessing sensitivity of the functional groups

Assessing the sensitivity of species or biotopes to human pressures via evidence review is a time-consuming process and within the resources of the project, it was not possible to create new sensitivity assessments for each functional group within the CEMS. Evidence for species sensitivity to pressures was extracted instead from existing sensitivity assessments. Sensitivity assessment sources for each pressure for each species (where available) are shown in Appendix 7. The sensitivity assessment sources used were:

- MarLIN Marine Evidence based Sensitivity Assessment (MarESA⁴);
- Tillin and Tyler-Walters (2014);
- Tillin and Hull 2013 (a-h).

The key resource for these were the Marine Evidence based Sensitivity Assessments (MarESA) developed by MarLIN (www.marlin.ac.uk). An advantage with using the MarESA assessments are that these are based on pressures within the ICG framework (see Table 11) and therefore align with the human pressures considered in this project as the same framework was adopted. A key drawback however, is that MarESA methodology has been used largely to assess the sensitivity of **biotopes** based on selected key functional and structuring species and/or habitat characteristics, with the sensitivity assessment presented for the biotope rather than selected species. For use within this project, species sensitivities had to be disaggregated from the biotope assessment. The ease of this varied, in some cases the assessment was based on species and this was made clear, in other instances the sensitivity assessment was based on a range of species or other biotope features such as substratum.

The CEM model reports all identify the biotopes that were the basis of the study and were used to identify characterising species. All biotopes used to develop the CEM were checked and species-specific evidence extracted. The audit trail for these is contained in the Excel spreadsheets which identify the biotopes used and in Appendix 7 which identifies the biotopes in the CEM and the species information that was extracted from these from MarLIN. Where these biotopes contained little species-specific evidence or the species was not assessed as part of the biotope assessment further searches were undertaken of the MarLIN website to identify further evidence. Where no species information was found the World Register of Marine Species (WoRMS) was checked in case the species name had been changed (see Table 2 for taxonomic changes).

The sensitivity of the sand eel has not been assessed within any of the consulted sources and the sensitivity of this information was taken from the Feature Activity Sensitivity Tool⁵ developed by Scottish Natural Heritage.

Table 11 Comparative table showing sensitivity assessments used in this project.

Sensitivity Assessments	Species Basis of sensitivity	ICG_pressures framework
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⁴ www.marlin.ac.uk

⁵ <https://www.marine.scotland.gov.uk/feast/>

	assessment?	
MarESA	No	Yes
Tillin and Tyler-Walters (2014)	Yes	Yes
Marine Institute reports (Tillin & Hull (2013a-g))	Yes	No

2.15.1 Creating sensitivity scores for biological assemblage, sub-functional groups

Existing sensitivity scores and supporting evidence were collated into Excel spreadsheets for each habitat. For each species x pressure combination, the existing information and scores were considered, and an overall summary assessment created. These summary scores were then aggregated to create a functional group sensitivity assessment, following a set of simple rules

- 1) If appropriate the most frequently represented sensitivity score was used.
- 2) If no score was the most frequently represented, for example two scores were represented or there was a spread of scores then the most precautionary score was used instead.
- 3) If distribution of scores was strongly bimodal e.g. the group contained species with high and low sensitivity assigning a score between both groups was considered to represent the range of sensitivities.

Confidence assessments were provided for each functional group x pressure combination. These considered the level of evidence, the amount of species for which there was no evidence where expert judgement was required and the level of disparity between scores in the group. Given the level of variability within function groups in terms of number of sensitivity assessments, evidence base and evenness of coverage, assigning scores was relatively subjective. Table 12 below outlines the confidence scoring and general considerations.

Table 12. Confidence scores based on evidence type, amount, quality and consistency and level of agreement / consensus.

Category	Description
High	There is a good understanding of the sensitivity and/or the assessment is well supported by evidence. There is consensus amongst the experts and where more than one species represents the functional group the assessments scores are the same, e.g. sensitivity is consistent within the functional group.
Medium.	Whilst there is an understanding of the sensitivity, this may be based on limited evidence and/or proxy information for resistance and /or recovery. There is a majority agreement between experts; but conflicting evidence/opposing views exist. When there is more than one species represented in the functional group the assessments scores are very similar, e.g. sensitivity is relatively consistent within the functional group.
Low.	There is limited or no understanding of the sensitivity and/or the assessment is based on expert judgement. Where more than one species represents the functional group, the assessments scores are dissimilar and encompass a range of sensitivities so that there is a high degree of uncertainty in the score.

2.16 Conservation attribute review

JNCC provided a list of conservation attributes for sites. A wide range of literature on the environmental and ecological impacts of anthropogenic pressures on these conservation objective attributes (extent, distribution, structure, function) was reviewed and evidence collated as follows:

- The anthropogenic pressure x attribute interactions;
- The magnitude and nature of the interaction between the anthropogenic pressure and the conservation attribute, (qualified based on the strength and quality of the evidence); and
- The relative duration of the pressure impact (the duration of the pressure) and the recovery time of the attribute.

There is considerable overlap between the parameter of the pressure and conservation attribute review. The ecological components reviewed relate to the conservation attributes, so the results of the review were not collated separately. A separate category was added to the ecological components 'sediment topography' to refer to the conservation attribute structure and the sub-attribute physical structure: finer scale topography.

For each pressure x conservation attribute interaction, a short summary of the key evidence and information in the final report is provided in the proformas (Appendix 8) with an estimate of the confidence or reliability of the evidence using the confidence categories outlined in Table 12 above). A short knowledge gap analysis was undertaken to highlight specific pressure and pressure attributes where knowledge to characterise the pressure and/or the effects on ecological components are lacking (Section 4.2).

All literature search terms were recorded and search terms included both pressure and activities as key words as well as relevant habitat and ecological attributes (Appendix 4).

3 Results

3.1 Pressure and Conservation Attribute Review

3.1.1 Summary Table Interpretation

The summary tables (one for each broad habitat) outline the impact of pressures caused by human activities on the ecological components and conservation attributes. The evidence proformas that summarise key information on the pressure impacts on ecological components are provided in Appendix 8. As there was little evidence for ecological impacts from removal of target and non-target species (beyond physical damage caused by their removal) these pressures do not have an associated evidence proforma. Similarly, there was very little evidence for changes in wave exposure and associated effects and this pressure does not have an evidence proforma.

3.1.2 Sensitivity Review

The sensitivity assessment process chosen provided a systematic approach for the collation of existing evidence to assess resistance, recovery and hence sensitivity to a range of pressures. When creating the final sensitivity assessment score for the biological assemblage expert judgement was often required because the evidence base itself is incomplete both in relation to the biology of the features and understanding of the effects of human pressures. Notwithstanding the limitations of the evidence base, the collated sensitivity assessments provide a large volume of general evidence on which to make judgements on the most likely effects of pressures on species and habitats based on past experience; especially with respect to fishing. However, a key gap is the lack of specific studies that consider impacts of a given activity (or pressure) on a large number of species and habitats.

The results of the sensitivity assessments show:

- The majority of species and hence ecological groups in sedimentary habitats are sensitive to physical change, especially loss of habitat and change in sediment type and the deposition of thick layers of sediment;
- Most species are sensitive to physical damage, e.g. abrasion and penetration of the seabed and sediment extraction;
- Sedentary species and ecological groups that dominate top layer of the sediment (shallow burrowing) or are epifauna, remain the most sensitive to physical damage;
- Mobile species and species associated with coarse sediments in particular (e.g. interstitial and burrowing amphipods, and perhaps cumaceans) are the least sensitive to physical change or damage, and hydrological change as they are already adapted to unstable, mobile substrata and recover rapidly;

3.2 Ecosystem Service Review

3.2.1 Summary Table Interpretation

The summary tables (one for each broad habitat) outline the contribution of each ecological component to each of the assessed marine ecosystem services. The table is designed to be read across rows with the cell information relating to the relationship of the ecological component to the ecosystem service within an idealised conceptual habitat represented by the CEM. For example, primary production in rock habitat leads to the export of organic matter, thus the service supports that ecological component. However, the export of organic matter is not considered to directly influence primary production within a habitat and this component is therefore not considered to support the ecosystem service and the cell entry is 'not relevant'.

The strength of the relationship and the confidence is based on review and is generic rather than specific to particular biotopes, the applicability of these assessments is discussed further in the sections on limitations (Section 5). The ecosystem service review proformas provide further information to support the assessments.

3.2.2 Ecological components that mediate services

A large number of ecological components at CEM levels 1, 2 and 3 (regional and global drivers, water column processes and local processes/inputs at the seabed) were identified as mediating the supply of ecosystem services produced by the biological assemblages. This is unsurprising as the original CEM models on which this work is based, were diagrams of the influences and functioning of the ecosystem and the nodes were selected for inclusion in the CEM (see Table 1 for references) on the basis that they influenced biological assemblages. Therefore, all ecosystem services that are delivered by the biota are likely to be mediated by these components of the ecosystem.

The magnitude of influence of each of these interactions were defined in the original CEM reports and these form the basis of the assigned values for level of mediation (influence) and the confidence. These interactions were also assessed in the literature review where information was available and the original information supplemented. Confidence in the links between ecological components and mediation of ecosystem service delivery by biological assemblages are typically high.

3.2.3 Ecological components that support services

At the output levels, (5, 6 and 7) ecological components were frequently identified as likely to support rather than mediate services. This is to be expected as at these model levels, the components represent outputs of the biological assemblage, rather than drivers and influencers. A number of these nodes are identified as ecological processes and functions that are intermediate (supporting) services (based on Potts *et al* 2014) and support final ecosystem services. Examples of supporting ecological function and process nodes, include the node sediment stability that is likely to support primary production. Fewer ecological components at levels 1, 2, 3 and 4 were identified as supporting the delivery of intermediate or final (CICES) ecosystem services. Examples include:

3.2.4 Intermediate services

To be updated

3.2.5 CICES Final services

To be updated

3.3 Model Input parameters for MESO BBN

Based on evidence from the ecosystem service review, BBN model input categories (Table 13) were selected to characterise the magnitude of contribution of each biological assemblage to the ecosystem services that could be included in the model. This information is used to parameterise the edges that link nodes within the BBN model, contribution was scored between 0 and 1. Parameter selection was constrained to categories that could be applied consistently across the biological assemblage groups and that were supported by evidence. The classes within each category, where possible, were chosen to encompass a wide range of habitat types, not just those represented by the CEMs. This was intended to allow the modelling approach to be applied across habitats in the future. Table 13 shows the nodes that were already in the CEM models or added to the BBN to represent ecosystem services. The categories define the magnitude of contribution from 0-1 and provide a definition of each category from None-High that was used in the summary table. Two input categories 0.75 and 1 were considered to represent high contribution to the service. The categories discriminate relative contribution between assessed features, it was considered that there was too little information to differentiate between these two categories in the summary table.

The evidence used to categorise relative contribution of ecological components (largely the biota but some habitat parameters) varied across services:

- Relative contribution to bioturbation (which supports a range of ecosystem services) was categorised according to existing functional classification schemes with relative contribution based on bioturbation potential. A key resource to assign species and therefore the biological assemblage groups to bioturbation categories was the review by Queiros *et al* (2013) that provided a functional classification for 1033 benthic invertebrate species based on information from the literature and expert opinion.
- No functional classification for biodeposition currently exists that is comparable to the bioturbation classification (Mermillod-Blondin and Rosenberg 2006).
- Input to secondary production biological assemblage was ranked based on feeding and food type using the secondary estimates from Cusson and Bourget (2005).
- Input to primary production was based on annual contribution values derived from the literature review
- Habitat provision was based on the volume and complexity of epifaunal structures
- CICES 1.1.6 Wild animals (terrestrial and aquatic) for nutrition, materials or energy: based on the identity of targeted species and commercial importance;
- CICES 1.1.5 Wild plants (terrestrial and aquatic) for nutrition, materials or energy: based on the identity of targeted species and commercial importance;
- CICES 5.2.1: Regulation of baseline flows and extreme events: based on sediment type as ranked by Liquete *et al* (2013b);

- Carbon sequestration: based on sediment type as a proxy.

Table 13 Input categories and classes within categories for the ecosystem service BBN model nodes.
The input parameter row indicates the magnitude of contribution between 0-1. The magnitude of contribution categories show how the input parameters were translated to indicate contribution magnitude in the summary tables.

Input parameter categories (MESO BBN)	0	0.25	0.5	0.75	1
Magnitude of contribution (summary table categories) Categories	None	Low	Medium	High	High
BBN Model Nodes					
Bioturbation	Non-bioturbating species e.g. epifauna	Surficial modifiers	Biodiffusers	Upward and downward conveyors	Regenerators
Biodeposition	Not suspension feeder or switches between deposit/suspension feeder		Small suspension feeders	Passive suspension feeders	High density bivalve / active suspension feeder
Secondary production	Primary producers	Omnivores / predators	Deposit feeders	Grazers	Filter feeders
Primary production	Animals	0.25 kg/m ² /yr Low- e.g. Sparse <i>Sacharrina latissima</i> in sand habitats	0.5 -2 kg/m ² year saltmarsh/ seagrass	5-10kg/m ² /yr	Dense macroalgal beds (15 kg/m ² /yr)
Habitat provision	None, infauna, predatory epifauna, mobile epifauna	Low relief, mounds / pits	Tube building /low reef /mat forming	Solitary epifauna / sparse epiflora	Biogenic reef forming organisms /dense macroalgae
CICES 1.1.6 Wild animals (terrestrial and aquatic) for nutrition, materials or energy	Plant or a not targeted animal		Sporadic targeting in some locations		Species actively targeted
CICES 1.1.5 Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Animal or plant not targeted		Sporadic targeting in some locations		Species actively targeted
CICES 2.2.1 Regulation of baseline flows and		Mud	Sand	Coarse / mixed substrates	Reef habitat

extreme events: (sediment input & habitat provision)					
Carbon sequestration (sediments)	Coarse / sand/ gravel /shingle/cobble	Mud/ mixed	Dense macroalgae		Saltmarsh /biogenic reef

3.3.1 Outputs

The findings of the ecosystem service review were captured in the proformas (Appendix 10), the Excel summary spreadsheets and the summary tables.

<To be updated>

4 Bayesian Belief Network Models

4.1.1 Introduction

Bayesian Belief Networks (developed by Judea Pearl in the early 1980s) are a compact visual representation of a situation and the associated probabilities. Created from nodes (which represent entities within a habitat) and edges (showing the influence one node has on another), conditional probabilities can be used to express the relationships between the nodes via belief propagation algorithms (Lauritzen and Spiegelhalter, 1999).

Overall, a Bayesian Belief Network can be considered as the interface between a causal diagram and the available data (Pearl, 2018) which allows for both predictive and diagnostic reasoning to be investigated, through the use of Bayes Theorem. Figure 1 shows a simplified Bayesian Belief Network (BBN).

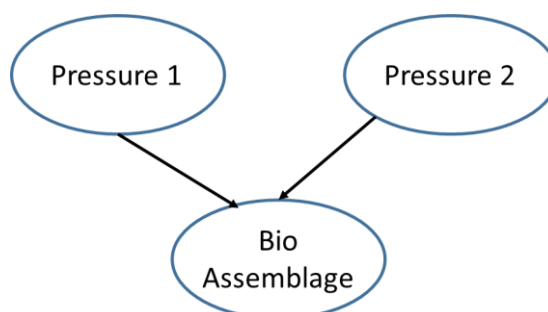


Figure 2 Simplified Bayesian Belief Network

In Figure 2, two pressures can be seen to impact upon a biological assemblage. The pressures are defined as parent nodes (that is there are no arrows leading into them), whilst the biological assemblage is a child node – the value of this node is conditional on the values of Pressure 1 and Pressure 2.

Within discrete Bayesian Belief Networks, states can be applied to the variables, for example the pressure could be considered as being low, medium or high, whilst the biological assemblage could decrease, remain the same or increase.

However, assigning such values is in itself non-trivial: what genuinely constitutes a “high” pressure in terms of a probability? Often, “gut instinct” answers such as “higher than 90%” are provided, often with little or no scientific rigour behind them. Following this example through, the child node will need a series of conditional probabilities defining in terms of the “states” for the pressures. For example, the probability of the biological assemblage decreasing, remaining the same or increasing when both Pressure 1 and Pressure 2 are low. In total nine sets of conditional probabilities would be required for this example, either through derivation from available data sets or elicitation from expert judgement.

Defining the required conditional probabilities, even for a simple network, rapidly becomes time consuming if indeed it is at all possible. In many real-world situations to which BBNs are applied, there is insufficient data to develop the conditional probability distributions from data. In these situations, the required conditional values must be derived from standard distributions or elicited from expert judgement.

Within this project, the minimal data sets available were not suitable for the development of conditional distributions based on experimental or research-based information. Furthermore, the volume of variables and scenarios being considered meant that the use of expert judgement for the elicitation of the required values was impractical.

Hence, a more flexible approach, which allows for multiple nodes to have influence on other nodes, was required, whilst providing for rapid translation of sensitivity scores in the Bayesian Belief Network. At the design stage, the team concluded that a Gaussian Bayesian Belief Network was the most suitable approach.

4.1.2 Adoption of Gaussian Bayesian Belief Network

Within a Gaussian BBN each variable is defined by a normal distribution. Every node follows a normal distribution with parent nodes being described by their respective marginal distributions (that is the totals for the probabilities of interest, conditional probabilities are a subset of the marginal distribution).

Within a Gaussian BBN information flow between variables through the use of Bayes Theorem, with the distributions being defined in terms of a linear relationship (with the underlying assumption that residual error follows a normal distribution for the variance).

In this project, the distributions incorporated into the network explicitly include uncertainty in both the lack empirical data and the natural occurring variance in the variable of interest. This natural variance can assume a wide range of random factors – such as a variation in occurrence of a bio-assemblage in a habitat – or the random element of impact of a pressure (e.g. a contamination event occurring simultaneously with a powerful sea swell).

At the completion of this project the standard deviation of the distribution is entered as a habitat specific value, however in future it is considered more appropriate for these variations on pressure application and bio-assemblage to be scenario specific.

It is important to remember that whilst complex marine scenarios are being considered, there are in many cases only sparse data sets available. Often, in such situations, simple models often perform better than more sophisticated ones.

Again considered the simple BBN presented within Figure 1, the variables being included within the network could be defined as a standard normal distribution with, values below zero representing a negative impact from an equilibrium state, and values above zero equating to a positive impact (Figure 3).

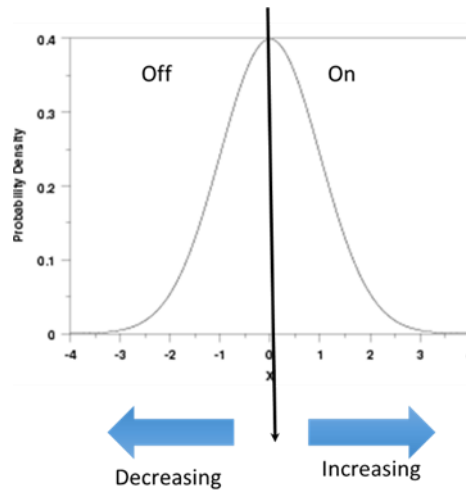


Figure 3 Nodes are defined in terms of a steady state equilibrium with a variance defined as a standard normal distribution

The local distribution of the variation of each child node is expressed as a Gaussian linear model which includes an intercept (which equates to steady state condition) and the node's parents as explanatory variables, without any interaction term.

The use of linear dependencies provides tractability and the availability of closed-form results for many inference procedures. Overall, this approach develops a regression model for the response variable (child node) to describe how the response distribution depends upon the parent nodes. This approach assumes that:

1. The variables represented by the nodes are normally distributed:

$$X \sim N(\mu, \sigma)$$
2. Where X is a variable, N represents a normal distribution defined in terms of a mean, μ and a standard deviation σ

3. The standard deviation of the response variable is the same for all values of the parent node:

$$\sigma_C = \sigma$$

4. The mean of the response variable is linearly related to the parent node or nodes:

$$\mu_C = \beta_0 + \beta_P$$

5. Where the subscripts P and C refer to parent and child respectively with β being a coefficient.

It is important to remember that a normal linear model does not explain the distribution of the parent, rather it describes the conditional distribution of the child at each value of the parent. Of key importance to this project is how to interpret and define the regression coefficients. Again, referring to the simple BBN in Figure 1, let P_1 be Pressure 1 and P_2 be Pressure 2. This leads to the definition for Bio Assemblages as:

$$R_{Bio\ Assemblage} = \beta_0 + \beta_1 P_1 + \beta_2 P_2 + e$$

where β_0 is the intercept, with the regression coefficients and predictor variables also shown. The residual error term is defined by the factor e .

Working over the whole BBN, the joint distribution is a multivariate normal which is the product of all the local distributions⁶.

The intercept term is the value that is predicted if both pressures equal zero. This is only meaningful interpretation if it is reasonable that both the predictor variables (pressures 1 and 2) can be zero. If this is not the case, then the intercept has no real meaningful interpretation and serves merely to anchor the regression to a suitable point.

The regression coefficients for the predictor variables represent the difference in the prediction of the biological assemblage for “one-unit change in the pressures”. This approach supports the flow of information through the BBN whilst enabling the required values to be developed from the available data based upon the scope of expert knowledge.

In order to compute all the required calculations for the scenarios and research questions of interest, a Gaussian linear model must be defined for each node (and the variable it represents) within the BBN. Subsequently, the BBN will use statistical theory to calculate the probability distribution over the whole network.

The changes in the distributions of variables represented within the nodes are calculated through Bayesian inference:

$$\text{Posterior distribution} = \frac{\text{likelihood} \times \text{prior distribution}}{\text{normalising constant}}$$

Which for the continuous network in Figure 1 is expressed as:

$$p(BA|P_1, P_2) = \frac{p(P_1|BA, P_2)p(BA|P_2)}{p(P_1|P_2)}$$

Where the normalising constant $p(P_1|P_2)$ can be further defined as

$$p(P_1|P_2) = \int p(P_1|BA, P_2)p(BA|P_2)d\theta$$

A review of the available information resulted in the following approach being utilised:

All pressures nodes (the influences), are defined to be either on or off (1 or 0) with a normal distribution catering for variation in presence.

Child node regression coefficients were based upon the response variables resistance to the parent node.

Currently, all parent nodes are defined in terms of a standard normal distribution (mean of zero and a standard deviation of 1) though it is accepted that over time this could change based on the analysis of available evidence/data sources. Within a Gaussian Bayesian Network, the conditioning effect of the parent nodes is given by an additive linear term in the

⁶ A multivariate normal distribution in its simplest form describes the joint distribution of a random vector of mutually independent univariate normal random variables with a mean of zero and variance of one. Generally, a multivariate normal distribution describes the joint distribution of a random vector represented as a linear transformation of a standard multivariate normal vector.

mean and does not affect the variance. In other words, each node has a variance that is specific to that node and does not depend on the values of the parents (Figure 4).

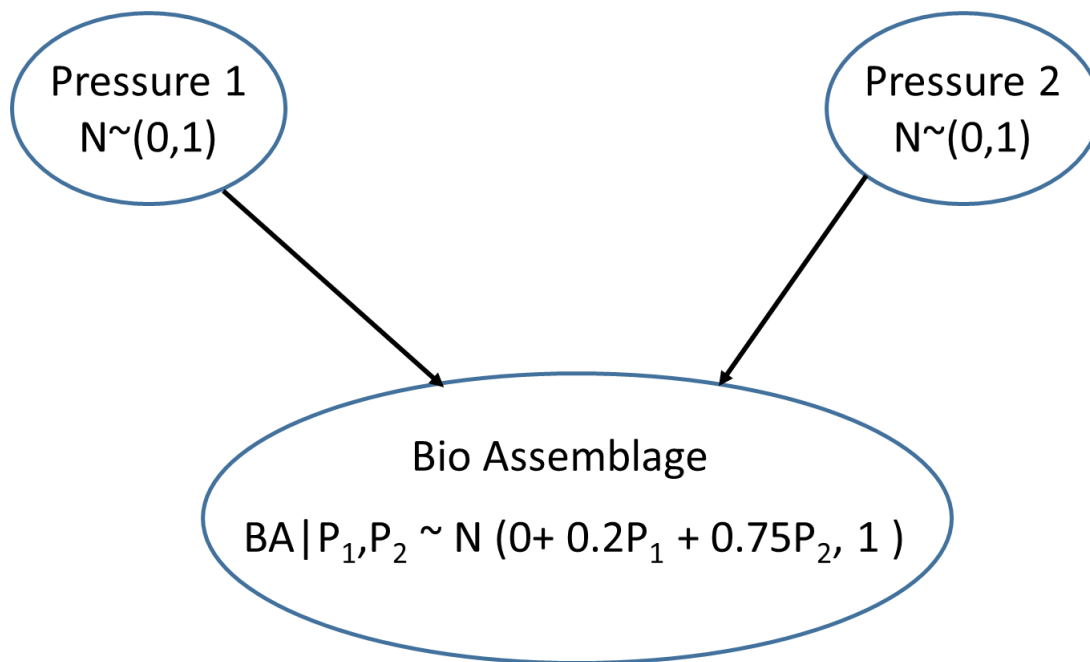


Figure 4 Development of linear representation

Moving from the simple BBN in Figure 2, the impact of nodes flowing through the network was defined in terms of whether the node increased, decreased or had no effect upon the nodes to which it was linked.

Overall, the approach provides a tractable, robust approach to the development of a wide range of BBNs within a short timeframe. The approach can be expanded as additional information becomes available to refine the regression coefficients used and to support sensitivity analysis within the final output of the BBNs.

4.1.3 Implementation of the BBN within R scripts

In order to establish a scalable approach to importing resistance and resilience scores into a modelling environment, a set of R scripts were written to handle the import, storage, calculation and display of the habitat models within a web-based tool.

The scripts perform the following functions:

- Data import from spreadsheet structure
- Compilation of Bayesian Belief Network
- Calculating the impact of pressures upon the developed model

Each of these elements is described in further detail below.

Data import from spreadsheet structure

The data ingest process uses a predefined Excel spreadsheet comprising 4 sheets, as follows:

- The first sheet holds the pressures list as names in the first row. The second row holds the intercept and confidence values for these pressures.
- The second sheet defines the biological assemblages and provides a mapping from the pressures nodes to each assemblage. The degree of impact (i.e. the inverse of resistance) is defined for each node biological assemblage, which is influenced by the pressure. The growth rate at equilibrium and confidence level (i.e. the standard deviation of the variance for the Gaussian Model) is defined for each node.
- The third sheet defines the output processes and provides the mapping from pressures and biological assemblages to the output processes.
- The fourth sheet defines the ecosystem services and provides the mapping from pressures, or bio-assemblages or output processes to the ecosystem services themselves.

These models have been built for the five main habitat types (coarse sediment, mixed sediment, mud, sand and rocky reef).

The R script runs a validation check on each spreadsheet checking for the presence of each sheet, consistency of naming conventions and gathers data about the nodes and edges in order to build the network. This process defines a valid set of nodes and edges which can then be compiled into a Bayesian Network.

Compilation of Bayesian Belief Network

Once a spreadsheet has been validated, the model is imported into the toolset. All of the data necessary to describe the Bayesian Belief Network is held in the sheet.

The first stage of the compilation process defines the network itself using the bnlearn library within R to describe the network structure.

Following successful import of the network, the script builds the conditional probability distributions of each node within the network. This data is then stored and made available to the GUI when required.

Calculating the impact of pressures upon the developed model

From the GUI, a list of applied pressures can be passed to the selected habitat model as a binary indicator of presence. This process uses the bnlearn conditional probability method to stimulate the model with an evidence statement based upon the defined state of the input pressures. The method uses a monte carlo approach to estimate impact on variance. The method uses a cycle of 10000 runs to define the distributions.

It can therefore be expected that there will be minor variation in outputs as a result of the effect of the number of runs. The number of runs is a trade-off between accuracy and speed of response. Tests to date indicate that variation between runs is minor.

The method returns a summary of the distribution of each node within the network in terms of a mean, minimum, maximum, one and two standard deviations from the mean.

This is used to display the impact to the user through the GUI but can also be used programmatically to calculate hypothesis probabilities based upon priors and a suitable hypothesis as in discrete BBNs.

4.1.4 Graphical User Interface

A Graphical User Interface (GUI) has been added as a viewing facility onto the underlying R scripts. The GUI allows a user to select a habitat model, run simple pressure assessment tests, view the results and navigate around the network.

The selectors on the left-hand side of the page allow for a model to be selected and also a transition viewer allows for a progression of information to be displayed, starting with mapping pressures to assemblages, followed by the subsequent impact on output processes and finally the impact on ecosystem services.

The GUI has two primary components as follows:

- Pressure Test page for viewing impacts
- Network viewer

Each GUI component is described in further detail below.

Pressure Test page for viewing impacts

The user interacts with the BBNs using this page. The primary method of interaction is the radio buttons towards the left-hand side of the page. Application of a pressure represents the pressure benchmark as defined in the sensitivity analysis.

Multiple pressures can be applied simultaneously, and a cumulative impact of concurrent pressures can be assessed.

The model shall only update when the 'Calc' button is pressed in the top left-hand side of the page.

The data is presented as a series of box and whisker plots which represent the change in a node as a result of the application of pressures. The values presented on the graph are the maximum, 3rd quartile, median, first quartile and minimum value for each node.

This provides a relatively straightforward method of visualising the relative impact upon a node coupled with the magnitude and direction of impact. The addition of the whiskers and box plots allows a visual assessment of a likelihood of hypothesis, i.e. the probability that a node is in decline can be viewed by where the mean, quartiles and limits are versus the steady state (i.e. $y=0$).

The graphing display allows for zoom, selection, de-selection of nodes to improve readability.



Figure 5 Pressure Test User Interface

Network viewer

The network viewer page provides the user with the ability to investigate the network and understand the nodes, edges and values associated with each element of the network. The upper half of the display provides a graphical display of the network with nodes coded by identifier and influences displayed as arrows.

The lower half of the model allows for the user to search for node parameters in the lefthand side of the display and the edges (i.e. influences) on the right-hand side.

Search and sort facilities are provided to simplify the process of viewing the impact levels of one node on its child nodes.



Figure 6 Network Viewer Page

4.1.5 Summary of Features

As illustrated the model can be set-up through the structured entry of information into an Excel spread-sheet. This is ingested into software written in R (a free and widely available open source language), leveraging the graphic interface capability of R-shiny, to model the distribution of posterior values under the effect of applying different combinations of pressures. The nodes being acted upon represent the components of each ecosystem; its biota; its services, and the forcing pressures, providing a visual summary of these interactions.

Discrete BBNs use discrete state variables and associated conditional probability tables (CPT) which grow exponentially with every new state we might wish model. Given the relative complexity of the original MESO conceptual models they could rapidly create BBNs for which it is impossible to develop the required CPTs. In turn it would be more difficult, and less intuitive, to modify relationships between pressures, functional groups and their output processes that map either directly or indirectly to ecosystem services. To overcome these limitations we implemented a Gaussian Bayesian Belief Network (BBN) framework to facilitate the modelling of complex maritime scenarios with a large number of nodes and edges, and with system responses most appropriately expressed along a continuum.

Continuum responses fit well with the way physical pressures act on biota and, in turn, their responses to them. While thresholds or step changes are not unknown in nature (and these can still be accommodated), continuous distributions provide the scope for finer control over responses to pressure that would otherwise too complex to derive and present within CPTs. This latter point also has implications for the ease with which a system can be comprehended by a user and keep track of relevant variables.

The design enables complete model flexibility for the addition (as required) of greater detail by routing outputs through alternative processes across scenarios. Incorporating simplicity through the combination of nodes wherever possible predisposes the models to scale in dimension, giving them the potential to be taken out of the conceptual and into the actual world domain.

In their present state the models are dimensionless and the nodes representing biotic assemblages, output processes and ecosystem services are highly abstracted and notional. It is difficult to attribute metrics to them or, rather, it is for the user to interpret them in their own operational context. As previously noted the user has access to the structure and parameterisation of the model through the primary spreadsheet input however it is important to bear in mind that there is no spatial or temporal scale associated with the models as they stand. Modelling the imposition of a pressure on the belief network is to observe a state change in child node responses. The model does not include recovery; it is simply concerned with the instantaneous effect of a pressure, or combination thereof, on down-graph nodes.

Input, or pressure, nodes are generally well defined and the interpretation given to them is that when they are “on” the pressure node is delivering one dose of that pressure up to its benchmark. Pressure benchmarks were derived from previous work conducted by members of the project team (Tillin, H. M. et al. 2010, Tillin, H. M. and Tyler-Walters, H. 2015).

4.1.6 Limitations of Approach

Interpretation is straightforward for most pressures but becomes slightly problematic in two cases: Removal of Target species, and the Generic Contamination scenario. Here the pressures map to multiple benchmarks depending on which species is considered the target species, or what specific contaminant is being introduced into the system. In either case the

associated pressure benchmark will be determined by that choice and it would be difficult to justify modelling multiple contaminants, or species, on the same path. Our recommendation would be to set as many paths as contaminants to be modelled, or target species to be extracted, which then allows individual sensitivities to be set for each functional biological group. It is a simple task to add or subtract pathways through the graph according to the desired use case. Similarly it is simple to introduce additional nodes with their unique assessment of resistance through the mechanism of the input excel spread-sheet.

With the Gaussian distribution model there is also the possibility, though not currently implemented, to alter the level of an input pressure to represent a partial pressure situation. Discussions within the design team have considered this aspect, which is technically feasible though not universally applicable from an ecological point of view. A common argument advanced against providing this facility is that there is no underpinning evidence to support assessments of resistance, resilience and sensitivity along a dose/response gradient, in other words we are unable to characterise a dose/response curve for any of these pressures. This holds for partial unit applications of pressure below, or indeed above, the benchmark on a population. However, the ability to alter the level of a pressure when in a spatial framework has a great deal more justification. In fact, it could almost be deemed necessary due to the patchiness of impact for many pressures in the spatial domain and the heterogeneous nature of species distributions within a habitat, not to mention habitat heterogeneity. For modelling purposes, the result would be interpreted as a mix of impacted, to the benchmark, and un-impacted parts of the population. This is a future potential for these models and the format of the network allows for it without major structural changes. To extend the model application to a real world situation involving a discrete area we would strongly recommend implementing this feature.

In summary, currently there is no spatial, nor temporal, component to the developed BBNs. Rather, they respond to a change in pressure state with a corresponding change in state across all nodes within the network as information flows through it. The model represents the un-quantified abstracted properties of the biota leading to output processes that only have meaning in a relative sense by the time they link to ecosystem services (which themselves notoriously hard to assign value to).

Throughout the design process we have endeavoured to meet best practice as defined through the literature on the topic, e.g. (Landuyt, D. et al. 2013, Marcot, B. G. et al. 2006). Recommendations were to limit the number of layers to five or less and keep the number of inputs to any node to a minimum (Marcot, B. G. 2017). We reviewed the inclusion of every node in the conceptual models for relevance according to the overriding paradigm that the models must be expressed in terms of the ecosystem services that relate to them, avoiding spurious associations that would reduce model adequacy and robustness. By conducting an analysis across all models, a reduced list of ecosystem services was derived, from the CICES lists (ref Table 3). The final list of ecosystem services were those which could be expressed in terms of preceding nodes, and for which a causal connection could be justified. Intermediate nodes between the biotic elements and the ecosystem services selected were permitted if they can be parameterised, (if not immediately then at least in theory), against a quantifiable metric. Bioturbation for instance can be reasonably estimated through the density of inhabited burrows of burrowing fauna; nutrient cycling can, in theory, be determined by measuring nutrient fluxes or their proxies, and sediment stability can be determined through assessment of its mobility or shear strength with appropriate instruments.

4.1.7 Parameterising the model

Having established the structure, the model was parameterised according to the results of the simultaneous literature review (Section 3.3). Once existing published data on the

biotopes containing the relevant organisms were disaggregated and reassessed, organism sensitivities were recombined for the functional biological groups specified in the conceptual models. A resistance and resilience score was attributed to the biotopes to produce a sensitivity index in a manner consistent with MarESA methodology. These methods are described in more detail elsewhere in this report. The overall effect was that, while based on a synthesis of published, and other, evidence, the values available for input into the model are derived from expert opinion and require treating as such (Kuhnert, P. M. et al. 2010, Marcot, B. G. et al. 2006), this will have implications with the on-going validation and calibration of the models.

The models present changes in the conditional distributions for each child node in response to the application of a pressure (or combination of pressures). It is important to note that the models do not provide a mechanism for including events occurring after this such as recovery (or resilience to use its sensitivity assessment meaning). In the absence of any pressure the biological functional groups reside at their default distribution values (mean = 0, SD = 1). Any differences apparent between functional groups at this stage are small and arise from the representativeness of the distribution which is gained from a Monte Carlo sampling of the underlying default normal distribution. Each distribution is sampled 10,000 times, providing a balance between processing time and consistency between comparable distributions. A higher sampling rate will further reduce differences between node distributions of functional groups and their underlying distribution.

Only the resistance component of the sensitivity assessment was used. In the absence of a temporal component resilience could not be accommodated with meaning. The resistance values used were assessed as High, Medium, Low and No Resistance to the applied pressure. Subsequently these were expressed numerically as -0.2 (High), -0.75 (Medium), -0.95 (Low) and -0.999 (No Resistance). A further category of -0.01 was used to denote insensitivity or no data, which are treated as the same thing. So far these values have been developed through iterative subject matter expert review and represent the relative proportions required to achieve an expected response across each node within the network. It should be noted that the values used are subject to review for each scenario considered and it is accepted that other values may be more robust in certain scenarios. This process cannot objectively be conducted until such time as we have datasets available from which each node response can be calibrated.

We will continue to review and refine the value ranges that constrain child node responses to within realistic limits based on expert judgement. This could be achieved through a range of approaches. Currently, the normal distribution for each node defaults to the standard normal distribution (that is a mean of 0 and a standard deviation of 1). At each node this distribution can be edited. With suitable evidence the standard deviation could be altered to reflect the relative certainty or uncertainty of the parameter under consideration and would improve the local quality of output from that part of the network. Alternatively, there may be advantage in grouping the functional groups into aggregations, as exemplified by the more general groups detailed in the original CEM, which would then pass a single score to an output process, reducing the number of inputs into any one node. This would have the effect of reducing the variance of any child node, which can become sensitive to a large number of inputs, because of the way normal distribution variances combine. This can lead to the probability distribution flattening out causing imprecision in the assessment of the child node response and propagating that imprecision further down the network.

For nodes relating to output processes and ecosystem services, parameter values were even more reliant on expert opinion and were assigned on an assessed judgement of proportional influence. In some ways these might be considered as representing default values that created a link between nodes where one needed to be but are open to updating as and when data is available to more precisely define them, or as a particular scenario might suggest to the user of the model at the time.

4.1.8 Current stage of development

This leads to a consideration of what these models can achieve in their existing form and what information can be extracted from them. With current parameterisation the models can consistently indicate the direction of the state change (increase, decrease or no change) in response to a pressure combination with reasonable fidelity. This limitation is based upon the inclusion of parameterisation from single source expert judgement. The appropriate way to proceed from this point is to conduct a formal peer review process of the structure and parameterisation choices made and to then formulate a synthesis of these opinions that will inform the final values to drive the response of each pathway through the model.

In order to be able to provide a traceable, proportionate, response the models require calibration against multiple exemplary data sets. This is out of scope of the current project, which has instead sought to specify the attributes of such a data set for future application. The best option for the continuing development of these models is to submit them to real world case studies comprising sufficiently detailed data to fully parameterise the network as they stand or as they might reasonably be modified to fit.

Working within the limitations of the project, it has been possible to begin to assess the sensitivity of the model in order to fully understand its adequacy to describe the scenarios under review and to ensure that uncertainty is dealt with appropriately. This will be achieved by determining if there are any systemic differences that could indicate failings in the model structures. This will give us an understanding of the propagation of uncertainty maintaining the least complicated, fit for purpose model possible based on the information we have been given.

To aid this process we have begun to develop versions of the model that differ structurally from each other and include different pathways for pressures and responses to propagate through the models. These are based on groupings that exist within the CEM provided to us at the beginning of the project (for instance (Alexander, D. et al. 2016)) and represent justifiable complications of our original model design, which had been pared down to a minimal functional structure to keep the weight of evidence for edges and nodes as high as possible. By relaxing these constraints a little we can formulate different structures that allow their inter and intra model measures of effectiveness and efficiency to be assessed using measure of divergence and information loss.

This means that currently the models represent a completed Alpha-level model (Marcot, B. G. et al. 2006) that is still in need of peer review to validate the current parameterisation. When appropriate data sets are available, the models will require calibration. Our aims for the remainder of this project are to refine further the parameterisation of nodes and provide a description of what attributes an appropriate calibration data set must have as an aid to either designing the field data collection exercise necessary or to compare against any existing data sets to assess for suitability.

5 Limitations and Knowledge Gaps

Key limitations for this study was gaps within the available evidence to assess the impacts of pressures on ecological components and conservation attributes of designated sites, and the links between ecological components and ecosystem services. These knowledge gaps are discussed separately below, for pressures and activities (Section 4.1), species and habitat sensitivity (Section 4.2) and ecosystem services (Section 4.5).

5.1 Activity and Pressure information gaps

A key aim of this study was to identify how pressure from human activities xxx. Of all activities fishing was associated with the largest evidence base, with numerous examples of impacts from various gear types sources.

Aggregate extraction is also well-studied, resulting from stringent licensing, a producer's organisation and the previous existence of a fund specifically set-up to study the industry impacts.

Other activities although widespread are less well-studied. Anchoring and mooring are widespread in the marine environment but a recent literature review on evidence for anchoring and mooring identified key evidence gaps regarding the level, scale and intensity of the pressures and impacts on sensitive seabed habitats and species (Griffiths *et al* 2017). Worldwide, studies and observations of the effects of anchoring and mooring have focussed on seagrass beds and corals and there is little direct evidence for impacts on other species and habitats. Most studies that evaluate impacts have considered recreational vessels and direct observations and empirical studies of the impacts of commercial vessel anchoring and mooring are rare (Griffiths *et al* 2017).

5.1.1 Pressure evidence for impacts

Physical damage (abrasion, subsurface penetration and disturbance) can be more clearly spatially and temporally defined than some other pressure types. The impact occurs within the footprint of the activities leading to the pressure and the species traits that determine tolerance have been well studied and can be relatively easily defined.

Abrasion/disturbance of the substratum on the surface of the seabed

Evidence for the effects of surface abrasion on subtidal habitats is poorly studied compared to penetration and disturbance of the sub-surface of the seabed. This is considered due to the lack of impacting activities which lead to surface abrasion alone and the difficulties inherent in studying this impact for subtidal habitats. The sensitivity assessments for the abrasion pressure consider the likely direct, physical impact on individuals that are exposed to this pressure. Abrasion of the seabed may result in resuspension of fine sediments in muddy habitats, this indirect effect is reviewed under the changes in suspended solids (Pressure proforma 5) and the siltation pressures' (Pressure proforma 4). This pressure was associated with fishing activities, anchoring and mooring, offshore wind-farm operations, aggregate dredging, cable and pipeline laying among others (see pressure scenario spreadsheets).

Penetration and/or disturbance of the substratum below the surface of the seabed, including abrasion

The evidence base for substratum disturbance is most developed for fishing activities using towed gears in contact with the sediment. This is the most widespread human activity leading to this pressure. This pressure was also associated with anchoring and mooring,

offshore wind-farm operations, aggregate dredging, cable and pipeline laying among others (see pressure scenario spreadsheets).

Siltation and suspended solids

Siltation and sediment deposition result from activities that disturb the seabed and have been studied in relation to dredging for aggregates and capital and maintenance dredging to remove sediment in shipping channels as well as the disposal of wastes at sea such as levels of sediment deposition in terms of deposit thickness. Siltation and water clarity changes (included as physical damage pressures) may occur over wider areas than the footprint of the activity as water currents and wave action may transport finer sediment that remains in suspension. For the activities studied the pressure is usually temporary, with sediment plumes created by aggregate, fishing and cable pipeline laying activities (among others) rapidly subsiding when the activity ceases. Sediment plumes relating to sediment disturbance have been characterised for aggregates and fishing (see Pressure proforma 5). Unlike abrasion, penetration and extraction changes in suspended sediment from these activities (when considered as single events) do not match the pressure benchmark used in sensitivity assessments which relate to a change in turbidity for one year.

Removal of target Species

Both the pressure review and the ecosystem service review identified targeted species, both for consumption and other uses such as fertiliser, pharmaceutical products and curios etc. The final ecosystem service tables and proformas (Appendix 10) collate this evidence. In general, the evidence base for commercial fisheries is well developed although there were some key uncertainties around whether species that are not subject to quotas such as small bivalves, are being actively targeted. A further uncertainty is whether species were being removed by recreational divers for consumption or the curio trade, for some species there may have been past fisheries that are no longer in operation e.g. *Echinus esculentus* (Kelly *et al* 2001)

It should be noted that the pressure benchmark and interpretation has not been consistently applied between the sensitivity assessments consulted. The pressure reviews for this assessment identify either whether the characterising species are either targeted by commercial fisheries, or whether the characterising species are dependent on any commercially targeted organisms.

Wave exposure changes- local

No evidence was found from the pressure review for effects on wave exposure and this pressure does not result from most of the assessed activities which either occur offshore or do not involve the placement of infrastructure which could alter wave energy. As a proxy indicator of resistance, evidence from the Marine Nature Conservation Review database for the wave exposure categories experienced by biotopes or species (based on presence in biotopes) is typically used to assess sensitivity. These categories take account of the aspect of the coast (related to direction of prevailing or strong winds), the fetch (distance to nearest land), its openness (the degree of open water offshore) and its profile (the depth profile of water adjacent to the coast). However, it should be noted that a) not all biotopes or species have full habitat/site information, and b) the extraction only recorded the habitat conditions where the biotope was recorded and not the relevant species presence, abundance or biomass within each site. Therefore, this information represents the range of habitat conditions in which the biotopes can be found rather than identifying optimum habitats for species.

5.2 Knowledge gap analysis- species and habitat sensitivity

The sensitivity assessments are accompanied by confidence assessments which take account of the relative scientific certainty of the assessments on a scale of high, medium and low. In the revised methodology adopted here, confidence examines distinguishes between the quality of the evidence (peer review, vs. grey literature), and its applicability to the assessment in question, and the degree of concordance (agreement) between studies in the magnitude and direction of the effect. The level of confidence should be taken into account when considering the possible requirements for management measures.

In general, the following evidence gaps for pressure –sensitivity assessments developed for the biological assemblages within this study were noted:

- Sand: In general, there were few evidence gaps for sand species, the most obvious gap was the lack of information (even basic life history data) for the polychaete *Aricidea cerrutii* which was the sole representative of a biological assemblage. Other polychaetes for which there was little, or no evidence, were *Ophelia borealis* and *Travisia forbesii*, *Sphaerosyllis bulbosa* and *Paraexegone hebes*. Predatory epifauna including starfish and decapods were a key evidence gap for this and other habitats.
- Coarse: Species for which little information was available are: *Alcyonidium diaphanum*, the predatory decapods, *Pagurus bernhardus* and *Liocarcinus* spp. The ophiurid, *Ophiura albida*. Information was relatively sparse for polychaetes with no evidence available for *Travisia forbesii*, and the interstitial polychaetes. The MarLIN assessments note that sandy and coarse offshore sediments are poorly studied compared to other biotopes, and the sensitivity of species such as venerid bivalves was largely based on expert judgement for most pressures.
- Mixed: No sensitivity assessments were found for *Styela clava* an invasive tunicate, the sponge *Amphilectus fucorum*, the anemones *Sagartia elegans* and *Cereus pedunculatus*, the cumacean *Eudorella truncatula*, the amphipod *Maera grossimana* and the small mollusc *Calyptrea chinensis*.
- Mud: The tube builders *Phoronis muelleri*, *Photis longicaudata* and *Galathowenia oculata* had not been previously assessed and there was little information for burrowing polychaetes; *Malacoceros fuliginosus*, *Maxmuelleria lankesteri*, *Mediomastus fragilis*, *Scalibregma inflatum* and *Scoloplos armiger*. No previous sensitivity assessments were found for the burrowing holothurians, *Labidoplax media* and *Leptosynapta bergensis*. As with other habitats the mobile predatory epifauna were a clear gap in sensitivity understanding.
- Rock: Species for which little information was available were the sponges *Cliona celata*, *Dysidea fragilis*, *Haliclona viscosa*, and *Myxilla incrustans* and the ascidians *Corella parallelogramma* and *Polyclinum aurantium*. The gastropod molluscs *Gibbula cineraria*, *Janolus cristatus* and *Margarites helycinus* have not been assessed by the previous projects. The crustaceans *Dexamine spinosa*, *Dyopodos porrectus* and *Pandalus montagui* were a further group without associated sensitivity assessments.

Where only the genera were identified or where evidence was missing, information from other species, preferable those in the same genus where available, was used to fill evidence gaps:

- *Bathyporeia elegans* (sand CEM) assessment based on *Bathyporeia* spp. and *Bathyporeia pelagica* assessments (coarse CEM);
- *Pagurus* spp. (Coarse) assessment based on *Pagurus bernhardus* (sand CEM);

- *Spisula* spp (Coarse assessment based on *Spisula subtruncata* assessments (sand CEM);
- *Ampelisca spinipes* (coarse) assessment based on *Ampelisca* spp and *Ampelisca brevicornis* (sand);
- *Sertularia argentea* (rock, coarse) assessment based on *Sertularia cupressina*
- *Tubificoides pseudogaster* (mud) assessed based on *Tubificoides benedii* (MarLIN)
- *Nemertesia ramosa* (mixed) assessed based on *Nemertesia antennina* (rock)

Where no information was available, assessments made for similar taxonomic or functional groups were used:

cumacean *Eudorella truncatula* (mixed), assessments used the cumacean assessments in sand (largely based on *Diastylis rathkei*).

Burrowing amphipod *Maera grossima* (mixed) assessment based on *Bathyporeia elegans* (sand)

In summary, sensitivity assessment gaps exist across all the biological assemblage groups studied. Mobile predators, such as starfish and crabs are not considered generally to characterise biotopes, which are largely defined based on sessile and sedentary species. They are not considered within the MarESA method, although Tillin and Tyler-Walters (2014) assessed the sensitivity of this ecological group. As these species are habitat generalists, present in all the broad habitats they present a key evidence gap.

In general, non-native species are considered to be nuisances, rather than species of conservation interest and their sensitivity has not been extensively studied within the existing resources. There was therefore little information to assess the invasive non-natives, within the biological assemblages, such as: *Crepidula fornicata* and *Sargassum muticum* (although these both have MarESA assessments) and *Styela clava*.

Within the CEMs the evidence base for sessile epifauna is greater than burrowing infauna. More information is available for larger species, that are of particular interest either for conservation or commercial purposes. The evidence base on which to assess sensitivity was much less for species that are small and of no commercial value such as many polychaetes, cumaceans, tanaids and others.

5.3 Confidence in pressure-sensitivity assessments

The confidence assessments made throughout the sensitivity assessment score aggregation process, were designed to demonstrate the source of the uncertainty in the evidence and the degree of expert judgement and interpretation required to make an assessment. For example, 'High' quality evidence may still not be directly applicable to the assessment, and excellent evidence may disagree.

Table 14 below shows patterns in confidence in the pressure sensitivity assessments across biotopes. For each habitat and pressure, the proportion of biotopes for which confidence was assessed as low, medium and high are shown. The patterns in confidence reflect both the quality of evidence available to make the assessment, the evidence gaps and the level of disparity between species. More information on confidence can be found in the accompanying pressure-sensitivity spreadsheets.

The only pressures where the majority of sensitivity assessments were assessed with high confidence were the changes in physical substratum type. This pressure represents a significant impact on sediment habitats resulting from a change in substratum type from sediment to rock or artificial habitats. The high confidence reflects the relatively good understanding in the marine environment, of the physical processes that structure

sedimentary and rocky habitats. The lower confidence for coarse and mixed habitats for this pressure is a result of the presence of a number of species that are found attached to stones in this habitat and that are also present in reef habitats such as bryozoans

The pressure extraction was generally awarded a 'Medium' confidence, for most species there was little specific evidence to support the sensitivity assessment but the extraction pathway to impact is clear, removing the sediment would removal either the majority or all species.

Confidence in abrasion and penetration was fairly evenly split between low and medium confidence across the sedimentary habitats. Although there is a large evidence base for the effects of abrasion from fishing pressures in particular low assessments were often the result of evidence gaps for species within a group where the applicability of the assessment could not be judged. Few biological assemblages were assessed with high confidence for either pressure.

Confidence in siltation pressures varied markedly between the two pressure benchmarks. For low siltation (a deposit of 5cm) confidence was greater (medium confidence in more biological assemblages) than for a thicker deposit of 30cm. For thinner deposits many species that occur in depositional environments were considered likely to be able to burrow through a deposit. For thicker deposits this confidence reduces. Although there is some experimental evidence to support assessments of siltation these relate to very few species and the uncertainty in these pressures results from a lack of evidence.

Sensitivity to changes in suspended solids at the pressure benchmark are difficult to infer from habitat evidence and biological traits that are difficult to relate to the pressure benchmark of a change for a year. In general species tolerances were assessed based on biological traits with permanently buried in fauna considered to be resistant while suspension feeding epifauna were considered likely to be more sensitive. Macroalgae were also considered likely to be sensitive to this pressure.

Table 14 below summarises the confidence in each pressure across habitats (rock requires updating). The % of the biological assemblage sensitivity assessments that were assigned each confidence level are shown for each pressure type.

Habitat and confidence level	Abrasion	Penetration	Extraction	Siltation (Low)	Siltation (High)	Wave exposure	Suspended solids	Physical change (Substratum)	Physical change (sediment) (finer)	Physical change (sediment) (Coarse)
Sand-Low	62	48	24	38	86	5	48	5	43	29
Coarse-Low	50	57	21	50	86	21	29	14	29	43
Mixed-Low	46	54	25	63	88	25	58	17	29	33
Mud-Low	50	29	7	29	64	21	43	14	Not assessed	29
Rock-Low										
Sand-Medium	38	52	71	57	14	0	48	0	19	29
Coarse-Medium	43	36	71	43	7	50	71	29	43	29
Mixed-Medium	46	46	71	38	8	25	42	33	54	50
Mud-Medium	36	50	71	50	14	43	36	7	Not assessed	50
Rock-Medium										
Sand-High	0	0	5	5	0	95	0	95	38	43
Coarse-High	7	7	7	0	7	29	0	57	29	29
Mixed-High	8	0	4	0	4	46	0	50	8	17
Mud-High	0	7	7	7	7	21	7	64	Not assessed	7
Rock-High										

5.4 Sensitivity assessment limitations

The MarLIN project has identified key limitations around the application of sensitivity assessments and these apply to both the collated species sensitivity assessment scores and the aggregated biological assemblage scores and should be considered when using the project outputs and any future use.

- The sensitivity assessments are generic and NOT site specific. They are based on the likely effects of a pressure on a 'hypothetical' population in the middle of its 'environmental range'⁷;
- Sensitivity assessments are NOT absolute values but are relative to the magnitude, extent, duration and frequency of the pressure effecting the species or community and

⁷'Environmental range' indicates the range of 'conditions' in which the species or community occurs and includes habitat preferences, physic-chemical preferences and, hence, geographic range.

habitat in question; thus, the assessment scores are very dependent on the pressure benchmark levels used;

- The assessments are based on the magnitude and duration of pressures (where specified) but do not take account of spatial or temporal scale;
- The significance of impacts arising from pressures also needs to take account of the scale of the features;
- The sensitivity assessment methodology takes account of both resistance and resilience (recovery). Recovery pre-supposes that the pressure has been alleviated but this will generally only be the case where management measures are implemented; and
- There are limitations of the scientific evidence on the biology of features and their responses to environmental pressures on which the sensitivity assessments have been based.

5.4.1 Disaggregating ecological group and biotope scores.

The MarESA assessments are based on biotope sensitivity and may consider characterising species or other factors such as substratum that characterise the biotope. In some instances, biotope sensitivities are very different to constituent species sensitivity. For example, when considering changes in sediment type, the biotope *character* would alter considerably if the sediment or substratum type changed but species themselves may not be as sensitive to a change. For example, the biotope, A5.141 *Pomatoceros triqueter* with barnacles and bryozoan crusts on unstable circalittoral cobbles and pebbles, is characterised by the presence of cobbles and pebbles and would be 'lost' if these were removed. However, the characterising species can be found on a range of substrata including hard rock and artificial substratum. The species, therefore, can be present even if the biotope would no longer be supported. In such instances, the biotope assessment or parts of the assessment text have been presented in the spreadsheet, but the sensitivity assessment has been adapted to the species.

In some instances, the biotope assessment and species assessments may not align where the species densities are considerably different. For example, *Sabellaria spinulosa* assessments are based on the *Sabellaria spinulosa* reef biotopes. However, these biotopes were not used in the construction of the CEMs and we understand that in the biotopes considered *Sabellaria spinulosa* may occur as individuals in low densities. The sensitivity of these is likely to be different from a reef but this has not been studied or quantified.

5.5 Ecosystem services

A key challenge in applying ecosystem service frameworks in management and decision-making is to have clear assessment frameworks that allow services to be measured. A systematic review of ecosystem services by Lique et al (2013a) found that some services are much better studied. There has been a focus on high priority and obvious goods such as fisheries and the provisioning services that underpin them than other services. There are particular gaps in knowledge around regulating and maintaining services, such as storm and erosion protection, habitat support for fisheries and pollution control (Barbier, 2017).

Services with high economic value and which are delivered by species that are larger and relatively tractable to study or experimentally manipulate are associated with more evidence. For example, primary production by kelp has been estimated by a number of studies and is

well supported (see Smale *et al* 2013 for overview), while estimates of primary production by other components including microphytobenthos are less understood.

Challenges in interpreting ecosystem services, particularly in marine and freshwater have been identified both generally (Liquete *et al* 2013a; Maes *et al* 2014) and for specific services, e.g. waste remediation (Watson *et al* 2016) and nursery provision (Liquete *et al* 2016). These services have proved more challenging to assess as the basis of the service itself had to be reviewed and considered in order to link to ecological components and parameterise for the MESO BBN development.

5.5.1 Provisioning Services

For all the ecosystem services considered, the abiotic and biotic components that directly provide the service were identified. In most cases the level of understanding of these services is greater than regulating and cultural services as they are more clearly linked to specific ecological components, e.g. species targeted by fisheries and harvesters or specific materials such as aggregates. A good level of literature information was sourced for most provisioning ecosystem services; gaps in the literature gathered on provisioning services are more likely to be a reflection of the time/resource constraints than an absence of available sources.

As this service primarily relates to the extraction of biological materials, most of the components which affect service delivery are those which directly influence the presence, growth and abundance of marine flora and fauna, and many influencing components are common to all services (Alexander *et al* 2016).

Abiotic components and processes such as water temperature (e.g. Lee *et al* 2007), light attenuation (e.g. Forster & Dring 1994; Franklin & Forster 1997), water pH (e.g. Callaway *et al* 2012), sediment type (e.g. Cognetti *et al* 2001; Sharples *et al* 2013) and wave and tidal flows (e.g. Nybakken 2001; Callaway *et al* 2012) were identified as influencing all ecosystem services considered. Ecosystem services relating to aquaculture (both algae and animals) are the general exception to these common features, largely due to the amount of human input which is required as the basis for these services, resulting in effectively less input from the marine environment.

5.5.2 Regulating services

< To be updated >

Linking ecological components from the CEMS to the capacity to deliver regulating and maintenance service for the MESO BBN models to create a meaningful basis for assessment was challenging. In many instances the service can be considered to be ubiquitous, for example all habitats with fauna can be considered to provide ecological services such as habitat provision and larval and gamete supply and to have the potential to support genetic resources. As the basis of defining an ecosystem service is the flow of goods and benefits to people and that xxx.

5.5.3 Cultural services

<to be updated>

5.5.4 Ecosystem services, demand and realisation

Demand and realisation of ecosystem services will vary. In some instances, although there may be potential for a service to be provided, there is no requirement for it and the potential

benefit is not realised. For example, *Mytilus edulis* reefs growing on an offshore wind farm have the potential to provide the services waste remediation and to be a harvestable good. However, if there are no wastes introduced into the marine environment the waste remediation service is not realised and similarly, their remoteness means they will not be targeted by a commercial fishery and the benefit is not realised.

Similarly, the value of ecosystem services can change according to demand. For example, the demand for cleaner wrasse from Scottish salmon farms has created a new fishery and increased the monetary value of the wrasse and therefore the supporting kelp bed services that produce these.

5.5.5 Ecosystem service provision varies temporally and spatially and according to condition

Spatial, temporal and condition variations compound uncertainties around the link between ecosystem services and ecosystem structure and function. The provision of a service may vary spatially across a habitat type, for example, a nursery function within a seagrass habitat may increase towards the centre of a dense bed rather than at the periphery. The nursery function may also vary seasonally and also according to changes in other adjacent habitats. For example, the bed may become more significant as a nursery if adjacent habitats are impacted or lost. In the same way, the condition of the kelp bed will also influence the provision of services, for example a dense bed is more likely to provide greater wave attenuation than a sparse bed.

5.6 Ecosystem service knowledge gaps

The ecosystem service review found that the evidence base supporting linkages between the ecological components identified in the CEMs and ecosystem services is highly inconsistent; with some features offering the potential for relatively strong conclusions on the strength of links (mediating, supporting, provisioning) whereas for others there was little or no evidence. The review found that:

- Substantially more evidence was available for provisioning services than for regulating and maintaining and cultural services. Commercial fisheries (food provisioning) are the most studied ecosystem service.
- Previous reviews (e.g. Fletcher *et al* 2012, Potts *et al* 2014, Tempera *et al* 2016 and Culhane *et al* 2018) have focussed on habitats and therefore more evidence is related to habitats than species. It is difficult to separate cultural services, in particular, to individual species rather than habitats.
- The evidence base for individual species for processes and ecosystem services is limited with no evidence at all for most species.
- In order to support the MESO BBN modelling, proxy indicators of service level were required, e.g. levels of bioturbation as a proxy for waste remediation potential.
- certain processes that support or deliver intermediate and/or final ecosystem services are better understood than others, primary and secondary production, food web dynamics and formation of species habitat are better understood and more predictable than waste remediation and carbon sequestration although many of the factors underlying the service delivery are understood.

5.7 Applicability of assessments

The CEMs represent a conceptual habitat and while they have been developed based on evidence on marine habitats they cannot be considered to apply to every biotope on which they are based. Between biotopes there will be variation in the relationships between the

ecological components and ecosystem services based on habitat and biological assemblage differences. The ecosystem service assessments should be considered to represent a conceptual assessment of the likely links between ecological components and ecosystem services, scaled on evidence that may relate to the most (or conversely) the least productive biotopes for that service.

5.8 Model Limitations

The model limitations were discussed in section 3.3.6. ([Update and Link in final report](#))

6 Conclusions

6.1 Pressure review

The review has identified how key pressures impact the marine ecosystem through impacts on the ecological components identified in the CEMs. The evidence base was most developed for physical damage pressures resulting from fishing activities and aggregate dredging. Within the CEMs the ecological component habitats and sessile benthos are best studied, with more information available for larger species, that are of particular interest either for conservation or commercial purposes. The evidence base on which to assess sensitivity was much less for species that are small and of no commercial value.

There was little evidence for impacts on local hydrological conditions, it is likely that there is little impact on these from the studied activities.

6.2 Ecosystem Service review

The review identified how ecosystem service delivery is provided, mediated and supported by ecosystem components and processes identified in the CEMs. The level of contribution and the confidence in these linkages was described. A lack of specific data on ecological thresholds for individual ecosystem components that contribute to ecosystem service delivery and the response of these to pressures was identified.

The literature review has shown that there is a large variability in the understanding of ecosystem services depending on the type (e.g. cultural) or level of exploitation (less information relating to less well developed uses of the marine environment such as the use of genetic resources) being considered.

6.3 Models

The application of BBNs to the modelling of ecosystem services is not uncommon and there are many good examples that provided guidance and inspiration during the design phase of this project (e.g. (Gonzalez-Redin, J. et al. 2016, Haines-Young, R. 2011, Landuyt, D. et al. 2013, Pérez-Miñana, E. 2016)). This project established a Bayesian Belief network (BBN) framework capable of evaluating parameters, causal connections, and relationships between independent, functional components of an ecosystem. It then set them in the context of the provision of ecosystem services that are, by definition, anthropocentric. This framework model will provide a context for further research and indicate where effort would best be focussed to advance both the model and our understanding of relationships between the ecosystem components and their contingent services.

The models are generic and are based on generic links between ecosystem structure and function and the potential to provide ecosystem services. They cannot account for spatial and temporal variation in ecosystem services.

Another limitation for this study is that the aspect of ecosystem services modelled is potential delivery of a service, based on likely changes in ecosystem processes and functions in response to impacts from pressures resulting from human activities. The study does not consider the demand for the ecosystem service or its realisation, or the value of ecosystem service benefits and goods that result from services.

Other limitations include no specific weighting for the relative importance of a functional group or biological assemblage within a habitat. For example, subtidal sand includes

macroalgae, but these are extremely sparse and in terms of biomass would comprise a small component, whereas all biological assemblages are equally weighted in the model, and not weighted according to their relative abundance, density or biomass.

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Appendix 1 List of assessed pressures.

Table 15 Final List of Pressures assessed and rationale for exclusion of other pressures within the framework.

Pressure theme	Included in Model	Proforma Number
Physical change (reversible)	Habitat structure changes - removal of substratum (extraction)	1
	Abrasion/disturbance of the substratum on the surface of the seabed	2
	Penetration and/or disturbance of the substratum below the surface of the seabed, including abrasion	3
	Smothering and siltation changes (depth of vertical sediment overburden) (light and heavy)	4
	Changes in suspended solids (water clarity)	5
Physical loss (permanent change)	Physical loss (to land or freshwater habitat) (include in later spatial models)	N/A
	Physical change (to another seabed type)	6
	Physical change to another sediment type	7
Biological Pressures	Removal of non-target species	N/A
	Removal of target species	N/A
Hydrological changes (inshore/local)	Wave exposure changes - local	N/A
High-level review - Assessed through a generic reduction in environmental condition scenario		
Pollution and other chemical changes	Hydrocarbon & PAH contamination.	NR
	Synthetic compound contamination	NR
	Transition elements & organo-metal (e.g. TBT) contamination.	NR
	Introduction of other substances (solid, liquid or gas)	NR
	De-oxygenation	NR
	Nutrient enrichment	NR
	Organic enrichment	NR
Biological Pressures	Introduction or spread of non-indigenous species (INIS)	NR
Not relevant to offshore habitats		
	Emergence regime changes - local, including tidal level change considerations	
	Water flow (tidal current) changes - local, including sediment transport considerations	
	Salinity changes – local, increase	
	Salinity changes – local, decrease	
	Temperature changes – local, increase	
	Temperature changes- local, decrease	
Not relevant to ecological components within CEMs		
Physical pressure (other)	Barrier to species movement	
	Electromagnetic changes	
	Death or injury by collision	
	Introduction of light or shading	
	Litter	

	Noise changes	
	Visual disturbance	
	Vibration	
Not included-evidence base too limited		
Physical pressure (other)	Radionuclide contamination	
Biological Pressures	Genetic modification & translocation of indigenous species	
	Introduction of microbial pathogens	

Appendix 2 List of Reviewed Activities

Table 16 List of activities reviewed

Activity	Description
Exploratory drilling	Exploratory drilling to evaluate commercial viability of geological features.
Gas storage operations (carbon capture and natural gas storage)	The deposition/ injection of natural gases or carbon into identified submarine storage sites.
Offshore wind: Construction (if relevant see also Cables)	Seabed preparation (possibly dredging), cuttings/dredgings disposal, piling, drilling, anchoring, mooring, vessel movement, vessel discharges/emissions, installation of scour protection, introduction of artificial substrate. This also includes the presence of the turbine structures and foundations – large offshore windfarms will be constructed over many years and the pressures due to the presence of turbines will therefore be present during the construction phase. For cabling please see and include the separate activity.
Offshore wind: Decommissioning (if relevant see also Cables)	Vessel movement, vessel discharges, use of jack up barges, removal of structures/scour protection and associated habitat, use of explosives, cutting, drilling, excavation of seabed close to foundations. This also includes the presence of the turbine structures and foundations – large offshore windfarms may be decommissioned over long time scales and the pressures due to the presence of turbines will therefore be present during the decommissioning phase. For cabling please see and include the separate activity.
Offshore wind: Operation and maintenance (if relevant see also Cables)	Regular vessel movement, vessel discharges, rotor sweep, lighting, presence of turbine and foundation structures. Also includes use of jack up barges for maintenance and deposition of additional scour protection. For cabling please see and include the separate activity.
Oil and gas infrastructure: Construction (see also piling and pipelines)	This activity includes the construction of oil and gas infrastructure in the marine environment including, but not limited to, the installation of rock dump to stabilise jack up rigs, cementing, introduction of other protection material such as concrete mattresses, matting and gravel, the temporary installation of infrastructure (such as pipelines, debris baskets etc.), drilling wells and plugging and abandonment, accidental effects, vessel movement, installation of subsea infrastructure etc.
Oil and gas infrastructure: Decommissioning	The plugging and abandonment of wells, removal of structures and associated habitat, use of explosives, cutting, drilling. Disturbance of drill arisings and cuttings. Placement of rock to cover remaining structures or to provide base for jack-up legs. Includes operation by supporting vessels, vessel discharges, use of ROVs, lifting and jack-up rigs.
Oil and gas infrastructure: Operation and maintenance	Production/operation, with routine supply, return of wastes to shore, power generation, chemical use, produced water, and re-injection of reservoirs.
Aggregate dredging	The regular excavation of aggregates (a mixture of sand and/or gravel sediments) for use generally in construction and beach recharge. Seabed sediments are removed through trailing suction or

	static grab dredgers. Dredging is associated with numerous vessel movements, sediment alteration and resuspension. NOTE: This assessment does NOT include aggregate dredging in the intertidal. Please contact Natural England for advice on intertidal aggregate dredging.
Dredge and spoil disposal	The disposal of dredged materials originating from the seabed.
Demersal seine netting	Activity includes demersal anchor/Danish seines and Scottish seines, as well as beach seines that come into contact with the seabed.
Demersal trawling	Activity includes beam trawls, demersal otter trawls, demersal pair trawls (excludes electronic pulse fishing).
Diving (incl. removal of living resources)	Collection of target species by divers, snorkelers. Includes recreational diving.
Dredging (shellfish)	Activity includes dredging (non-hydraulic) for shellfish e.g. scallops, oysters, mussels (including seed), clams & cockles. Includes dredges towed by vessels and tractors.
Electrofishing	Activity that includes trawls that interact with the seabed and use electric fields to fish for shellfish e.g. razor shells, shrimp or fish e.g. plaice, sole.
Hydraulic dredging	Activity includes hydraulic/suction dredging e.g. clams, cockles, razor shells.
Traps	Activity includes pots, creels & traps, as well as fyke nets and other similar gear.
Pipelines	Installation, maintenance and removal of pipeline including operations by supporting vessels.
Power cable: Decommissioning	Cables sometimes need to be retrieved or accessed for repairs or maintenance and are then reburied or protected. Additional cable protection can also be added where cable becomes unburied. Other specific pressures can also arise from power cable operation such as local temperature changes and electromagnetic field emission. The activity includes possible localised changes in physical environment as well as hydrodynamic changes through exposed cable/structures on the seabed, as well as vessel movement and anchoring during the operation.
Power cable: Laying, burial and protection	Methods and ways of laying cables vary depending on the water depth and the diameter of the cable. Submarine power cables have a diameter between 70 and up to 450mm. Cables can be laid either directly on the seabed, covered with material for protection or buried. The method used will depend on the area, the economic/ operational risk or environmental impacts. Protection is afforded in hazardous areas to avoid cable damage, i.e. where interaction with other activities is possible or likely. The most common method of protection is cable burial. This is usually done by seabed trench excavation through ploughing and hydraulic jetting. However, cables might be laid on the surface of the seabed if the area is unsuitable for burial (e.g. exposed rock or rocky outcrops). Cable protection is added in some cases when protection is needed due to the risk of damage. This can be done through rock placement on the seabed over the cable, mattressing, the addition of split pipe, concrete shells, etc. The activity includes seabed preparation activities (e.g. preparatory dredging, pre-lay grapnel runs, boulder removal, etc.), vessel movements and anchoring within the footprint.

Power cable: Operation and maintenance	Cables sometimes need to be retrieved or accessed for repairs or maintenance and are then reburied or protected. Additional cable protection can also be added where cable becomes unburied. Other specific pressures can also arise from power cable operation such as local temperature changes and electromagnetic field emission. The activity includes possible localised changes in physical environment as well as hydrodynamic changes through exposed cable/structures on the seabed, as well as vessel movement and anchoring during the operation.
Telecommunication cable: Decommissioning	When a cable is no longer needed or in use the general rule is the complete removal. However, this is often not feasible or appropriate and alternative approaches exist. When removal is deemed appropriate, cables are retrieved through grabbing and raising. Cables are also frequently disconnected and left buried to minimise environmental effects when the safe use of the seabed for other users is possible. The decommissioning process includes vessel movements and anchoring along the cable route.
Telecommunication cable: Laying, burial and protection	Methods and ways of laying cables vary depending on the water depth and the use of seabed by other activities. Telecommunication cables have a diameter similar to that of a garden hose, 17-22mm or up to 50mm when protective wire armour is used. Cables can be laid either directly on the seabed, covered with material for protection or buried. The method used will depend on the area, the economic/operational risk or environmental impacts. Protection is afforded in hazardous areas to avoid cable damage, i.e. where interaction with other activities is possible/likely. The most common method of protection is cable burial. Seabed trench excavation through ploughing and hydraulic jetting is frequently used for burial. However, cables might be laid on the surface of the seabed if the area is unsuitable for burial (e.g. exposed rock or rocky outcrops). Cable protection is occasionally added where there is a reasonable risk of damage. This is usually done by rock placement on the seabed over the cable. The activity includes vessel movements and anchoring within the footprint.
Telecommunication cable: Operation and maintenance	Cables sometimes need to be retrieved or accessed for repairs or maintenance and are then reburied or protected. Additional cable protection can also be added where cable becomes unburied. The activity also includes vessel movement and anchoring during the operation.
Exploratory drilling	Exploratory drilling to evaluate commercial viability of geological features.
Physical Sampling (see also fishing and Extraction of genetic resources e.g. bioprospecting)	Sampling of the seabed, foreshore (intertidal) and/or water column in situ using a variety of marine survey techniques.
Vessel anchorages	A place where a vessel is anchored. Covers activity of anchoring generically and use of allocated anchorage areas where ships are permitted to anchor inside and outside harbours/ports. Including consideration of vessels when anchoring, anchored or weighing anchor.
Vessel moorings	Use of vessel moorings and activity associated with mooring of vessel. Mooring is a temporary or permanent structure to which a

	vessel may be secured e.g. swing mooring, trot, fore and aft mooring, pile mooring. Includes consideration of vessels when mooring or moored.
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Appendix 3 Ecosystem Service Framework

Table 17. Intermediate ecosystem service and definitions from Potts *et al* (2014). Those in grey were not considered to be relevant to sublittoral habitats or were relevant but it was not possible to consistently parameterise these within the BBN model. Information was reviewed for all relevant services, but evidence was prioritised where it supports the modelling work. Unless otherwise stated the definitions are taken from Fletcher *et al* 2011.

Ecosystem Service			Definition	Overlap with CICES v5.1	Proforma
Intermediate services	Supporting services	Primary production	Production of plant biomass	Supports CICES 1.1.5.1 and 1.1.5.2	1
		Larval/ Gamete supply	Transport of larvae and gametes (Equivalent to 2.2.2.1	2
		Nutrient cycling	Cycle by which a chemical element or molecule moves through both biotic and abiotic compartments of ecosystems.	Supports all provisioning services through biomass:	3
		Water cycling	Regulation of the timing of water flow through an ecosystem.		Not relevant
		Formation of species habitats	Formation of the physical properties of the habitats necessary for the survival of species.	Overlaps with CICES 2.2.2	4
		Formation of physical barriers	Formation of structures that attenuate (or block) the energy of water flow.	Equivalent to CICES 2.1.1	5
		Formation of seascape	Formation of seascapes that are attractive to people.		Not relevant
	Regulating services	Biological control	Interactions resulting in reduced abundance of species that are pests, diseases or invasive species.	CICES 2.2.3.1 Pest and disease control	6
		Natural hazard regulation	Regulating the formation of physical barriers service	CICES 2.1.1.1 CICES 2.1.1.2	5
		Regulation of water & sediment quality	Regulation of the removal of contaminants from water flowing through an ecosystem.	CICES 2.2.1.1 CICES 2.2.1.2	13
		Carbon sequestration	Large, slowly-changing store of carbon (Armstrong <i>et al</i> 2012). For instance, marine organisms act as a reserve or sink for carbon in living tissue and by facilitating burial of carbon in seabed sediments (Armstrong <i>et al</i> 2012).	CICES 2.2.6.1 Regulation of chemical composition of atmosphere and oceans	7

Table 18 Final ecosystem services from CICES (v5.1; Haines-Young and Potschin 2018). The finer class divisions are not shown for brevity.

Section	Division	CICES Code	Group
Ecosystem services included in MESO BBN and prioritised in literature review			
Provisioning (Biotic)	Biomass	1.1.5.	Wild plants (terrestrial and aquatic) for nutrition, materials or energy.
	Biomass	1.1.6.2	Wild animals (terrestrial and aquatic) for nutrition, materials or energy.
Regulation & Maintenance (Biotic)	Transformation of biochemical or physical inputs to ecosystems	2.1.1.	Mediation of wastes or toxic substances of anthropogenic origin by living processes.
	Regulation of physical, chemical, biological conditions	2.2.1.	Regulation of baseline flows and extreme events.
	Regulation of physical, chemical, biological conditions	2.2.2	Lifecycle maintenance, habitat and gene pool protection.
	Regulation of physical, chemical, biological conditions	2.2.6.1	Atmospheric composition and conditions.
	Non-aqueous natural abiotic ecosystem outputs	4.3.1.	Mineral substances used for nutrition, materials or energy.
	Transformation of biochemical or physical inputs to ecosystems	5.1.1.	Mediation of waste, toxics and other nuisances by non-living processes.
	Regulation of physical, chemical, biological conditions	5.2.1.1	Regulation of baseline flows and extreme events.
Ecosystem services not included in MESO BBN but supported and reviewed with well-developed evidence base.			
Provisioning (Biotic)	Biomass	1.1.2.	Cultivated aquatic plants for nutrition, materials or energy.
	Biomass	1.1.4.1	Reared aquatic animals for nutrition, materials or energy

Cultural (Biotic)	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	3.1.1.1	Physical and experiential interactions with natural environment
Ecosystem services- with significant evidence gaps, reviewed but low priority.			
Provisioning (Biotic)	Genetic material from all biota (including seed, spore or gamete production)	1.2.1.	Genetic material from plants, algae or fungi
Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions	2.2.3.	Pest and disease control
	Regulation of physical, chemical, biological conditions	2.2.4.2	Regulation of soil quality- Considered to be captured in waste remediation service.
	Regulation of physical, chemical, biological conditions	2.2.5.2	Water conditions Considered to be captured in waste remediation service.
Cultural (Biotic)	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	3.1.2.	Intellectual and representative interactions with natural environment
	Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting	3.2.2.	Spiritual, symbolic and other interactions with natural environment
Regulation & Maintenance (Abiotic)	Regulation of physical, chemical, biological conditions	5.2.2.1	Maintenance of physical, chemical, abiotic conditions
Cultural (Abiotic)	Direct, in-situ and outdoor interactions with natural physical systems that depend on presence in the environmental setting	6.1.2.1	Intellectual and representative interactions with abiotic components of the natural environment
	Indirect, remote, often indoor interactions with physical systems that do not require presence in the environmental setting	6.2.1.1	Spiritual, symbolic and other interactions with the abiotic components of the natural environment
	Indirect, remote, often indoor interactions with physical systems that do not require presence in the environmental setting	6.2.2.1	Other abiotic characteristics that have a non-use value
	Direct, in-situ and outdoor interactions with natural physical systems that depend on presence in the	6.1.1.1	Physical and experiential interactions with natural abiotic components of the environment

	environmental setting		
Ecosystem services not relevant to marine sublittoral habitats within study and excluded from review.			
Regulation & Maintenance (Biotic)	Transformation of biochemical or physical inputs to ecosystems	2.1.2	Mediation of nuisances of anthropogenic origin
Provisioning (Abiotic)	Water	4.2.1	Surface water used for nutrition, materials or energy
	Water	4.2.2	Ground water for used for nutrition, materials or energy
	Non-aqueous natural abiotic ecosystem outputs	4.3.2.1	Non-mineral substances or ecosystem properties used for nutrition, materials or energy
Regulation & Maintenance (Abiotic)	Transformation of biochemical or physical inputs to ecosystems	5.1.2.1	Mediation of nuisances of anthropogenic origin

Appendix 4 Literature Review

First sift for each habitat type

Table 19 Date, database and searches and number of hits for each broad habitat type.

Date	Keywords	Name of database	No of hits.
27/11/18	Marine sand	Web of science	8,351
28/11/18	Marine sand	ASFA	66,347
	Marine sand – 2000-2019	ASFA	49,056
04/12/18	Subtidal mud	Web of science	402
	Subtidal mud	Science Direct	6,226
	Subtidal mud	ASFA	2,566
05/12/18	Subtidal rock	Web of Science	638
	Subtidal rock	Science Direct	5,715
18/12/18	Subtidal rock	ASFA	3,475
	Marine coarse sediment	Web of Science	2,109
08/01/19	Subtidal coarse sediment	Science Direct	5,100
	Subtidal coarse sediment	ASFA	1,750
09/01/19	Marine mixed sediment	Web of Science	4,483

Additional Ecosystem Service Literature Review

Table 20 Ecosystem Service literature review of Google scholar for ecosystem services delivered by sedimentary habitats. Ecosystem service papers were also identified in the first and second literature sifts see above.

Date	Keywords	Name of database	Number of hits
28/11/2018	Circalittoral sand function	Google Scholar	1,070
28/11/2018	Circalittoral sand process	Google Scholar	1,550
28/11/2018	Circalittoral sand service	Google Scholar	760
28/11/2018	Dissolved oxygen AND offshore sand habitat	Google Scholar	25,200
29/11/2018	Infralittoral sand process	Google Scholar	3,550
29/11/2018	Infralittoral sand service	Google Scholar	1,640
30/11/2018	Sand benthic ecological process	Google Scholar	124,000
30/11/2018	Marine offshore ecosystem service	Google Scholar	111,000
30/11/2018	Sublittoral sand ecosystem service	Google Scholar	5,790
30/11/2018	Secondary production benthic habitat	Google Scholar	88,900
30/11/2018	Marine sublittoral function	Google Scholar	20,400
30/11/2018	Marine sublittoral process	Google Scholar	24,000

15/01/2019	Marine Secondary Production	Google Scholar	2, 490,000
15/01/2019	Secondary production benthic macrofauna	Google Scholar	18,400
15/01/2019	Secondary production functional groups marine	Google Scholar	1,030,000
15/01/2019	Marine bioturbation	Google Scholar	62,100
15/01/2019	Bioturbation functional groups	Google Scholar	26,800
15/01/2019	Waste remediation marine	Google Scholar	52
15/01/2019	Marine nursery habitat	Google Scholar	82,900
15/01/2019	Marine biodeposition	Google Scholar	5,770
15/01/2019	Macrofauna biodeposition groups	Google Scholar	1,680

Table 21 Ecosystem service review for reef habitats.

Date	Keywords	Name of database	No of hits.
15/01/19	Subtidal rock function	Google Scholar	720
15/01/19	Subtidal rock process	Google Scholar	698
15/01/19	Subtidal rock service	Google Scholar	341
15/01/19	Sublittoral rock function	Google Scholar	195
15/01/19	Sublittoral rock process	Google Scholar	201
17/01/19	Sublittoral rock service	Google Scholar	135
	Marine rock ecosystem service		
25/01/19	Alaria esculenta uses	Google Scholar	2780
25/01/19	Alaria esculenta habitat	Google Scholar	1740
25/01/19	Alaria esculenta value	Google Scholar	2300
25/01/19	Laminaria ochroleuca value	Google Scholar	1050
25/01/19	Laminaria ochroleuca uses	Google Scholar	1250
25/01/19	Laminaria ochroleuca habitat	Google Scholar	816
28/01/19	Cancer pagurus habitat rock	Google Scholar	1070
29/01/19	Echinus esculentus collection UK	Google Scholar	1070
29/01/19	Wave attenuation kelp	Google Scholar	5640
29/01/19	Wave attenuation mussel	Google Scholar	5300
29/01/19	Ophiothrix fragilis value	Google Scholar	1540
08/02/19	Mytilus services subtidal	Google Scholar	6640
08/02/19	Mytilus ecosystem services	Google Scholar	21200
11/02/19	Primary production rate algae red brown green	Google Scholar	122,000
11/02/19	Primary production rate	Google Scholar	15,300

	macroalgae red brown green review		
11/02/19	Primary production rate macroalgae red brown green review	Google Scholar	14,900
14/02/19	<i>Anemonia viridis</i> ecosystem service	Google Scholar	56
14/02/19	<i>Metridium senile</i> ecosystem service	Google Scholar	35

Additional Pressure and Conservation Attribute Review

Table 22 Pressures and conservation attribute literature review- Search Terms.

Date	Keywords	Name of database	No of hits.
27-28/11/2018	Seabed, abrasion, impacts	Google Scholar	5,560
28/11/2018	Seabed, disturbance,	Google Scholar	34,700
28/11/2018	Sublittoral, disturbance,	Google Scholar	15,400
29/11/2018	Trawling, sublittoral,	Google Scholar	6,330
29/11/2018	Dredging, sublittoral,	Google Scholar	8,510
29/11/2018	Smothering, sublittoral	Google Scholar	1,330
29/11/2018	Seabed, substratum, abrasion	Google Scholar	1,430
29/11/2018	Disturbance/abrasion	Google Scholar	27
29/11/2018	Aggregate extraction, marine, (2010+)	Google Scholar	18,100
29/11/2018	Marine, infrastructure	Google Scholar	144,000
30/11/2018	Siltation, marine, (2016+)	Google Scholar	4,360
28/11/2018	Seabed, abrasion	Google Scholar	7,640
30/11/2018	Marine cables	Google Scholar	133,000
30/11/2018	Marine pipelines *	Google Scholar	97,600
30/11/2018	Anchoring, mooring (2016+)	Google Scholar	3,240
30/11/2018	Anchoring, mooring, sublittoral (2016+)	Google Scholar	64
2/12/2018	Seabed abrasion	Natural England	213
2/12/2018	Seabed disturbance	Natural England	305
2/12/2018	Sublittoral disturbance	Natural England	145
2/12/2018	Trawling sublittoral	Natural England	131
2/12/2018	Dredging sublittoral	Natural England	131
2/12/2018	Smothering sublittoral	Natural England	67
2/12/2018	Aggregate extraction, impacts	Natural England	382
2/12/2018	Pipelines, cables	Natural England	60
2/12/2018	No clear way to search publications on website, looked through list of marine publications and added to library based on title		
2/12/2018	Seabed abrasion	JNCC	387
2/12/2018	Seabed disturbance	JNCC	1067
2/12/2018	Sublittoral disturbance	JNCC	767
2/12/2018	Trawling sublittoral	JNCC	527
2/12/2018	Dredging sublittoral	JNCC	416
2/12/2018	Smothering sublittoral	JNCC	217
2/12/2018	Aggregate extraction,	JNCC	698

	impacts		
2/12/2018	Pipelines, cables	JNCC	236
2/12/2018	Seabed abrasion	SNH	46
2/12/2018	Seabed disturbance	SNH	145
2/12/2018	Sublittoral disturbance	SNH	110
2/12/2018	Trawling sublittoral	SNH	11
2/12/2018	Dredging sublittoral	SNH	11
2/12/2018	Smothering sublittoral	SNH	11
2/12/2018	Aggregate extraction, impacts	SNH	323
2/12/2018	Pipelines, cables	SNH	2
2/12/2018	Seabed abrasion	DEFRA	8
2/12/2018	Seabed disturbance	DEFRA	19
2/12/2018	Sublittoral disturbance	DEFRA	13
2/12/2018	Trawling sublittoral	DEFRA	5
2/12/2018	Dredging sublittoral	DEFRA	7
2/12/2018	Smothering sublittoral	DEFRA	1
2/12/2018	Aggregate extraction, impacts	DEFRA	341
2/12/2018	Pipelines, cables	DEFRA	9

Appendix 5 Sensitivity assessment methodology

Sensitivity assessment

The sensitivity assessment methods used by the sources for this project (Tillin and Tyler-Walters *et al* 2014 Tillin and Hull, 2012-2013 and the MarESA methodology) involve the following stages:

- A. Defining the key elements of the feature to be assessed (in terms of life history, and ecology of the key and characterising species)
- B. Assessing feature resistance (tolerance) to a defined intensity of pressure (the benchmark)
- C. Assessing the resilience (recovery) of the feature to a defined intensity of pressure (the benchmark); and
- D. The combination of resistance and resilience to derive an overall sensitivity score
- E. Assess level of confidence in the sensitivity assessment
- F. Written audit trail

A) Defining the key elements of the feature

When assessing habitats/biotopes the key elements of the feature that the sensitivity assessment will consider must be selected at the outset.

B and C) Assessing feature resistance (tolerance) and resilience to a defined intensity of pressure (the benchmark)

To develop each sensitivity assessment, the resistance and resilience of the key elements are assessed against the pressure benchmark using the available evidence. The benchmarks are designed to provide a 'standard' level of pressure against which to assess sensitivity.

The assessment scales used for resistance (tolerance) and resilience (recovery) are given in Tables 22 and 23 and respectively.

'Full recovery' is envisaged as a return to the state that existed prior to impact. However, this does not necessarily mean that every component species or other key elements of the habitat have returned to its prior condition, abundance or extent, but that the relevant functional components are present and the habitat is structurally and functionally recognisable as the initial habitat of interest.

Table 23 Assessment scale for resistance (tolerance) to a defined intensity of pressure. These scales were used for all three sensitivity assessment methods used within this project.

Resistance (Tolerance)	Description
None	Key functional, structural, characterising species severely decline, and/or physico-chemical parameters are also affected e.g. removal of habitats causing change in habitats type. A severe decline/reduction relates to the loss of 75% of the extent, density or abundance of the selected species or habitat element e.g. loss of 75% substratum (where this can be sensibly applied).
Low	Significant mortality of key and characterising species with some effects on

	physico-chemical character of habitat. A significant decline/reduction relates to the loss of 25-75% of the extent, density, or abundance of the selected species or habitat element e.g. loss of 25-75% of substratum.
Medium	Some mortality of species (can be significant where these are not keystone structural/functional and characterising species) without change to habitats relates to the loss <25% of the species or element.
High	No significant effects to the physico-chemical character of habitat and no effect on population viability of key/characterising species but may affect feeding, respiration and reproduction rates.

Table 24 Assessment scale for resilience (recovery). (MarESA and Ecological group work)

Resilience (Recovery)	Description
Very Low	Negligible or prolonged recovery possible; at least 25 years to recover structure and function
Low	Full recovery within 10-25 years
Medium	Full recovery within 2-10 years
High	Full recovery within 2 years

Table 25 Assessment scale for resilience (recovery) used for the Marine Institute work (Tillin & Hull, 2010).

Recovery Category	Description
Low	Full recovery 6+ years
Medium	Full recovery within 3-5 years
High	Full recovery within ≤ 2 years
Very High	Full recovery within 6 months

D) The combination of resistance and resilience to derive an overall sensitivity score

The resistance and resilience scores can be combined, as follows, to give an overall sensitivity score as shown in Table 25.

Table 26. Combining resistance and resilience scores to categorise sensitivity.

	Resistance			
Resilience	None	Low	Medium	High
Very Low	High	High	Medium	Low
Low	High	High	Medium	Low
Medium	Medium	Medium	Medium	Low
High	Medium	Low	Low	Not sensitive

Table 27 Overall sensitivity-Marine Institute- (MarESA sensitivity assessment equivalent in brackets) where different

Recovery		Resistance			
		None (severe decline)	Low (25-75% decline)	Medium (≤25% decline)	High (no effects)
	Low (6+ years)	Very High (Assess on recovery information)	High (Assess on recovery information)	Low (Medium)	Not Sensitive (Low)
	Medium (3-5 years)	High (medium)	Medium (Medium)	Low (Medium)	Not Sensitive (Low)
	High (≤2 years)	Medium (medium)	Medium (Low)	Low (low)	Not Sensitive (=NS)
	Very High (6 months)	Low (medium)	Low (low)	Low (low)	Not Sensitive

The following options can also be used for pressures where an assessment is not possible or not felt to be applicable (this is documented and justified in each instance):

No exposure (NX) - where there will be no exposure to a particular pressure, for example, deep mud habitats are not exposed to changes in emersion.

Not assessed (NA) – where the evidence base is not considered to be developed enough for assessments to be made of sensitivity

No evidence (NEv) - unable to assess the specific feature/pressure combination based on knowledge and unable to locate information regarding the feature on which to base decisions. This can be the case for species with distributions limited to a few locations (sometimes only one), so that even basic tolerances could not be inferred. An assessment of 'No Evidence' should not be taken to mean that there is no information available for features.

Appendix 6 Pressure correspondence between sensitivity assessments used in the pressure review

Key to table:

Green	Assessment at same pressure benchmark and directly equivalent
Amber	Some differences in benchmark, apply with caution and consider differences and implication for sensitivity
Red	Benchmarks different or no benchmark. Evidence may be applicable, but sensitivity assessment will need to be re-thought.

	Pressure	MARESA Benchmark	JNCC Ecological Groups (Tillin & Tyler –Walters 2014)	Marine Institute
	Wave exposure changes - local	A change in nearshore significant wave height >3% but <5% for one year	Yes	No equivalent
Physical damage (Reversible Change)	Changes in suspended solids (water clarity)	A change in one rank on the WFD (Water Framework Directive) scale e.g. from clear to intermediate for one year.	Yes	Changes in turbidity suspended sediments
	Habitat structure changes - removal of substratum (extraction)	Extraction of substratum to 30cm (where substratum includes sediments and soft rocks but excludes hard bedrock)	Yes	Extraction
	Abrasion/disturbance of the substrate on the surface of the seabed	Damage to seabed surface features (species and habitats)	Yes	Surface disturbance Trampling by foot Trampling by vehicle
	Penetration and/or disturbance of the substrate below the surface of the seabed, including abrasion	Damage to sub-surface seabed.	Yes	Shallow disturbance Deep disturbance
	Smothering and siltation changes (depth of vertical sediment overburden)	'Light' deposition of up to 5 cm of fine material added to the seabed in a single, discrete event	No equivalent	Siltation Smothering pressure refers to coarse sediments/other material
		'Heavy' deposition of up to 30 cm of fine material added to the seabed in a single discrete event	Yes	See above

Physical loss (Permanent Change)	Physical change (to another seabed type)	Change in 1 Folk class (based on UK SeaMap simplified classification).	Yes	Changes to sediment-increased coarseness- not at benchmark Changes to sediment composition-increased fines-not at benchmark
		Change from sedimentary or soft rock substrata to hard rock or artificial substrata or vice-versa.	No equivalent	No equivalent
	Physical loss (to land or freshwater habitat)	Permanent loss of existing saline habitat within site	Yes	No equivalent
	Removal of non-target species	Removal of features or incidental non-targeted catch (by-catch) through targeted fishery, shellfishery or harvesting at a commercial or recreational scale.	Yes- but rationale different	Yes- but rationale different
	Removal of target species	Benthic species and habitats: removal of species targeted by fishery, shellfishery or harvesting at a commercial or recreational scale.	Yes- but rationale different	Yes- but rationale different

Appendix 7 Sensitivity assessment sources used to assess sensitivity for biological assemblages within each broad habitat type.

Table 28 Sand biotopes identified in the CEM matrix and checked against MarESA sensitivities.

Biotope Sources	MarESA
A5.14- Circalittoral coarse sediment	
A5.141 Pomatoceros triqueter with barnacles and bryozoan crusts on unstable circalittoral cobbles and pebble	<i>Pomatoceros triqueter</i>
A5.23 Infralittoral fine sand	
A5.231 - Infralittoral mobile clean sand with sparse fauna	<i>Nephtys cirrosa</i> , <i>Eurydice pulchra</i> , <i>Bathyporeis elegans</i>
A5.232 - Sertularia cupressina and Hydrallmania falcata on tide-swept sublittoral sand with cobbles or pebbles	<i>Sertularia cupressina</i> , <i>Hydrallmania falcata</i>
A5.233 - Nephtys cirrosa and Bathyporeia spp. in infralittoral sand	<i>Nephtys cirrosa</i> , <i>Bathyporeia</i> spp.
A5.234 - Semi-permanent tube-building amphipods and polychaetes in sublittoral sand	<i>Polydora ciliata</i> , <i>Spiophanes bombyx</i> , <i>Corophium</i> and <i>Ampelisca</i> spp
A5.24 - Infralittoral muddy sand	
A5.241 - Echinocardium cordatum and Ensis spp. in lower shore and shallow sublittoral slightly muddy fine sand	<i>Echinocardium cordatum</i> , <i>Ensis ensis</i>
A5.242 - Fabulina fabula and Magelona mirabilis with venerid bivalves and amphipods in infralittoral compacted fine muddy sand	<i>Tellina fabula</i>
A5.243 - Arenicola marina in infralittoral fine sand or muddy sand	<i>Arenicola marina</i>
A5.244 - Spisula subtruncata and Nephtys hombergii in shallow muddy sand	<i>Spisula subtruncata</i> - information gap
A5.25 - Circalittoral fine sand	
A5.251 - Echinocyamus pusillus, Ophelia borealis and Abra prismatica in circalittoral fine sand	<i>Echinocyamus pusillus</i>
A5.252 - Abra prismatica, Bathyporeia elegans and polychaetes in circalittoral fine sand	<i>Abra</i> spp, <i>polychaetes</i> .
A5.26 - Circalittoral muddy sand	
A5.261 - Abra alba and Nucula nitidosa in circalittoral muddy sand or slightly mixed sediment	<i>Abra alba</i> , <i>Nucula nitidosa</i>
A5.262 - Amphiuira brachiata with Astropecten irregularis and other echinoderms in	<i>Acrocnida brachiata</i> , <i>Astropecten irregularis</i> , <i>Owenia fusiformis</i>
Additional Biotopes checked	
A4.1343 Flustra foliacea and colonial ascidians on tide-swept exposed circalittoral mixed substrata	<i>Flustra foliacea</i>
A4.213 Urticina felina and sand-tolerant fauna on sand-scoured or covered circalittoral rock	<i>Urticina felina</i>
A5.136 Cumaceans and Chaetozone setosa in infralittoral gravelly sand	<i>Chaetozone setosa</i>
A5.231. Infralittoral mobile clean sand with sparse fauna.	<i>Bathyporeia</i> spp.
A5.441 Cerianthus lloydii and other burrowing anemones in circalittoral muddy mixed sediment	<i>Cerianthus lloydii</i>
A5.5213 Laminaria saccharina and filamentous red algae on infralittoral sand	<i>Sacharrina latissima</i>

Table 29 Coarse sediment biotopes identified in the CEM matrix and checked against MarESA sensitivities

Biotope Sources	MarESA
A5.13: Infralittoral coarse sediment	
A5.131: Sparse fauna on highly mobile sublittoral shingle (cobbles and pebbles)	No species assessed
A5.132: <i>Halcampa chrysanthellum</i> and <i>Edwardsia timida</i> on sublittoral clean stone gravel	<i>Halcampa chrysanthellum</i>
A5.133: <i>Moerella</i> spp. with venerid bivalves in infralittoral gravelly sand	<i>Moerella</i> (<i>Tellina pygmaea</i>), <i>Dosinia lupinus</i> , <i>Timoclea ovata</i>
A5.134: <i>Hesionura elongata</i> and <i>Microphthalmus similis</i> with other interstitial polychaetes in infralittoral mobile coarse sand	No relevant species
A5.135: <i>Glycera lapidum</i> in impoverished infralittoral mobile gravel and sand	<i>Glycera lapidum</i>
A5.136: Cumaceans and <i>Chaetozone setosa</i> in infralittoral gravelly sand	<i>Chaetozone setosa</i>
A5.137: Dense <i>Lanice conchilega</i> and other polychaetes in tide-swept infralittoral sand and mixed gravelly sand	<i>Lanice conchilega</i>
A5.14: Circalittoral coarse sediment	
A5.141: <i>Pomatoceros triqueter</i> with barnacles and bryozoan crusts on unstable circalittoral cobbles and pebbles	<i>Pomatoceros triqueter</i> , <i>Balanus crenatus</i>
A5.142: <i>Mediomastus fragilis</i> , <i>Lumbrineris</i> spp. and venerid bivalves in circalittoral coarse sand or gravel	<i>Mediomastus fragilis</i> , <i>Lumbrineris</i>
A5.143: <i>Protodorvillea kefersteini</i> and other polychaetes in impoverished circalittoral mixed gravelly sand	<i>Protodorvillea kefersteini</i>
A5.144: <i>Neopentadactyla mixta</i> in circalittoral shell gravel or coarse sand	<i>Neopentadactyla mixta</i>
A5.145: <i>Branchiostoma lanceolatum</i> in circalittoral coarse sand with shell gravel	<i>Branchiostoma lanceolatum</i>
Additional Biotopes	
A5.611 <i>Sabellaria spinulosa</i> on stable circalittoral mixed sediment	<i>Sabellaria spinulosa</i>

Table 30 Mixed sediment biotopes identified in the CEM matrix and checked against MarESA sensitivities

Biotope Sources	MarESA
A5.43 Infralittoral mixed sediments	
A5.431 - <i>Crepidula fornicata</i> with ascidians and anemones on infralittoral coarse mixed sediment	<i>Crepidula fornicata</i>
A5.432 - <i>Sabella pavonina</i> with sponges and anemones on infralittoral mixed sediment	<i>Sabella pavonina</i>
A5.433 - <i>Venerupis senegalensis</i> , <i>Amphipholis squamata</i> and <i>Apseudes latreilli</i> in infralittoral mixed sediment	<i>Venerupis senegalensis</i> ; <i>Amphipholis squamata</i>
A5.434 - <i>Limaria hians</i> beds in tide-swept sublittoral muddy mixed sediment	<i>Limaria hians</i>
A5.435 - <i>Ostrea edulis</i> beds on shallow sublittoral muddy mixed sediment	<i>Ostrea edulis</i>
A5.44 Circalittoral mixed sediments	
A5.441 - <i>Cerianthus lloydii</i> and other burrowing anemones in circalittoral muddy mixed sediment	<i>Cerianthus lloydii</i>
A5.442 - Sparse <i>Modiolus modiolus</i> , dense <i>Cerianthus lloydii</i> and burrowing holothurians on sheltered circalittoral stones and mixed sediment	<i>Modiolus modiolus</i>
A5.443 - <i>Mysella bidentata</i> and <i>Thyasira</i> spp. in circalittoral muddy mixed sediment	<i>Thyasira flexuosa</i>
A5.444 - <i>Flustra foliacea</i> and <i>Hydrallmania falcata</i> on tide-swept circalittoral mixed sediment	
A5.445 - <i>Ophiothrix fragilis</i> and/or <i>Ophiocomina nigra</i> brittlestar beds on sublittoral mixed sediment	<i>Ophiothrix fragilis</i>
Additional biotopes	
A4.252 <i>Halichondria bowerbanki</i> , <i>Eudendrium arbusculum</i> and <i>Eucratea loricate</i> on reduced salinity tide-swept circalittoral mixed substrata	<i>Halichondria bowerbanki</i>

Table 31 Mud sediment biotopes identified in the CEM matrix and checked against MarESA sensitivities

Biotope Sources	MarESA
A5.33 - Infralittoral sandy mud	
A5.331 - <i>Nephtys hombergii</i> and <i>Macoma balthica</i> in infralittoral sandy mud	<i>Nephtys hombergii</i> , <i>Macoma balthica</i>
A5.332 - <i>Sagartiogeton undatus</i> and <i>Asciidiella aspersa</i> on infralittoral sandy mud	<i>Sagartiogeton undatus</i>
A5.333 - <i>Mysella bidentata</i> and <i>Abra</i> spp. in infralittoral sandy mud	<i>Kurtiella bidentata</i> , <i>Abra</i> spp.
A5.334 - <i>Melinna palmata</i> with <i>Magelona</i> spp. and <i>Thyasira</i> spp. in infralittoral sandy mud	<i>Melinna palmata</i> , <i>Abra nitida</i> , <i>Magelona</i> spp.
A5.335 - <i>Ampelisca</i> spp., <i>Photis longicaudata</i> and other tube-building amphipods and polychaetes in infralittoral sandy mud	
A5.336 - <i>Capitella capitata</i> in enriched sublittoral muddy sediments	<i>Capitella capitata</i>
A5.34 - Infralittoral fine mud	
A5.341 - <i>Cerastoderma edule</i> with <i>Abra nitida</i> in infralittoral mud	<i>Cerastoderma edule</i>
A5.342 - <i>Arenicola marina</i> in infralittoral mud	See Sand Table

A5.343 - <i>Philine aperta</i> and <i>Virgularia mirabilis</i> in soft stable infralittoral mud	<i>Virgularia mirabilis</i>
A5.344 - <i>Ocnus planci</i> aggregations on sheltered sublittoral muddy sediment	<i>Ocnus planci</i>
A5.35 - Circalittoral sandy mud	
A5.351 - <i>Amphiura filiformis</i> , <i>Mysella bidentata</i> and <i>Abra nitida</i> in circalittoral sandy mud	<i>Amphiura filiformis</i>
A5.352 - <i>Thyasira</i> spp. and <i>Nuculoma tenuis</i> in circalittoral sandy mud	<i>Nuculoma tenuis</i>
A5.353 - <i>Amphiura filiformis</i> and <i>Nuculoma tenuis</i> in circalittoral and offshore sandy mud	
A5.354 - <i>Virgularia mirabilis</i> and <i>Ophiura</i> spp. with <i>Pecten maximus</i> on circalittoral sandy or shelly mud	<i>Pecten maximus</i>
A5.355 - <i>Lagis koreni</i> and <i>Phaxas pellucidus</i> in circalittoral sandy mud	<i>Lagis koreni</i>
A5.36 - Circalittoral fine mud	
A5.361 - Seapens and burrowing megafauna in circalittoral fine mud	<i>Calocaris macandreae</i> , <i>Nephrops norvegicus</i> , <i>Callianassa subterranea</i>
A5.362 - Burrowing megafauna and <i>Maxmuelleria lankesteri</i> in circalittoral mud	<i>Maxmuelleria lankesteri</i> ; <i>Calocaris macandreae</i> , <i>Nephrops norvegicus</i> , <i>Callianassa subterranea</i>
A5.363 - <i>Brissopsis lyrifera</i> and <i>Amphiura chiajei</i> in circalittoral mud	<i>Brissopsis lyrifera</i>
Additional biotopes	
A5.322 <i>Aphelochaeta marioni</i> and <i>Tubificoides</i> spp. in variable salinity infralittoral mud	<i>Aphelochaeta marioni</i>
A2.322 <i>Hediste diversicolor</i> in littoral mud.	<i>Hediste diversicolor</i>

Table 32 Rock biotopes identified in the CEM matrix and checked against MarESA sensitivities

Biotope Sources	MarESA
A3.1: Atlantic and Mediterranean high energy infralittoral rock	
A3.11: Kelp with cushion fauna and/or foliose red seaweeds	
A3.111: <i>Alaria esculenta</i> on exposed sublittoral fringe bedrock	<i>Alaria esculenta</i>
A3.112: <i>Alaria esculenta</i> forest with dense anemones and crustose sponges on extremely exposed infralittoral bedrock	Not reviewed
A3.113: <i>Laminaria hyperborea</i> forest with a faunal cushion (sponges and polyclinids) and foliose red seaweeds on very exposed infralittoral rock	<i>Laminaria hyperborea</i>
A3.114: Sparse <i>Laminaria hyperborea</i> and dense <i>Paracentrotus lividus</i> on exposed infralittoral limestone	Not reviewed
A3.115: <i>Laminaria hyperborea</i> with dense foliose red seaweeds on exposed infralittoral rock	Not reviewed
A3.116: Foliose red seaweeds on exposed lower infralittoral rock	<i>Delesseria sanguinea</i>
A3.117: <i>Laminaria hyperborea</i> and red seaweeds on exposed vertical rock	Not reviewed
A3.12: Sediment-affected or disturbed kelp and seaweed communities	

A3.121: Saccorhiza polyschides and other opportunistic kelps on disturbed upper infralittoral rock	
A3.122: Laminaria saccharina and/or Saccorhiza polyschides on exposed infralittoral rock	
A3.123: Laminaria saccharina, Chorda filum and dense red seaweeds on shallow unstable infralittoral boulders and cobbles	
A3.124: Dense Desmarestia spp. with filamentous red seaweeds on exposed infralittoral cobbles, pebbles and bedrock	<i>Desmarestia aculeata</i>
A3.125: Mixed kelps with scour-tolerant and opportunistic foliose red seaweeds on scoured or sand-covered infralittoral rock	Not reviewed
A3.126: Halidrys siliquosa and mixed kelps on tide-swept infralittoral rock with coarse sediment	<i>Halidrys siliquosa</i>
A3.127: Polyides rotundus, Ahnfeltia plicata and Chondrus crispus on sand-covered infralittoral rock	<i>Polyides rotundus</i> , <i>Ahnfeltia plicata</i> and <i>Chondrus crispus</i>
A3.2: Atlantic and Mediterranean moderate energy infralittoral rock	
A3.21: Kelp and red seaweeds (moderate energy infralittoral rock)	
A3.211: Laminaria digitata on moderately exposed sublittoral fringe rock	
A3.212: Laminaria hyperborea on tide-swept, infralittoral rock	Not reviewed
A3.213: Laminaria hyperborea on tide-swept infralittoral mixed substrata	Not reviewed
A3.214: Laminaria hyperborea and foliose red seaweeds on moderately exposed infralittoral rock	Not reviewed
A3.215: Dense foliose red seaweeds on silty moderately exposed infralittoral rock	
A3.216: Laminaria hyperborea on moderately exposed vertical rock	Not reviewed
A3.217: Hiatella arctica and seaweeds on vertical limestone / chalk	
A3.22: Kelp and seaweed communities in tide-swept sheltered conditions	
A3.221: Laminaria digitata, ascidians and bryozoans on tide-swept sublittoral fringe rock	<i>Halichondria panicea</i>
A3.222: Mixed kelp with foliose red seaweeds, sponges and ascidians on sheltered tide-swept infralittoral rock	<i>Chondrus crispus</i>
A3.223: Mixed kelp and red seaweeds on infralittoral boulders, cobbles and gravel in tidal rapids	Not reviewed
A3.224: Laminaria saccharina with foliose red seaweeds and ascidians on sheltered tide-swept infralittoral rock	
A3.225: Filamentous red seaweeds, sponges and Balanus crenatus on tide-swept variable-salinity infralittoral rock	<i>Balanus crenatus</i>
A3.3: Atlantic and Mediterranean low energy infralittoral rock	
A3.31: Silted kelp on low energy infralittoral rock with full salinity	
A3.311: Mixed Laminaria hyperborea and Laminaria ochroleuca forest on moderately exposed or sheltered infralittoral rock	<i>Laminaria ochroleuca</i>

A3.312: Mixed Laminaria hyperborea and Laminaria saccharina on sheltered infralittoral rock	Not reviewed
A3.313: Laminaria saccharina on very sheltered infralittoral rock	
A3.314: Silted cape-form Laminaria hyperborea on very sheltered infralittoral rock	
A3.315: Sargassum muticum on shallow slightly tide-swept infralittoral mixed substrata	<i>Sargassum muticum</i>
A4.1: Atlantic and Mediterranean high energy circalittoral rock	
A4.11: Very tide-swept faunal communities on circalittoral rock	
A4.111: Balanus crenatus and Tubularia indivisa on extremely tide-swept circalittoral rock	Not reviewed
A4.112: Tubularia indivisa on tide-swept circalittoral rock	
A4.12: Sponge communities on deep circalittoral rock	
A4.121: Phakellia ventilabrum and axinellid sponges on deep, wave-exposed circalittoral rock	<i>Axinella dissimilis</i>
A4.13: Mixed faunal turf communities on circalittoral rock	
A4.131: Bryozoan turf and erect sponges on tide-swept circalittoral rock	<i>Bugula plumosa</i>
A4.132: Corynactis viridis and a mixed turf of crisiids, Bugula, Scrupocellaria, and Cellaria on moderately tide-swept exposed circalittoral rock	
A4.133: Mixed turf of hydroids and large ascidians with Swiftia pallida and Caryophyllia smithii on weakly tide-swept circalittoral rock	Not reviewed
A4.134: Flustra foliacea and colonial ascidians on tide-swept moderately wave-exposed circalittoral rock	<i>Flustra foliacea</i>
A4.135: Sparse sponges, Nemertesia spp., and Alcyonidium diaphanum on circalittoral mixed substrata	<i>Nemertesia</i> spp. and <i>Alcyonidium diaphanum</i>
A4.136: Suberites spp. with a mixed turf of crisiids and Bugula spp. on heavily silted moderately wave-exposed shallow circalittoral rock	<i>Suberites</i> spp.
A4.137: Flustra foliacea and Haliclona oculata with a rich faunal turf on tide-swept circalittoral mixed substrata	
A4.138: Molgula manhattensis with a hydroid and bryozoan turf on tide-swept moderately wave-exposed circalittoral rock	
A4.139: Sponges and anemones on vertical circalittoral bedrock	<i>Clavelina lepadiformis</i> , <i>Metridium senile</i> and <i>Holothuria forskali</i>
A4.2: Atlantic and Mediterranean moderate energy circalittoral rock	
A4.21: Echinoderms and crustose communities on circalittoral rock	
A4.211: Caryophyllia smithii and Swiftia pallida on circalittoral rock	<i>Swiftia pallida</i>
A4.212: Caryophyllia smithii, sponges and crustose communities on wave-exposed circalittoral rock	<i>Caryophyllia smithii</i>
A4.213: Urticina felina and sand-tolerant fauna on sand-scoured or covered circalittoral rock	<i>Urticina feline</i>
A4.214: Faunal and algal crusts on exposed to moderately wave-exposed circalittoral rock	

A4.215: Alcyonium digitatum and faunal crust communities on vertical circalittoral bedrock	<i>Alcyonium digitatum</i>
A4.23: Communities on soft circalittoral rock	
A4.231: Piddocks with a sparse associated fauna in sublittoral very soft chalk or clay	<i>Pholas dactylus</i>
A4.232: Polydora sp. tubes on moderately exposed sublittoral soft rock	<i>Polydora</i>
A4.233: Hiatella-bored vertical sublittoral limestone rock	Not relevant
A4.241: Mytilus edulis beds with hydroids and ascidians on tide-swept exposed to moderately wave-exposed circalittoral rock	<i>Mytilus edulis</i>
A4.242: Musculus discors beds on moderately exposed circalittoral rock	
A4.3: Atlantic and Mediterranean low energy circalittoral rock	
A4.31: Brachiopod and ascidian communities on circalittoral rock	
A4.311: Solitary ascidians, including Ascidia mentula and Ciona intestinalis, on wave-sheltered circalittoral rock	<i>Ascidia mentula</i> and <i>Ciona intestinalis</i>
A4.312: Large solitary ascidians and erect sponges on wave-sheltered circalittoral rock	
A4.313: Antedon spp., solitary ascidians and fine hydroids on sheltered circalittoral rock	<i>Antedon bifida</i> , <i>Antedon petasus</i>
A4.314; Neocrania anomala and Protanthea simplex on sheltered circalittoral rock	<i>Novocrania anomala</i>
Additional biotopes	
A3.3134 Grazed Laminaria saccharina with Echinus, brittlestars and coralline crusts on sheltered infralittoral rock	<i>Echinus esculentus</i>
A1.444 Audouinella purpurea and Cladophora rupestris on upper to mid-shore cave walls.	<i>Cladophora rupestris</i>
A1.122 Corallina officinalis on exposed to moderately exposed lower eulittoral rock.	<i>Corallina officinalis</i>
A4.111 Balanus crenatus and Tubularia indivisa on extremely tide-swept circalittoral rock.	<i>Balanus crenatus</i>

Tab 33. Species information obtained from Marine Institute reports (Tillin Hull 2013a-e) used to assess sensitivity of biological assemblages to pressures within this project.

Polychaetes	Algae	Molluscs
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<i>Lumbrineris latreilli</i>	<i>Halydris siliquosa</i>	<i>Abra alba</i>
<i>Magelona filiformis</i>	<i>Laminaria digitata</i>	<i>Abra nitida</i>
<i>Protodorvillea kefersteini</i>	<i>Laminaria hyperborean</i>	<i>Cerastoderma edule</i>
<i>Pholoe inornata</i>	<i>Laminaria saccharina</i>	<i>Fabulina fabula</i>
<i>Glycera alba</i>	Porifera	<i>Macoma balthica</i>
<i>Glycera lapidum</i>	<i>Halichondria panicea</i>	<i>Mysella bidentata</i>
<i>Hediste diversicolor</i>	Oligochaetes	<i>Nucula turgida</i>
<i>Nephtys cirrosa</i>	<i>Tubificoides benedii</i>	<i>Nucula nitidosa</i>
<i>Nephtys hombergii</i>	<i>Tubificoides pseudogaster</i>	<i>Phaxas pellucidus</i>
<i>Arenicola marina</i>	Amphipods	<i>Thracia papyracea</i>
<i>Capitella capitata</i>	<i>Ampelisca brevicornis</i>	<i>Thyasira flexuosa</i>
<i>Scoloplos armiger</i>	<i>Ampelisca typica</i>	<i>Timoclea ovata</i>
<i>Euclymene oerstedii</i>	<i>Bathyporeia sp</i>	<i>Venerupis senegalensis</i>
<i>Clymenura leiopygous</i>	<i>Corophium volutator</i>	
<i>Heteroclymene robusta</i>	Echinodermata	
<i>Owenia fusiformis</i>	<i>Echinus esculentus</i>	
<i>Pomatoceros lamarkii</i>	Cnidaria	
<i>Pomatoceros triqueter</i>	<i>Metridium senile</i>	
<i>Prionospio</i>	<i>Caryophyllia smithi</i>	
<i>Prionospio fallax</i>	<i>Alcyonium digitatum</i>	
<i>Pygospio elegans</i>		
<i>Spio filicornis</i>		
<i>Spio martinensis</i>		
<i>Spiophanes bombyx</i>		
<i>Streblospio shrubsolii</i>		
<i>Melinna palmata</i>		
<i>Lanice conchilega</i>		

Table 34. Ecological groups and representative species from previous JNCC work (Tillin & Tyler-Walters, 2014) used to assess sensitivity of biological assemblages to pressures within this project.

Ecological group	Key or characterising species assessed
1(a) Erect, longer-lived epifaunal species with some flexibility	<i>Virgularia mirabilis</i>
1 (b) Erect, shorter lived epifaunal species.	<i>Obelia longissima</i> <i>Sertularia argentea</i> <i>Nemertesia ramosa</i>
1 (c) Soft-bodied epifaunal species	<i>Alcyonium digitatum</i> <i>Flustra foliacea</i> <i>Ascidella aspera</i> <i>Styela gelatinosa</i> <i>Urticina felina</i>
1 (d) Small epifaunal species with hard or protected bodies.	<i>Balanus crenatus</i> <i>Pomatoceros triqueter</i>
2 Temporary or permanently attached surface dwelling or shallowly buried larger bivalves.	<i>Pecten maximus</i> <i>Modiolus modiolus</i>
3 Mobile predators and scavengers	<i>Asterias rubens</i> <i>Astropecten irregularis</i> <i>Pagurus bernhardus</i>

Ecological group	Key or characterising species assessed
4 Infaunal very small to medium sized suspension and/or deposit feeding bivalves	<i>Abra alba</i> (as <i>Abra</i> spp.) <i>Abra prismatica</i> (as <i>Abra</i> spp.) <i>Phaxas pellucidus</i> <i>Timoclea ovata</i> <i>Thyasira flexuosa</i>
5. Small- medium suspension and/or deposit feeding polychaetes	<i>Ampharete falcata</i> <i>Caulleriella zetlandica</i> <i>Lanice conchilega</i> <i>Polydora caulleryi</i> <i>Scoloplos armiger</i>
6. Predatory polychaetes	<i>Glycera lapidum</i> <i>Nephtys hombergii</i> <i>Protodorvillea kefersteini</i>
7 Very small-small, short lived (<2 years) free-living species	<i>Bathyporeia elegans</i> <i>Eudorellopsis Deformis</i> . <i>Iphinoe trispinosa</i>
8a Echinoderms – Subsurface dwelling echinoids	<i>Brissopsis lyrifera</i> <i>Echinocyamus pusillus</i> <i>Echinocardium cordatum</i>
8b Surface dwelling echinoids	<i>Echinus esculentus</i>
8c Free living interface suspension/deposit feeders: Ophiuroidea	<i>Ophiura albida</i> <i>Amphiura filiformis</i> <i>Ophicomina nigra</i> <i>Ophiothrix fragilis</i>
8d Large burrowing Holothuroidea	<i>Neopentadactyla mixta</i>
9 Burrowing, hard bodied species	<i>Calocaris macandrae</i> <i>Nephrops norvegicus</i>
10 Soft bodied species	<i>Branchiostoma lanceolatum</i> <i>Cerianthus lloydii</i> <i>Maxmuelleria lankesteri</i>

Appendix 8 Pressure proformas

Proforma 1 Habitat structure changes - removal of substratum (extraction)

Proforma 1	Habitat structure changes - removal of substratum (extraction)											
ICG pressure description Unlike the "physical change" pressure type where there is a permanent change in sea bed type (e.g. sand to gravel, sediment to a hard artificial substrate) the "habitat structure change" pressure type relates to temporary and/or reversible change, e.g. from mineral extraction where a proportion of seabed sands or gravels are removed but a residual layer of seabed is similar to the pre-dredge structure and as such biological communities could re-colonise; navigation dredging to maintain channels where the silts or sands removed are replaced by non-anthropogenic mechanisms so the sediment typology is not changed												
Pressure benchmark from Tillin <i>et al.</i> (2010) and subsequently revised by Tillin & Tyler-Walters (2014; 2015a&b) in liaison with the UK SNCBs												
Extraction of substratum to 30 cm (where substratum includes sediments and soft rocks but excludes hard bedrock)												
Links to other pressures This pressure may result in other pressures which are assessed separately; these include physical change to sediment type where the sediments uncovered are different to those removed or recovery results in a different sediment type through, for example, differences in flow regime or sediment supply (see physical change to another seabed type). Sediment disturbance may also lead to re-suspension of sediments (see change in suspended solids) and subsequent sediment deposition (see siltation rate changes).												
Activities that contribute to this pressure												
Category: Extraction (and disposal) of non-living resources			Pressure benchmark		Confidence							
Activity: footprint (scale), duration of pressure, impact, recovery			<	=	>	H M L						
Aggregate Dredging: Direct impacts on the seabed are typically local, confined to dredge pits (static) (20m deep x 75m diameter), or tracks/furrows (trailer suction) (4-6m long x 0.1-5m wide x 0.3-0.5m deep) (Kenny and Rees, 1994; Boyd <i>et al</i> 2004; Rees, 2006; LeBot <i>et al</i> 2010; Hill <i>et al</i> 2011). Dredging is usually undertaken for 1 to 14 hours annually (Frojan <i>et al</i> 2001), with reports of a site being dredged for up to 25 years (Hill <i>et al</i> 2011). Recovery of furrows is apparent in areas of high natural disturbance (Bellew and Drabble, 2004; Hill <i>et al</i> 2011). Boyd <i>et al</i> (2004), reported recovery of dredge tracks (0.3-0.5 m deep) in 8 months, whereas Bellew and Drabble (2004) suggest a recovery time of 2-4 years												
Category: Other man-made structures												
Cables and Pipelines Construction: Construction of cables and pipelines generally involves pre-operational 'sweeping' of the seafloor, trenching or ploughing the sediment, and cable installation and burial. Operation and Maintenance: During operation, scouring or strumming can cause abrasion on the seafloor. Maintenance can include the reburial and repairing of cables and pipelines. Decommissioning: Varies depending on the scenario, can												

involve removal, cutting, or burial							
Category: Energy generation							
Offshore Windfarms							
Construction: The construction stage of offshore windfarms depends on the scenario, but typically involves preparation of the seabed, drilling and pile driving, rock placement and cable laying, and scour protection placement, which can all impact the seafloor.							
Operation and Maintenance: Offshore windfarm operation doesn't tend to cause abrasion but can influence wave exposure changes and siltation changes. Maintenance can involve placement of additional scour protection, and rock, and dredging.							
Decommissioning: This stage is dependent on the scenario, but often involves rock placement, dredging, and the removal of structures.							
Oil and Gas							
Impacts on the seabed from oil and gas platforms are most evident during the construction and decommissioning phases. The impact footprint will depend on the size of the platform, but indirect impacts have been detected 1-2km from platforms (Cordes <i>et al</i> 2016).							
Construction: Construction of an oil and gas platform involves a multitude of subsea operations, including seabed levelling, trenching, jetting, structure placement, and rock dumps. There is limited literature detailing the length of the construction phase.							
Operation and Maintenance: Subsea operations involved in the operation and maintenance of an oil and gas platform include drilling, blasting and flaring. The duration of pressure will be scenario specific, however offshore structures are designed for lifetimes of 25 years (Sadeghi, 2007).							
Decommissioning: Decommissioning of and oil and gas platform is scenario specific; subsea operations can include: removal of cuttings, infrastructure, mattresses, and pipelines. The duration of pressure from decommissioning will be scenario specific; there is one study relating to a 15-year decommissioning programme for a 13-platform facility in the Norwegian North Sea (ConocoPhillips, 1999; Ekins <i>et al</i> 2006).							
Extraction of living resources: Fishing							
Regional to global drivers							
Evidence							
Climate	Not relevant. These activities do not directly impact on climate but will increase CO2 emissions through associated human activity. For example, the extraction, processing and burning of oil and gas to provide energy is very energy intensive resulting in high levels of associated carbon dioxide (CO ₂) emissions and concern over climate change impacts (Saunders, 2010). Marine aggregate dredging contributes to emissions of greenhouse gases through shipping and indirectly through downstream production activities (Saunders, 2010)						
Depth	Aggregate Dredging: In areas of high intensity trailer suction						

	dredging, the seabed can be lowered by 2-3m, and up to 5m over a number of years (Desprez, 2000; Tillin <i>et al</i> 2011). Infilling will support recovery.			
Geology	Aggregate Dredging: Removal of sand from aggregate dredging (without screening) typically leads to a coarser sediment composition, when gravel deposits are exposed (LeBot <i>et al</i> 2010; Hill <i>et al</i> 2011). During gravel extraction sediments may become finer; a similar change in composition is also observed when screening is used, to return fine sediments back to the seabed (Hill <i>et al</i> 2011). Infilling of the dredge furrows and pits by small particulate matter can also occur with reduced current velocity, leading to a decrease in sediment size (Hill <i>et al</i> 2011).			
Propagule Supply	Changes in spawning grounds			
Water Currents	Aggregate Dredging: Changes to topography as a result of substratum removal can lead to a change in bottom hydrography (Rees, 2006; OSPAR 2009), with observations of a drop in current strength from creation of depressions in the seafloor (Desprez, 2000).			
Wave Exposure	Aggregate Dredging: Evidence suggests that changes to wave exposure may be small and localised, with minimal changes in wave energy at the adjacent seabed or coastline (Brampton and Evans, 1998; Houghton <i>et al</i> 2011). Newell and Woodcock (2013) suggest that aggregate dredging on sand or gravel banks will result in lowered crest level, with potentially reduced wave dissipation across the feature.			
2 Water Column Processes				
Evidence				
Primary production	Not relevant to extraction but see changes in suspended sediment			
Suspended Sediment	See Proforma x (suspended sediment) Aggregate Dredging: Turbid plumes can be generated near the seabed by mechanical agitation, and close to the surface by over flow, and screening (LeBot <i>et al</i> 2010).			
	Oil and Gas Decommissioning: Activities involved in the decommissioning of an oil and gas platform, can result in the resuspension of fine sediments (Ivensen, 2009).			
Light Attenuation	See Proforma xX (suspended sediment)			
Water Chemistry and temperature	Not relevant to extraction but see changes in suspended sediment			
Dissolved oxygen	Not relevant to extraction but see changes in suspended sediment			
Sublittoral Sediment (topography)	Aggregate Dredging: Changes in topography from sediment extraction include the creation of furrows and dredge tracks in the sediment (Kenny and Rees, 1994; Boyd <i>et al</i> 2004; Cooper <i>et al</i> 2005, 2007a, 2007b; Hill <i>et al</i> 2011, Tillin <i>et al</i> 2011), and deep pits when static suction dredging has been used (Newell and Woodcock, 2013). Sediment instability associated with furrow infilling can also result from dredging			

	and have negative impacts on biological communities (Hill <i>et al</i> 2011). In areas of high intensity dredging with screening, creation of large sand waves can result; Hill <i>et al</i> (2011) observed 10m high sand waves, 200x400m wide. However, when substratum extraction is undertaken without screening, the lowering of sandbanks can result, removing coastal protection (Tillin <i>et al</i> 2011).			
	Cables and Pipelines Construction: Trenching for outflow pipes and cables can result in changes to seabed topography, with trenches 1.3m wide x 1.3m deep for offshore windfarm cables (Ludwig <i>et al</i> 1998; Taormina <i>et al</i> 2018).			
	Offshore Windfarms Construction: Loss of sublittoral habitat in the immediate area where turbines are placed (Sanders <i>et al</i> 2017).			
	Oil and Gas Construction: During pipeline installation trenches are dug into the seabed, causing seabed disturbance up to 20m from the pipeline (Iverson, 2009). Operation: Upheaval bucking of pipelines, or the development of free spans below the pipeline can result in seabed disturbance (Iverson, 2009).			
3 Local Processes/Inputs at the seabed				
Evidence				
Food Sources	Removed			
Grazing and predation	Reduced			
Seabed Mobility	No evidence. Will depend on site specific geology. More or less stable underlying habitats may be exposed by extraction.			
Recruitment	May begin rapidly after removal. Recovery of many benthic invertebrate populations will depend on new juvenile recruits settling at the location in the form of larvae rather than the migration of adults.			
4. Habitat and Biological assemblages				
See Sensitivity Assessment spreadsheets. The direct impact of sediment extraction on the benthic assemblage will be the removal of benthic organisms reducing the structure (abundance, biomass and diversity) of that habitat. Some individuals may survive entrainment and be returned to the sea in the outwash or during screening although heavily shelled species such as bivalves, snails and crabs are more likely to be retained within the hopper and therefore would be lost with the cargo.				
Sedimentary communities are likely to be highly intolerant of substratum removal, which will lead to partial or complete defaunation, and lead to changes in the topography of the area (Dernie, K. M. <i>et al</i> . 2003). Any remaining species, given their new position at the sediment / water interface, may be exposed to conditions to which they are not suited, i.e. unfavourable conditions. Newell <i>et al</i> (1998) stated that removal of 0.5m depth of sediment is likely to eliminate benthos from the affected area. Some epifaunal and swimming species may be able to avoid this pressure				
5 Output processes				
Evidence				
Biodeposition	Input from BBN			
Hydrodynamic	Input from BBN			

flow				
Bioturbation	Input from BBN			
Primary production	Input from BBN			
Secondary production	Input from BBN			
Sediment processing				
Habitat modification				
Supply of propagules	The settlement of many benthic species larvae has been demonstrated to be influenced by chemical cues from the same species or prey species or biofilms (Pawlik, J. R. 1992, Rodriguez, S. R. et al. 1993). By removing surficial deposits, the dredging process is likely to remove these cues inhibiting settlement rates within the dredging zone.			
6. Local ecosystem functions				
Evidence				
Food resource	Aggregate sediment plumes are rich in organic matter, most likely from fragments of dead or dying invertebrates (Newell, R. et al. 1998) and attract mobile predators to feed in the dredge tracks.			
Nutrient cycling	Likely to be negatively impacted			
Biogeochemical cycling	Likely to be negatively impacted			
Sediment stability	Likely to be negatively impacted			
Habitat provision	The damage inflicted upon nursery habitats by fishing gears (removal of epifauna and complex habitats) has been shown to negatively impact scallop recruitment (Collie <i>et al.</i> 1997; Bradshaw <i>et al.</i> 2002), whilst the protection of nursery habitats has been shown to dramatically enhance scallop settlement levels.			
Microbial activity	Not assessed. No evidence			
7. Regional to Global Ecosystem Functions				
Biodiversity Enhancement	Unlikely to result from pressure. Few benthic invertebrates are able to escape entrainment from aggregate dredging and research shows that under the path of an aggregate extraction draghead there is a 30-70% reduction in species diversity, a 40-95% reduction in the number of individuals and a similar reduction in biomass of benthic communities (Newell <i>et al</i> 1998).			
Biotope Stability	Unlikely to result from pressure			
Export of Biodiversity	Unlikely to result from pressure			
Export of Organic Matter	It is likely that high levels of fatal damage are suffered and sediment plumes from aggregate extraction are rich in organic matter, most likely from fragments of dead or dying invertebrates (Newell, R. et al. 1998).			

Knowledge Gaps	

Proforma 2 Abrasion/disturbance of the substratum on the surface of the seabed

Pressure	Abrasion/disturbance of the substratum on the surface of the seabed					
ICG pressure description Physical disturbance or abrasion at the surface of the substratum in sedimentary or rocky habitats. The effects are relevant to epiflora and epifauna living on the surface of the substratum. In intertidal and sublittoral fringe habitats, surface abrasion is likely to result from recreational access and trampling (inc. climbing) by human or livestock, vehicular access, moorings (ropes, chains), activities that increase scour and grounding of vessels (deliberate or accidental). In the sublittoral, surface abrasion is likely to result from pots or creels, cables and chains associated with fixed gears and moorings, anchoring of recreational vessels, objects placed on the seabed such as the legs of jack-up barges, harvesting of seaweeds (e.g. kelps) or other intertidal species (trampling) or of epifaunal species (e.g. oysters). In sublittoral habitats, passing bottom gear (e.g. rock hopper gear) may also cause surface abrasion to epifaunal and epifloral communities, including epifaunal biogenic reef communities. Activities associated with surface abrasion can cover relatively large spatial areas e.g. bottom trawls or bio-prospecting or be relatively localized activities e.g. seaweed harvesting, recreation, potting, and aquaculture.						
Pressure benchmark from Tillin <i>et al.</i> (2010) and subsequently revised by Tillin & Tyler-Walters (2014; 2015a&b) in liaison with the UK SNCBs						
Damage to surface features (e.g. species and physical structures within the habitat)						
Activities that contribute to this pressure						
Category: Extraction (and disposal) of non-living resources	Pressure benchmark			Confidence		
Activity: footprint (scale), duration of pressure, impact, recovery	>	=	<	H	M	L
Aggregate Dredging: Direct impacts on the seabed are typically local, confined to dredge pits (static) (20m deep x 75m diameter), or tracks/furrows (trailer suction) (4-6m long x 0.1-5m wide x 0.3-0.5m deep) (Kenny and Rees,1994; Boyd <i>et al</i> 2004; Rees, 2006; LeBot <i>et al</i> 2010; Hill <i>et al</i> 2011). Dredging is usually undertaken for 1 to 14 hours annually (Frojan <i>et al</i> 2001), with reports of a site being dredged for up to 25 years (Hill <i>et al</i> 2011). Recovery of furrows is apparent in areas of high natural disturbance (Bellew and Drabble, 2004; Hill <i>et al</i> 2011). Boyd <i>et al</i> (2004), reported recovery of dredge tracks (0.3-0.5 m deep) in 8 months, whereas Bellew and Drabble (2004) suggest a recovery time of 2-4 years.						
Category: Transport						
Recreational and Commercial Anchoring: The footprint of abrasion from anchoring is dependent on the length, size and weight of the chain deployed, and environmental conditions (Tillin <i>et al</i> 2017). The pressure duration is dependent on the scenario but is generally short term (<1 week) (Griffiths <i>et al</i> 2017), there is little information on the duration of impact or recovery of the sites.						
Recreational and Commercial Mooring: Observed mooring scars range from 3m ² to 300m ² depending on the size and structure of the mooring, and prevailing environmental conditions (Walker <i>et al</i> 1989; Griffiths <i>et al</i> 2017). Disturbance is localised, within and immediately around the anchor chain						

footprint (Keenan <i>et al</i> 2012). Duration of mooring pressures generally last over 1 year (Latham <i>et al</i> in prep; Herbert <i>et al</i> 2009), with impacts still apparent after 15 months (Herbert <i>et al</i> 2009). There is limited literature detailing recovery of sites after mooring.						
Category: Extraction of living resources						
Fishing- dredging: <i>will need adding</i>						
Category: Other man-made structures						
Cables and Pipelines Construction: Construction of cables and pipelines generally involves pre-operational 'sweeping' of the seafloor, trenching or ploughing the sediment, and cable installation and burial. Operation and Maintenance: During operation, scouring or strumming can cause abrasion on the seafloor. Maintenance can include the reburial and repairing of cables and pipelines. Decommissioning: Varies depending on the scenario, can involve removal, cutting, or burial.						
Category: Energy generation						
Offshore Windfarms Construction: The construction stage of offshore windfarms depends on the scenario, but typically involves preparation of the seabed, drilling and pile driving, rock placement and cable laying, and scour protection placement, which can all impact the seafloor. Operation and Maintenance: Offshore windfarm operation doesn't tend to cause abrasion but can influence wave exposure changes and siltation changes. Maintenance can involve placement of additional scour protection, and rock, and dredging. Decommissioning: This stage is dependent on the scenario, but often involves rock placement, dredging, and the removal of structures.						
Oil and Gas Impacts on the seabed from oil and gas platforms are most evident during the construction and decommissioning phases. The impact footprint will depend on the size of the platform, but indirect impacts have been detected 1-2km from platforms (Cordes <i>et al</i> 2016). Construction: Construction of an oil and gas platform involves a multitude of subsea operations, including seabed levelling, trenching, jetting, structure placement, and rock dumps. There is limited literature detailing the length of the construction phase. Operation and Maintenance: Subsea operations involved in the operation and maintenance of an oil and gas platform include drilling, blasting and flaring. The duration of pressure will be scenario specific, however offshore structures are designed for lifetimes of 25 years (Sadeghi, 2007). Decommissioning: Decommissioning of and oil and gas platform is scenario specific; subsea operations can include: removal of cuttings, infrastructure, mattresses, and pipelines. The duration of pressure from decommissioning will be scenario specific; there is one study relating to a 15 year decommissioning programme						

for a 13 platform facility in the Norwegian North Sea (ConocoPhillips, 1999; Ekins <i>et al</i> 2006).							
Category: Research							
Physical Sampling: Physical sampling can refer to a multitude of activities, including dredging, grabs, coring and sediment profile imaging. The pressure durations are typically short term, and the magnitude of impact dependant on the sampling technique. There is limited literature on the recovery from these pressures.							
Regional to global drivers							
Evidence							
Climate							
Depth	Aggregate Dredging: In areas of high intensity trailer suction dredging, the seabed can be lowered by 2-3m, and up to 5m over a number of years (Desprez, 2000; Tillin <i>et al</i> 2011). Fishing: Watling <i>et al</i> (2001) observed a loss of top few cm of the fine fraction of the upper sediment layers, shortly after scallop dredging. Offshore Windfarms Operation and Maintenance: Seafloor depth around tripods and jackets has been found to be lowered by over 3m and 1m respectively, as a result of scouring processes (Krone <i>et al</i> 2017).						
Geology	Aggregate Dredging: Frojan <i>et al</i> (2001) reported greater proportion of coarse and medium sand and dredged sites (with screening), than reference sites where dredging had not occurred. Fishing- dredging: Increase in coarseness of sediments after scallop dredging (Watling <i>et al</i> 2001).						
Propagule Supply							
Water Currents	Aggregate Dredging: Changes to topography and reductions in the depth of the seabed may have an impact on the local hydrodynamic regime, disrupting local current strengths and altering patterns of sedimentation (Tillin <i>et al</i> 2011).						
Wave Exposure	Aggregate Dredging: In areas of high intensity trailer suction dredging, the seabed can be lowered by 2-3 m (Desprez, 2000), this can lead to changes in wave exposure						
2 Water Column Processes							
Evidence							
Primary production	Not relevant (see suspended sediment)						
Suspended Sediment	See Proforma x (suspended sediment) Aggregate Dredging: Changes to topography and reductions in the depth of the seabed may have an impact on patterns of sedimentation (Tillin <i>et al</i> 2011).						
	Fishing: Resuspension of fine particles during scallop dredging (Watling <i>et al</i> 2001).						
	Cables and Pipelines Construction: Trenching for cable laying leads to an increase in suspended sediment in the water column, up to 200m from the site (Seacon, 2005). Using 'jetting' for the burial of cables and pipelines can lead to an increase in suspended sediment (Carter <i>et al</i> 2009).						

	Decommissioning: Removal of cables abrades the seabed and re-suspends sediment into the water column (Meißner <i>et al</i> 2006; Carter <i>et al</i> 2009).			
Light Attenuation	See Proforma X (suspended sediment)			
Water Chemistry and temperature	Oil and Gas Decommissioning: During decommissioning, if cutting piles are left in-situ and covered, the area can become exposed to trawling, which can re-suspend contaminants within the cutting piles (Ekins <i>et al</i> 2006).			
Dissolved oxygen				
Sublittoral Sediment (topography)	Aggregate Dredging: Abrasion from aggregate dredging from trailer suction dredges leads to the creation of dredge tracks or furrows in the sediment (Kenny and Rees, 1994; Boyd <i>et al</i> 2004; Rees, 2006; LeBot <i>et al</i> 2010; Hill <i>et al</i> 2011).			
	Recreational and Commercial Anchoring: Abrasion can occur on the seafloor when the anchor drags across the substratum in response to tidal changes or wind, the anchor may also move sideways 'crabbing' the sediment, abrasion can also occur during the retrieval of the anchor (Abdullah, 2008; Griffiths <i>et al</i> 2017). Commercial anchoring by large tankers leaves significant disturbance at the sites, with ridges and furrows formed, and accumulations of disturbed sediment (Keenan <i>et al</i> 2012).			
	Recreational and Commercial Mooring: Herbert <i>et al</i> (2009) and Latham <i>et al</i> (in prep) report no obvious changes in topography in areas impacted by mooring buoys for over a year.			
	Cables and Pipelines Construction: Ploughing for cable laying abrades the seabed and can leave a ploughed strip c.0.3m wide, the skids that support the plough can also leave a footprint on the seabed in soft substrates (Carter <i>et al</i> 2009). Operation and maintenance: Cable strumming from nearshore wave action can cause incisions in rocky outcrops (Kogan <i>et al</i> 2006; Taormina <i>et al</i> 2018). On rare occasions cables need reburial or repair, such activities can cause abrasion on the seabed (Berr, 2008).			
	Offshore Windfarms Operation and Maintenance: Contrasting evidence on operational abrasion has been found, with evidence of scouring around the foundations reported (Whitehouse <i>et al</i> 2011; Christie <i>et al</i> 2012), and evidence of minimal negative impact on the marine environment observed by Byrne and Firm (2000).			
	Oil and Gas Decommissioning: The process of decommissioning an offshore windfarm can vary and is dependent on the scenario. Activities undertaken during this stage that cause abrasion on the seafloor include: <ul style="list-style-type: none"> - Covering contaminated drill cuttings - Leaving structures in place, and monitoring of site (impacts 			

	<p>are minimal)</p> <ul style="list-style-type: none"> - Removal of cuttings with a suction dredge - Removal of footings with cuttings left in place - Covering pipelines with rocks (Ekins <i>et al</i> 2006). 			
	<p>Physical Sampling: Techniques that cause abrasion on the seabed include:</p> <ul style="list-style-type: none"> - Subtidal Biotope ID (using divers), deployment of a weighted shotline, with small anchor - Towed camera sledge (transects typically 100-250m) - Box coring 			
3 Local Processes/Inputs at the seabed				
Evidence				
Food Sources				
Detritus				
Carrion				
Living prey				
Phytobenthos incl. diatoms				
Bacteria. Microorganisms, fungi				
Macroalgae				
Grazing and predation				
Particulate organic matter				
Seabed Mobility				
Recruitment				
4. Habitat and Biological assemblages				
See Sensitivity Assessment spreadsheets.				
5 Output processes				
Evidence				
Biodeposition				
Bioengineering				
Hydrodynamic flow				
Bioturbation				
Primary production				
Secondary production				
Sediment processing				
Habitat modification				
Supply of propagules	The damage inflicted upon nursery habitats by fishing gears (removal of epifauna and complex habitats) has been shown to negatively impact scallop recruitment (Collie <i>et al.</i> 1997; Bradshaw <i>et al.</i> 2002), whilst the protection of nursery habitats has been shown to dramatically enhance scallop settlement levels (Howarth <i>et al</i> 2014).			

6. Local ecosystem functions				
Evidence				
Food Resources				
Habitat Provision				
Microbial Activity Enhancement				
Nutrient Cycling				
Population Control	The damage inflicted upon nursery habitats by fishing gears (removal of epifauna and complex habitats) has been shown to negatively impact scallop recruitment (Collie <i>et al.</i> 1997; Bradshaw <i>et al.</i> 2002), whilst the protection of nursery habitats has been shown to dramatically enhance scallop settlement levels.			
Sediment Stability				
Knowledge Gaps				

Proforma 3 Penetration and/or disturbance of the substratum below the surface of the seabed, including abrasion

Proforma 3		Penetration and/or disturbance of the substrate below the surface of the seabed, including abrasion					
ICG pressure description The disturbance of sediments where there is limited or no loss of substrate from the system. This pressure is associated with activities such as anchoring, taking of sediment/geological cores, cone penetration tests, cable burial (ploughing or jetting), propeller wash from vessels, certain fishing activities, e.g. scallop dredging, beam trawling. Agitation dredging, where sediments are deliberately disturbed by and by gravity & hydraulic dredging where sediments are deliberately disturbed and moved by currents could also be associated with this pressure type. Compression of sediments, e.g. from the legs of a jack-up barge could also fit into this pressure type. Abrasion relates to the damage of the sea bed surface layers (typically up to 50cm depth). Activities associated with abrasion can cover relatively large spatial areas and include: fishing with towed demersal trawls (fish & shellfish); bioprospecting such as harvesting of biogenic features such as maerl beds where, after extraction, conditions for recolonisation remain suitable or relatively localised activities including: seaweed harvesting, recreation, potting, aquaculture. Change from gravel to silt substrate would adversely affect herring spawning grounds.							
Links to other pressures. Sediment disturbance may also lead to the re-suspension of solids (see changes in suspended solids) and subsequent deposition which can result in changes to the substratum type.							
Pressure benchmark from Tillin <i>et al.</i> (2010) and subsequently revised by Tillin & Tyler-Walters (2014; 2015a&b) in liaison with the UK SNCBs.							
Damage to sub-surface features (e.g. species and physical structures within the habitat)							
Activities that contribute to this pressure							
Category: Transport				Pressure benchmark		Confidence	
Activity: footprint (scale), duration of pressure, impact, recovery				>	=	<	H M L
Recreational and Commercial Anchoring: The footprint of penetration from anchoring is dependent on the length, size and weight of the chain deployed, and environmental conditions (Tillin <i>et al</i> 2017). Commercial anchoring can penetrate to depths up to 9.2m in mud and silt, and 2.9m in sand (Griffiths <i>et al</i> 2017). The pressure duration is dependent on the scenario but is generally short term (<1 week) (Griffiths <i>et al</i> 2017), however there is little information on the duration of impact. Recovery of soft sediment topography after recreational anchoring has been observed after 6 months (Backhurst and Cole, 2000), however no recovery of a coral reef was observed 10 years after anchor penetration (Rogers and Garrison, 2001).							
Recreational and Commercial Mooring: Observed mooring scars range from 3m ² to 300m ² depending on the size and structure of the mooring, and prevailing environmental conditions (Walker <i>et al</i> 1989; Griffiths <i>et al</i> 2017). Disturbance is localised, within and immediately around the anchor chain footprint (Keenan <i>et al</i> 2012). Duration of mooring pressures							

generally last over 1 year (Latham <i>et al</i> in prep; Herbert <i>et al</i> 2009), with impacts still apparent after 15 months (Herbert <i>et al</i> 2009). There is limited literature detailing recovery of sites after mooring.						
Category: Other man-made structures						
Cables and Pipelines						
Construction: Construction of cables and pipelines generally involves pre-operational 'sweeping' of the seafloor, trenching or ploughing the sediment, and cable installation and burial.						
Operation and Maintenance: During operation, scouring or strumming can cause abrasion on the seafloor. Maintenance can include the reburial and repairing of cables and pipelines.						
Decommissioning: Varies depending on the scenario, can involve removal, cutting, or burial.						
Category: Energy generation						
Oil and Gas						
Impacts on the seabed from oil and gas platforms are most evident during the construction and decommissioning phases. The impact footprint will depend on the size of the platform, but indirect impacts have been detected 1-2km from platforms (Cordes <i>et al</i> 2016).						
Construction: Construction of an oil and gas platform involves a multitude of subsea operations, including seabed levelling, trenching, jetting, structure placement, and rock dumps. There is limited literature detailing the length of the construction phase.						
Operation and Maintenance:						
Subsea operations involved in the operation and maintenance of an oil and gas platform include drilling, blasting and flaring. The duration of pressure will be scenario specific, however offshore structures are designed for lifetimes of 25 years (Sadeghi, 2007).						
Decommissioning:						
Decommissioning of and oil and gas platform is scenario specific; subsea operations can include: removal of cuttings, infrastructure, mattresses, and pipelines. The duration of pressure from decommissioning will be scenario specific; there is one study relating to a 15-year decommissioning programme for a 13-platform facility in the Norwegian North Sea (ConocoPhillips, 1999; Ekins <i>et al</i> 2006).						
Category: Research						
Physical Sampling:						
Physical sampling can refer to a multitude of activities, including dredging, grabs, coring and sediment profile imaging. The pressure durations are typically short term, and the magnitude of impact dependant on the sampling technique. There is limited literature on the recovery from these pressures.						
Regional to global drivers						
Evidence						
Climate						
Depth						
Geology	Recreational and Commercial Mooring: Contrasting evidence on the impacts of recreational moorings on sediments, with observations of no obvious changes to the sediment composition (Latham <i>et al</i> in prep), and reports of					

	sediments favouring greater prominence of larger particles, such as gravel and shell fragments after a year of mooring in the sites (Herbert <i>et al</i> 2009).			
Propagule Supply				
Water Currents				
Wave Exposure				
2 Water Column Processes				
Evidence				
Primary production				
Suspended Sediment	Cables and Pipelines Construction: Cable laying, burial and protection can lead to an increase in suspended sediment (BERR, 2008). Drilling can lead to an increase in suspended sediments, detected 1000m downstream (Ulfesnes <i>et al</i> 2013). Decommissioning: Removal of cables and pipelines can lead to an increase in suspended sediment (Ekins <i>et al</i> 2006; BERR, 2008).			
Light Attenuation				
Water Chemistry and temperature				
Dissolved oxygen				
Sublittoral Sediment (topography)	Recreational and Commercial Anchoring: during anchor 'setting' penetration into the substratum can occur, disturbing sediments within its footprint. A poorly set anchor may drag through the sediment with vessel movement; penetration may also occur during anchor retrieval (Tillin <i>et al</i> 2017). Commercial anchor penetration into soft sediment can range from 0.19 to 0.88m, dependent on the anchor mass (Luger <i>et al</i> 2013), and create furrows with a maximum width of 5m, ridges and accumulations of disturbed sediment (Fader and Miller, 1990; Keenan <i>et al</i> 2012). Commercial 1t anchors deployed on coral reef habitats can create scars 128m x 3m wide (Rogers and Garrison, 2001).			
	Recreational and Commercial Mooring: No obvious changes in topography observed in intertidal muddy sediments after a year of recreational mooring (Herbert <i>et al</i> 2009; Latham <i>et al</i> in prep). In contrast, Smith <i>et al</i> (2017) observed a loss in structural complexity of the habitat after mooring impacts.			
	Cables and Pipelines Construction: Pre-operational sweeping on the seafloor by a ship towed grapnel penetrates between 0.5 and 1m into soft sediment (Carter <i>et al</i> 2009). Operation and Maintenance: Sediment penetration occurs during cable reburial or uncovering for repair (Merck and Wasserthal, 2009).			
	Oil and Gas			

	Construction: Direct impact on sediment at emplacement of export pipelines (Bakke <i>et al</i> 2013). Decommissioning: Activities that lead to changes in sediment topography: <ul style="list-style-type: none"> - Shallow disposal of topside and jacket (localised disturbance) - Removal of footings with cuttings in-situ - Recovery of pipelines (Ekins <i>et al</i> 2006) 			
	Physical Sampling: Techniques that cause penetration to the seabed include: <ul style="list-style-type: none"> - Sediment profile imaging- camera penetrates the sediment 2/3 the height of the face plate - Sublittoral coring- 			
3 Local Processes/Inputs at the seabed				
Evidence				
Food Sources				
Detritus				
Carrion				
Living prey				
Phytobenthos incl. diatoms				
Bacteria. Microorganisms, fungi				
Macroalgae				
Grazing and predation				
Particulate organic matter				
Seabed Mobility				
Recruitment				
4. Habitat and Biological assemblages				
<p>Abrasion and sub-surface damage can directly affect sedimentary habitats through impacts on the habitat substratum, particularly reduction of surface topography and habitat complexity (Gilkinson, K. D. et al. 2003, Nilsson, H. C. and Rosenberg, R. 2003). The direct physical impacts of this pressure on the ecological groups are considered in the sensitivity assessments.</p> <p>Substratum penetration and disturbance will directly impact organisms and may lead to damage that can be repaired or the contact may be lethal. Organisms, particularly small ones, may be moved within the sediment or pushed onto the surface either through direct contact or through movements of sediments, overturning of cobbles etc. Sub-surface damage operating over large spatial areas has the potential to directly alter the composition of the species assemblage and community structure (Kenchington, E. L. et al. 2007).</p> <p>The sensitivity of species to sub-surface abrasion is influenced by a number of biological traits. Size influenced the degree of damage suffered by by-catch caught in otter trawl hauls from the Clyde Sea <i>Nephrops</i> fishery grounds but the results were not consistent between species groups (Bergman, M. et al. 2001). Larger starfish and brittle stars suffered more damage than smaller individuals presumed to be due to the potential for damage over a larger body surface. Conversely, smaller <i>Buccinum undatum</i> and <i>Liocarcinus holsatus</i> suffered more damage, as these were thinner shelled and therefore less protected than larger individuals (Bergman, M. et al. 2001). Smaller species are generally less directly impacted (Bergman, M. J. N. and van Santbrink, J. W. 2000) as trawls and other sources of</p>				

sub-surface abrasion mainly impact smaller species through sediment disturbance- with an effect similar to storms and other natural disturbances to which these species are adapted. Species adapted to more mobile sediments would therefore be expected to have higher resistance and higher resilience to abrasion and sub-surface damage while those found in more stable sediments will be more sensitive. Larger species are exposed to direct physical impact of the gear due to their greater body surface. The impact is not comparable to natural disturbances. Habitat preferences will not influence sensitivity but may mediate impact factors such as the depth of penetration of the gears.

In summary, large, long-lived and fragile species are more sensitive to damage and their populations take longer to recover. Frequent disturbance therefore selects for smaller, less fragile organisms that have higher resistance to disturbance, through traits such as environmental position (infauna vs epifauna) and fragility (robust vs fragile). Size is also an important factor, as smaller organisms can pass through meshes or are pushed out of the way, although some smaller organisms are more vulnerable, as living closer to the surface means they are more exposed (Bergman and Hup, 1992). Size is also correlated with life history and smaller species are more likely to recover quickly due to their shorter life span and rapid life cycle.

Repeated disturbances may lead to the development of assemblages dominated by opportunistic species; typically deposit feeding polychaetes (Jennings and Kaiser, 1998, Rijnsdorp *et al* 1996, Jennings and Kaiser, 1998). Burrowing and tube dwelling infauna may be less affected than epifauna (Bullimore, 1985). Predators and scavengers may also benefit from disturbance and congregate in areas where disturbance has left macrofauna dead, injured or exposed (Kaiser and Spencer, 1996, Caddy, 1973, Kaiser and Spencer, 1994, Lindeboom and Groot, 1998). Overall the effect may be to change the composition of benthic assemblages in an area (Tillin *et al.* 2006).

5 Output processes

Evidence

Biodeposition	Biological traits analysis of species assemblages has identified a number of species traits which are linked to resistance. Tillin <i>et al.</i> (2006) found that epifauna, filter-feeders, attached and larger animals were more abundant in areas with lower levels of trawling, whereas areas with higher trawling levels had a greater abundance of mobile animals, scavengers and infauna.			
Bioengineering				
Hydrodynamic flow				
Bioturbation	Biological traits analysis of species assemblages has identified a number of species traits which are linked to resistance. Tillin <i>et al.</i> (2006) found that epifauna, filter-feeders, attached and larger animals were more abundant in areas with lower levels of trawling, whereas areas with higher trawling levels had a greater abundance of mobile animals, scavengers and infauna.			
Primary production				

Secondary production	Bolam <i>et al.</i> (2013) assessed the effects of fishing on secondary productivity, using size, morphology, living habit, sediment position and mobility as traits determining resistance to trawling. The study used longevity, development strategy (planktotrophic, lecithotrophic etc.) and egg development location (eggs shed into water column, brooded by adults etc.), to assess recovery/recolonisation.			
Sediment processing				
Habitat modification				
Supply of propagules				
6. Local ecosystem functions				
Evidence				
Food resource				
Nutrient cycling				
Biogeochemical cycling				
Sediment stability				
Habitat provision				
Microbial activity				
Biodeposition				
Bioturbation				
Knowledge Gaps				

Proforma 4 Smothering and siltation changes (depth of vertical sediment overburden) (light and heavy)

Pressure	Siltation rate changes, including smothering (depth of vertical sediment overburden)								
ICG pressure description When the natural rates of siltation are altered (increased or decreased). Siltation (or sedimentation) is the settling out of silt/sediments suspended in the water column. Activities associated with this pressure type include mariculture, land claim, navigation dredging, disposal at sea, marine mineral extraction, cable and pipeline laying and various construction activities. It can result in short lived sediment concentration gradients and the accumulation of sediments on the sea floor. “Light” smothering relates to the deposition of layers of sediment on the seabed. It is associated with activities such as sea disposal of dredged materials where sediments are deliberately deposited on the sea bed. For “light” smothering most benthic biota may be able to adapt, i .e. vertically migrate through the deposited sediment. “Heavy” smothering also relates to the Changes in siltation (e.g. by outfalls, increased run-off, dredging/disposal or dredge spoil) deposition of layers of sediment on the seabed but is associated with activities such as sea disposal of dredged materials where sediments are deliberately deposited on the sea bed.									
Pressure benchmark from Tillin <i>et al.</i> (2010) and subsequently revised by Tillin & Tyler-Walters (2014; 2015a&b) in liaison with the UK SNCBs.									
‘Light’ deposition of up to 5 cm of fine material added to the habitat in a single, discrete event ‘Heavy’ deposition of up to 30 cm of fine material added to the habitat in a single discrete event Siltation resulting from human activities occurs at the pressure benchmark when large amounts of material are placed on the seabed as in the disposal of capital and maintenance dredging. The disposal of sewage sludge may also result in thick deposits on the seabed. Aggregate dredging accompanied by screening (the process of discharging unwanted grades of sediment) may also lead to the deposition of sediment layers although this is unlikely to reach the benchmark level. Some siltation may also result from activities that lead to abrasion or disturbance of the seabed and consequent re-suspension of sediments that are transported and re-deposited. The activities will typically result in deposits much thinner than the pressure benchmark. Deposition of suspended sediments has two impacts on the seabed. Animals living in or on the seabed can be immediately smothered and buried, while the habitat change alters the character of the associated benthic assemblage (considered under the pressure ‘Physical change’).									
Activities that contribute to this pressure									
Category: Extraction (and disposal) of non-living resources				Pressure benchmark		Confidence			
Activity: footprint (scale), duration of pressure, impact, recovery				>	=	<	H	M	L
Aggregate Dredging: Direct impacts on the seabed are typically local, confined to dredge pits (static) (20m deep x 75m diameter), or tracks/furrows (trailer suction) (4-6m long x 0.1-5m wide x 0.3-0.5m deep) (Kenny and Rees,1994; Boyd <i>et al</i> 2004; Rees, 2006; LeBot <i>et al</i> 2010; Hill <i>et al</i> 2011). Dredging is usually undertaken for 1 to 14 hours annually (Frojan <i>et al</i> 2001), with reports of a site being dredged for up to 25 years (Hill <i>et al</i>									

2011). Recovery of furrows is apparent in areas of high natural disturbance (Bellew and Drabble, 2004; Hill <i>et al</i> 2011). Boyd <i>et al</i> (2004), reported recovery of dredge tracks (0.3-0.5 m deep) in 8 months, whereas Bellew and Drabble (2004) suggest a recovery time of 2-4 years.						
Category: Transport						
Recreational and Commercial Mooring: Observed mooring scars range from 3m ² to 300m ² depending on the size and structure of the mooring, and prevailing environmental conditions (Walker <i>et al</i> 1989; Griffiths <i>et al</i> 2017). Disturbance is localised, within and immediately around the anchor chain footprint (Keenan <i>et al</i> 2012). Duration of mooring pressures generally last over 1 year (Latham <i>et al</i> in prep; Herbert <i>et al</i> 2009), with impacts still apparent after 15 months (Herbert <i>et al</i> 2009). There is limited literature detailing recovery of sites after mooring.						
Need to add fishing pressures						
Category: Other man-made structures						
Cables and Pipelines Construction: Construction of cables and pipelines generally involves pre-operational 'sweeping' of the seafloor, trenching or ploughing the sediment, and cable installation and burial. Operation and Maintenance: During operation, scouring or strumming can cause abrasion on the seafloor. Maintenance can include the reburial and repairing of cables and pipelines. Decommissioning: Varies depending on the scenario, can involve removal, cutting, or burial						
Category: Energy generation						
Oil and Gas Impacts on the seabed from oil and gas platforms are most evident during the construction and decommissioning phases. The impact footprint will depend on the size of the platform, but indirect impacts have been detected 1-2km from platforms (Cordes <i>et al</i> 2016). Construction: Construction of an oil and gas platform involves a multitude of subsea operations, including seabed levelling, trenching, jetting, structure placement, and rock dumps. There is limited literature detailing the length of the construction phase. Operation and Maintenance: Subsea operations involved in the operation and maintenance of an oil and gas platform include drilling, blasting and flaring. The duration of pressure will be scenario specific, however offshore structures are designed for lifetimes of 25 years (Sadeghi, 2007). Decommissioning: Decommissioning of an oil and gas platform is scenario specific; subsea operations can include: removal of cuttings, infrastructure, mattresses, and pipelines. The duration of pressure from decommissioning will be scenario specific; there is one study relating to a 15-year decommissioning programme for a 13 platform facility in the Norwegian North Sea (ConocoPhillips, 1999; Ekins <i>et al</i> 2006).						
Regional to global drivers						
Evidence						

Climate				
Depth				
Geology	Aggregate Dredging: High intensity dredging with screening, can lead to heavily siltation, and a fining of sediments (Hill <i>et al</i> 2011). A change in sediment composition to smaller grain sizes (clay/silt) also results from the disposal of dredged sediments into the water column (OSPAR, 2008).			
Propagule Supply				
Water Currents	Aggregate Dredging: The creation of furrows and pits can change current velocity, this can lead to the deposition of small particles onto the seabed (Hill <i>et al</i> 2011; Tillin <i>et al</i> 2011).			
Wave Exposure				
2 Water Column Processes				
Evidence				
Primary production				
Suspended Sediment	Aggregate Dredging: the disposal of dredge materials into the water column leads to an increase in suspended sediment, and siltation on the seafloor (OSPAR Commission, 1998).			
	Recreational and Commercial Mooring: Mooring abrasion can lead to the resuspension of particles, which can smother associated flora and fauna, causing damage and mortality (Smith <i>et al</i> 2017).			
	Cables and Pipelines Construction: Operations including cable laying, burial and protection, and the maintenance and construction of outfall pipes can all cause localised heavy sediment resuspension (Ludwig, 1998; BERR, 2008). Smothering of coral structures was observed along a 100m corridor (Ulfsnes <i>et al</i> 2013). Operation and Maintenance: Cable reburial or uncovering for repair, and pipeline outflow discharge can all cause localised heavy sediment resuspension (Ludwig, 1998; BERR, 2008). Pipeline structures can also cause changes in hydrodynamics which can cause heavy siltation (Ludwig, 1998). Decommissioning: During cable uncovering spoil from the trench excavation smothers the adjacent seabed, and significant sedimentation can occur from increased suspended sediment (generally cables are left in place) (BERR, 2008).			
	Oil and Gas Construction: Pipeline installation into can mobilise sediments into suspension (Iverson, 2009). Operation: Suspended sediment can have an impact of 100-500m from the platform (Cordes <i>et al</i> 2016). Decommissioning: Excavation of drill cuttings using jetting can resuspend sediments.			
Light Attenuation				
Water				

Chemistry and temperature				
Dissolved oxygen				
Sublittoral Sediment (topography)	Aggregate Dredging: Heavy siltation from screening can lead to the infilling of dredging furrows (Hill <i>et al</i> 2011).			
3 Local Processes/Inputs at the seabed				
Evidence				
Food Sources				
Detritus				
Carrion				
Living prey				
Phytobenthos incl. diatoms				
Bacteria. Microorganisms, fungi				
Macroalgae				
Grazing and predation				
Particulate organic matter				
Seabed Mobility				
Recruitment	The first organisms to recolonise dredged material usually are not the same as those that originally occupied the site. They consist of opportunistic species whose environmental requirements are flexible enough to allow them to occupy the disturbed areas. Trends toward re-establishment of the original community are often noted within a year or two (Blanchard, A. L. and Feder, H. M. 2003). The general recolonisation pattern is often dependent upon the nature of the adjacent undisturbed community, which provides a pool of replacement organisms capable of recolonising the site by adult migration, passive advection, or larval recruitment.			
4. Habitat and Biological assemblages				
<p>See Sensitivity Assessment spreadsheets. Most benthic organisms live in the top 10cm of the seabed and must maintain some connection to the sediment-water interface for ventilation and feeding (Miller, D. C. et al. 2002). Organisms have various capabilities for moving upward through newly deposited sediments, such as dredged material, to reoccupy positions relative to the sediment-water interface that are similar to those maintained prior to burial by the disposal activity. The level of effect is system specific as natural adaptations can determine sensitivity to smothering effects. The depth of siltation at the benchmark level is relatively high. Many species are adapted to re-surface from thin deposits but 30cm is a substantial deposit. The depth of sediment overburden that benthic biota can tolerate is both trophic group and particle size/sediment type dependant (Bolam, S. G. et al. 2010).</p> <p>In high energy systems, the effects are relatively small as many of the species are capable of migrating up through the deposited sediments (Bijkerk, 1988 cited in Essink, K. 1999, Wilber, D. H. et al. 2007) as they are adapted to natural, high levels of background erosion and deposition. Relocation/disposal in high energy systems like tidal estuaries or coasts has less effect than relocation/disposal in low energy systems, for example lagoons. The effects are also mediated by the thickness of deposition and the intensity and frequency of deposition events, slower addition of thin layers has been shown to be better tolerated than</p>				

the same thickness of sediment deposited in a single event. An analysis of data from 18 disposal sites (intertidal and subtidal), confirmed that long-term impacts were disposal site specific and varied according to the prevailing hydrodynamic regime, ecological condition and the disposal activity (mode, timing, quantity, frequency and type of material) (Bolam, S. G. et al. 2006). This variability means that it is difficult to predict generalised impacts (Bolam, S. G. et al. 2006).

After the initial mortality that occurs immediately following deposition of sediments, initial recolonisation of the newly deposited dredged material begins via migration from surrounding areas (McLusky, D. S., Anderson, F.E. & Wolfe-Murphy, S. 1983, Richardson, M. D. et al. 1977) larval recruitment, and vertical migration (Maurer, D. et al. 1978, Maurer, D. et al. 1981b, a, 1982).

Defaunation and mortality due to dredge material disposal was addressed by Maurer and his co-workers in laboratory deposition experiments on Delaware Bay benthos (Maurer *et al* 1978, 1981a, 1981b, 1982; 1985; 1986). Conclusions from these studies are summarised below:

- some degree of upward mobility and recolonisation of dredged material is expected from the vertical migration of buried organisms;
- vertical migration ability is greatest in dredged material similar to the existing substratum and is minimal in sediments of dissimilar particle-size distribution;
- benthic organisms with morphological and physiological adaptations for crawling through sediments are able to migrate vertically through several inches of overlying sediment;
- physiological status of the organism and environmental variables are of great importance to vertical migration ability;
- organisms of similar lifestyle and morphology react similarly when covered with an overburden, e.g. most surface-dwelling forms are generally killed if trapped under dredged material overburdens, while sub-surface dwellers migrate to varying degrees; and
- Cooper (2005) suggested that impacts would also be greater on animal assemblages in stable coarse sediments characterised by attached epifauna that cannot escape smothering, than finer sediments inhabited by burrowing infauna which are adapted to live in sandy sediments and cope with periodic natural disturbance.

Bijkerk (1988, cited in Essink, K. 1999) compared results obtained at higher and lower temperatures (cf. summer and winter). At lower temperatures mortality among macrozoobenthos was lower and there was a higher tolerance of low oxygen conditions. The percentage of animals escaping from burial by crawling upward through the deposited sediment, however, was always lower at lower temperatures. These results are related to seasonal differences in metabolic activity.

In general, adverse effects from siltation have been observed for filter feeders where feeding appendages can be clogged, and sessile species found in areas of low sedimentation rates which are unable to reposition within the sediment leading to burial and smothering. For most benthic deposit feeders, food is suggested to be a limiting factor for populations (Levington, 1979, Hargrave, 1980).

5 Output processes

Evidence

Biodeposition	An increase in suspended organic particulates and subsequent increased deposition of organic matter in			
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	sheltered environments where sediments have high mud content will increase food resources to deposit feeders. This may lead to a shift in community structure with increased abundance of deposit feeders and a lower proportion of suspension feeders, as feeding is inhibited where suspended particulates are high, and the sediment is destabilised by the activities of deposit feeders (Rhoads and Young, 1970).			
Bioengineering				
Hydrodynamic flow				
Bioturbation				
Primary production				
Secondary production				
Sediment processing				
Habitat modification				
Supply of propagules				
6. Local ecosystem functions				
Evidence				
Food resource				
Nutrient cycling				
Biogeochemical cycling				
Sediment stability				
Habitat provision				
Microbial activity				
Knowledge Gaps				

Proforma 5 Changes in suspended solids (water clarity)

To be completed.

Proforma 6 Physical change (to another seabed/sediment type)

To be completed

Appendix 9 Conservation Attribute proformas

To be completed

Appendix 10 Ecosystem service review proformas

Proforma 1. Primary Production

Proforma 1		Intermediate Service (Potts <i>et al</i> 2014): Primary production
Ecosystem Service-Description This service is defined as the production of plant biomass (Fletcher <i>et al</i> 2011). This service is an intermediate service and ecosystem process that supports processes and ecosystem services and marine food webs.		
Specific node in model, added to models or based on existing nodes? Primary production is represented in the CEMs as an output process. This node is supported by biological assemblages that are primary producers: kelp, brown algae, green algae, and red algae.		
Any categories used to assess service provision. Primary production in the water column is a node in this model. The node to assess the level of primary production by the biological assemblage was included in the MESO BBN models.		
Contribution to this service: Biological assemblage We created a four point scale to assess contribution of biological assemblages as follows: <ul style="list-style-type: none"> • None: Biological assemblage or component does not represent primary producers; • Low: 0.25 kg/ms/yr Low- e.g. Sparse <i>Sacharrina latissima</i> in sand habitats; small red algae; • Medium: 0.5= 0.5 -2 kg/m2 year e.g. saltmarsh/seagrass; • High: 5-10kg/m2/yr e.g. stands of canopy forming brown algae; • High: Dense macroalgal beds (15 kg/m2/yr) e.g. Kelp forests; 		
1 Regional to Global Drivers		
Climate	Mediates (High): temperature mediates plant growth rates and other processes such as reproduction (see water chemistry and temperature). Climate also influences storminess, wave exposure and may therefore determine habitat suitability (see sections below). Increased temperatures related to anthropogenic climate change may impact the structure of kelp forests and the ecosystem services they provide (Smale <i>et al</i> 2016).	High
Depth	Mediates (High): through light attenuation and habitat suitability for macroalgae with changes in community at different depths (Markager and Sand-Jensen, 1992; Laffoley and Grimsditch 2009).	High
Geology	Mediates (High): through habitat suitability, requirements for attachment vary for macroalgae and some are free living or present in sediment, e.g. <i>Sacharina latissima</i> in the Sand CEM, however the densest macroalgae stands occur on rock substratum.	High
Propagule supply	Mediates (High): through provision of macroalgal spores.	High
Water currents	Mediates (High): through habitat suitability for biological assemblages that provide this service. Nutrient limitation related	High

	to low water flow can limit growth (Mann, 1982 cited in Scottish Government, 2016). Primary producers also alter hydrodynamic output processes by attenuating water flow (Blight and Thompson 2008), see Natural Hazard Regulation proforma.	
Wave exposure	Mediates (High): through habitat suitability for species including kelps (Birkett <i>et al</i> 1998), for example, <i>Laminaria hyperborea</i> density, biomass, morphology and age are generally greater in exposed sites (Smale <i>et al</i> 2016). At high levels of exposure (EUNIS A3.1) kelp may be replaced by more robust animal communities, and at lower levels of exposure (EUNIS A3.3) turbidity and sediment abrasion may reduce productivity (eftec, 2014).	High
2 Water Column Processes		
Evidence		
Dissolved oxygen	Mediates (High): Reduced oxygen concentrations can inhibit both photosynthesis and respiration in macroalgae (Kinne, 1977). Primary producers also affect dissolved oxygen levels through nutrient cycling, for example through conversion of carbon dioxide and other inorganic dissolved nutrients into organic material and oxygen (Hasselström <i>et al</i> 2018).	High
Primary production	Mediates (High): primary production in the water column is directly linked to provision of this service by the ecosystem.	High
Suspended Sediment	Mediates (High): through light attenuation (see below). Suspended Particle Matter (SPM) concentration has a positive linear relationship with sub surface light attenuation (K_d) (Devlin <i>et al</i> 2008) and controls the photic zone (Cloern, 1987)	High
Light Attenuation	Mediates (High): Light availability and water turbidity are principal factors in determining depth range at which macro-algae can be found (Birkett <i>et al</i> 1998) and is a key factor influencing ecosystem services based on marine primary producers (Alexander <i>et al</i> 2016). Kelp canopy biomass and the standing stock of carbon are positively correlated with large-scale wave fetch and light levels and negatively correlated with temperature (Smale <i>et al</i> 2016).	High
Water Chemistry and temperature	Mediates (High): Water temperature affects all provisioning services and is considered critical to ecosystem service generation (Alexander <i>et al</i> 2016). Temperature may mediate habitat suitability setting the range limits for a species (Hoek, 1982, Müller <i>et al</i> 2009), temperature may also determine other biological processes such as rates of growth and reproduction (Lee and Brinkhuis, 1988). Smale <i>et al</i> (2016) found that kelp canopy biomass and the standing stock of carbon were positively correlated with large-scale wave fetch and light levels and negatively correlated with temperature. Water chemistry also affects nutrient availability, with nutrient limitation identified as a limiting factor for growth (Mann, 1982 cited in Scottish Government, 2016). Alterations to features such as dissolved oxygen, pH, and dissolved compounds caused by a poor state of the environment are likely to have knock-on effects on marine flora and fauna (Alexander <i>et al</i> 2016).	High
3 Local Processes/Inputs at the seabed		
Evidence		
Food Sources	Not relevant: However, the following food sources are primary producers; diatoms, phytobenthos, plankton. Primary producers	NR

	do not directly consume the identified food sources.	
Grazing and predation	Mediates (Low): Grazing as a pressure mediates the supply of primary production. Excessive grazing by sea urchins can denude entire kelp forests. However, in more persistent stands grazers typically consume only a small fraction of the kelp that is produced (Reed and Brzezinski 2009). Herbivory is generally low in kelp forests, with less than 10% of live kelp biomass thought to be consumed by grazers (Norderhaug and Christie, 2011), and 80% being exported as detritus (Burrows <i>et al</i> 2014; Wernberg and Filbee-Dexter, 2018).	High
Seabed Mobility	Mediates habitat suitability. In the natural environment, values for maximum productivity are 10 times higher for a seaweed stand than for a plankton population which is due to the fixed position of a seaweed on a substrate (Lüning 1990). This ecological advantage allows macroalgae to form a stable, multi-layered, perennial vegetation capturing almost every photon falling on a square metre of rocky bottom, as in a dense terrestrial forest, where almost no light reaches the forest floor (Lüning and Pang, 2003).	High
Recruitment	Mediates supply of primary producers. See larval and gamete supply (proforma 2).	High
4. Habitat and Biological assemblages		
Kelp	<p>Kelp forests are acknowledged as one of the most productive ecosystems on earth (Dayton 1985, Steneck <i>et al</i> 2002, Smale <i>et al</i> 2013). In the Atlantic, kelp primary production can be in excess of 1,000 gC/m²/year (Mann 1973, Smale <i>et al</i> 2013), and that from <i>Laminaria</i> species has been estimated at between 110 and 1,780 g C/m²/year (Mann 1973, 2000), while primary production from phytoplankton in coastal temperate regions is typically between 100 and 300 g C/m²/year (Mann 2000). In Scotland, alone kelp biotopes are estimated to cover 8000km² (Walker, 1953), and account for ca 45% of primary production in UK coastal waters (Smale <i>et al</i> 2013).</p> <p><i>Laminaria hyperborea</i> is grazed directly by species such as <i>Patella pellucida</i>, however approximately 80% of primary production is consumed as detritus or dissolved organic material (Krumhansl 2012) which is both retained within and transported out of the parent kelp forest, providing valuable nutrition to potentially low productivity habitats such as sandy beaches (Smale <i>et al</i> 2013).</p> <p>Walker (1954) estimated an area of 2,900km² of kelp habitat in Scotland alone out of a total sublittoral area of 8,000km², which may produce 3.6MtC/year at typical production rates of 1,300gC/m²/year (Dayton 1985). Kelps therefore make a substantial contribution to primary production in coastal waters off the UK and Ireland.</p> <p>The categories for primary production are based on production rates of <i>Laminaria hyperborea</i> in the Isle of Man (Kain, 1977), where annual productivity (dry weight) of dense kelp patches was estimated as 15 kg/m²/year.</p> <p>Primary production rates vary between species, seasons and regions (Pessarrodona <i>et al</i> 2019). Deriving estimates of standing stock biomass, and therefore primary production, is challenging because the</p>	

	<p>biomass density and the cross- shore width varies greatly with species, time (both seasonally and inter-annually) and location (both within and among sites) (Reed and Brzezinski, 2009).</p> <p><i>Laminaria hyperborea</i> has a typical seasonal growth pattern, with growth starting in January, peaking in March and ending in June (Schaffelke and Lüning 1994). <i>Laminaria hyperborea</i> reaches a maximum height of 2–4 m (Abdullah <i>et al</i> 2017).</p> <p>Due to extensive recent peer reviewed literature, confidence is assessed as high.</p>
Brown Algae	Limited evidence was found on the primary production rates of brown algae. As large primary producers capable of fast growth, they are assessed to provide high levels of primary production at low confidence.
Green Algae	Limited evidence was found on the primary production rates of green algae. As primary producers which generally reach smaller sizes than kelp or brown algae, they are assessed to provide low levels of primary production at low confidence.
Red Algae	<p>Limited evidence was found on the primary production rates of red algae. As primary producers which generally reach smaller sizes than kelp or brown algae, they are assessed to provide low levels of primary production at low confidence.</p> <p>Bamber and Irving (1993, cited in Tillin <i>et al</i> 2015) reported that <i>Corallina officinalis</i> reached a biomass of up to 3.3-6.7 kg/m². Littler <i>et al</i> (1979, cited in Tillin <i>et al</i> 2015) determined the total daily productivity of an intertidal algal population in California, which peaked in autumn at 1.22 gC fixed /m²/day, and declined in winter to a spring low of 0.47 gC fixed /m²/day.</p>
Grazers	Mediate output, herbivory appears to be low in kelp and influence is assessed as low but with low confidence.
5. Output processes relevant to ecosystem service	
Evidence	
Biodeposition	Not relevant but macroalgae may trap sediments supporting biodeposition which in turn supports nutrient cycling (see proforma 3).
Bioengineering	Not relevant: primary producers do support bioengineering, (see proforma 4).
Hydrodynamic flow	Mediates? Macroalgae may alter hydrodynamic flows, (see proforma 5).
Bioturbation	Not relevant, however bioturbation supports primary production in the marine environment through nutrient cycling (see proforma 3).
Primary production	Provision. Marine primary producers contribute at least 50% of the world's carbon fixation and may account for as much as 71% of all carbon storage (Chung <i>et al</i> 2011). Primary production at the seabed occurs through microphytobenthos and macroalgae. Benthic algae contribute some 10% of the total marine primary production (Charpy-Roubaud and Sournia, 1990). Kelp may conservatively account for ~45% of primary production in UK coastal waters, and 12% of marine production in the entire UK EEZ. This estimate for annual UK kelp production does not include the extensive shallow subtidal rocky reef habitats found off England and Wales and will therefore be an underestimate. Although these coarse estimates should be interpreted with caution, it is clear that kelps make a substantial contribution to primary production in coastal waters off the UK and Ireland (Smale <i>et al</i>

	2013).
Secondary production	Not relevant. Kelp detritus, as broken plant tissue, particles and dissolved organic material supports soft bottom communities outside the kelp bed itself (Stamp and Hiscock).
Habitat modification	Not relevant (but see geology above). Macroalgae primary producers create habitat (see proforma 4). Kelp forests are the primary habitat for many commercial and recreational fisheries that include a wide diversity of mollusks, crustaceans, and finfish (Laffoley and Grimsditch 2009 and references therein).
Supply of propagules	Not relevant to service but primary producers support propagules that may be transported to other habitats (see proforma 2).
6. Local ecosystem functions	
Biogeochemical cycling	Supports: primary production underpins marine food webs and supports biogeochemical cycling (see proforma 3).
Control of algal growth	Not relevant. Primary production is an output of algal growth. Excessive grazing by sea urchins can denude entire kelp forests however, in more persistent stands grazers typically consume only a small fraction of the kelp that is produced (Reed and Brzezinski 2009).
Food resource	Not relevant. Primary production provides food to other species. However, herbivory is generally low in kelp forests, with less than 10% of live kelp biomass thought to be consumed by grazers (Norderhaug and Christie, 2011), and 80% being exported as detritus (Burrows <i>et al</i> 2014; Wernberg and Filbee-Dexter, 2018). The flow of detritus between habitats is an important form of connectivity that affects regional productivity and the spatial organization of marine ecosystems. Kelps produce detritus through incremental blade erosion, fragmentation of blades, and dislodgement of whole fronds and thalli. Rates of detrital production range from 8 to 2657 g C m ⁻² yr ⁻¹ for blade erosion and fragmentation, and from 22 to 839 g C m ⁻² yr ⁻¹ for loss of fronds and thalli. The estimated global average rate of detrital production by kelps is 706 g C m ⁻² yr ⁻¹ , accounting for 82% of annual kelp productivity (Krumhansl and Scheibling, 2012) (see Nutrient Cycling proforma 3). Detrital production rates are regulated by current and wave-driven hydrodynamic forces and are highest during severe storms and following blade weakening through damage by grazers and encrusting epibionts. Detritus settles within kelp beds or forests and is exported to neighboring or distant habitats, including sandy beaches, rocky intertidal shores, rocky and sedimentary subtidal areas, and the deep sea. Exported kelp detritus can provide a significant resource subsidy and enhance secondary production in these communities ranging from tens of meters to hundreds of kilometers from the source of production. Loss of kelp biomass is occurring worldwide through the combined effects of climate change, pollution, fishing, and harvesting of kelp, which can depress rates of detrital production and subsidy to adjacent communities, with large-scale consequences for productivity (Krumhansl and Scheibling, 2012).
Habitat provision	Primary production indirectly supports habitat provision through the growth of algae that provide habitat for other species including photosynthesising epiphytes (see proforma 4).
Microbial activity	Provision: where primary producers are maintained or enhanced.
Nutrient cycling	Supports: The availability of nutrients is a key component in controlling the abundance and diversity of marine flora which produce provisioning ecosystem services. A reduction in nutrient availability is therefore likely

	to reduce the delivery of any ecosystem services produced, and a total absence of nutrients is likely to result in non-delivery of any ecosystem service (Alexander <i>et al</i> 2016). Nutrients are transported by water movement and in-situ primary production may not rely on nutrient cycling within the biotope.
Population control	Mediates: control of local grazers will support biomass production of algae.
Sediment stability	Supports where sediment stability supports primary producers.
7 . Regional to global ecosystem functions	
Biodiversity enhancement	Supports where biodiversity increases support primary production.
Biotope maintenance	Supports where biotope maintained support primary production.
Biotope stability	Supports where stability refers to a biotope supporting primary production.
Carbon sequestration	Marine primary producers contribute at least 50% of the world's carbon fixation and may account for as much as 71% of all carbon storage (Chung <i>et al</i> 2011). Kelps are the major primary producers in UK marine coastal waters producing nearly 75 percent of the net carbon fixed annually on the shoreline of the coastal euphotic zone (Birkett <i>et al</i> 1998). Kelp plants produce 2.7 times their standing biomass per year. The kelps reduce ambient levels of nutrients, although this may not be significant in exposed sites, but increase levels of particulate and dissolved organic matter within the bed.
Export of biodiversity	Not relevant.
Export of organic matter	Not relevant to primary production within habitat. Mediates as part of wider marine food webs supporting nutrient cycling. Primary production may lead to the export of organic matter. The vast majority (>80%) of kelp-derived organic matter is typically exported from the kelp forest, rather than being consumed or remineralized within the source habitat (Krumhansl and Scheibling 2012).
Knowledge Gaps	
Production by kelp has been estimated by a number of studies and is well supported (see Smale <i>et al</i> 2013 for overview), estimates of primary production by other components including microphytobenthos are less understood.	

Proforma 2

Proforma 3

Proforma 4 CICES 2.2.2.3 Maintaining nursery populations and habitats

Proforma 4	Intermediate Service (Potts <i>et al</i> 2014): Formation of Species habitats CICES 2.2.2.3 Maintaining nursery populations and habitats
<p>Ecosystem Service-Description</p> <p>As an intermediate service Potts <i>et al</i> (2014) identified formation of species habitats, defined as formation of the physical properties of the habitats necessary for the survival of species (Fletcher <i>et al</i> 2011).</p> <p>The CICES service “maintenance of nursery populations and habitats” or “habitats for species” in The Economics of Ecosystems and Biodiversity (TEEB) has been identified as challenging to assess by Liqueste <i>et al</i> (2016) who reviewed the definition and indicators across assessments. The main reasons behind this are that, on the one hand, this ecosystem service could be interlinked or correlated with other services that directly rely on it (e.g. fisheries) and, on the other hand, it refers to biodiversity components and ecosystem functions (i.e. nursery function). In the UK NEA follow on nursery habitats aren't included as a final service and the functions are split between two intermediate services larval and gamete supply and formation of species habitats (Liqueste <i>et al</i> 2016). For the purposes of this project we have assessed the provision of habitat complexity by species as habitat complexity increases nursery functions and species richness across a range of biological groups (see biological assemblage sections for relevant examples)</p> <p>A nursery can be defined as a habitat that contributes more than the average, compared with other habitats, to the production of individuals of a particular species that recruit to adult populations (Beck <i>et al</i> 2001). The main factors that facilitate the reproduction and recruitment are density, growth and survival of juveniles, movement to adult habitats, or a combination of those (Beck <i>et al</i> 2001). Most habitats are likely to provide this service at some level.</p> <p>For the project purposes we have used habitat provision by biota as a proxy for the supply of this service. Marine organisms can create complex habitats above and below the sediment surface. Below sediment surface structures (burrows) are assessed through the bioturbation node in the MESO BBN models. Biological habitats can provide nursery functions and provide refugia from predators and increase feeding (Beaumont <i>et al</i> 2007). An example is <i>Sabellaria spinulosa</i> reef which enable a range of epibenthic species with their associated fauna and a specialised 'crevice' infauna, which would not otherwise be found in the area, to become established (Maddock 2008). Rabaut and others (2009) found that the density distribution of the flatfish species plaice <i>Pleuronectes platessa</i> was significantly explained by the presence of reefs built by the polychaete <i>L. conchilega</i>. The bioengineering/habitat provision node is understood to refer to above surface habitat structural elements include the presence of large bivalves, sponges, hydroids, and surficial sediment characteristics (e.g., sand rippled hash, sand, mud) (Thrush <i>et al</i> 2001, Auster, 1998). The organisms that inhabit the sediments create much of the structure in soft-sediment habitats, ranging from the micro-scale changes around individual animal burrows, the formation of pits, mounds, tubes to the formation of extensive biogenic reefs</p>	

(Thrush & Dayton, 2002).

Contribution to this service: Biological assemblage

A number of classification schemes exist for habitat complexity. We created a four-point scale informed by Auster *et al* (1998) with biological assemblages assigned as follows:

None: infauna, predatory epifauna, mobile epifauna

Low: mounds / pits

Medium: tube building /low reef /mat forming

High: Solitary epifauna / sparse epiflora

High: Biogenic reef forming organisms /dense macroalgae

Specific node in model, added to models or based on existing nodes?

The ecological component nodes linked to this service are habitat provision which is defined as 'provision of living space for other organisms through surface attachment of increased habitat complexity'. Bioengineering which was present in some of the original CEM model and defined as 'faunal modification of the natural habitat, e.g. tube building, burrow creation etc' was not used in the final MESO models. This service was considered to be captured through habitat provision and bioturbation model nodes.

Proforma 5

Proforma 6

Proforma 7

Proforma 8 CICES 1.1.2 Cultivated aquatic plants for nutrition, materials or energy

Proforma 8	CICES 1.1.2 Cultivated aquatic plants for nutrition, materials or energy
Ecosystem Service-Description Aquaculture is the farming or culturing of aquatic organisms (fish, molluscs, crustaceans, plants) using techniques designed to increase the production of the organisms in question beyond the natural capacity of the environment, such as through regular stocking, feeding and protection from predators (ONS, 2007b). This ecosystem service is divided by CICES into three classes <ul style="list-style-type: none"> • CICES 1.1.2.1 Plants cultivated by in- situ aquaculture grown for nutritional purposes; • CICES 1.1.2.2 Fibres and other materials from in-situ aquaculture for direct use or processing (excluding genetic materials); and • CICES 1.1.2.3 Plants cultivated by in- situ aquaculture grown as an energy source. 	
Specific node in model, added to models or based on existing nodes? This service is supported by the marine ecosystem but is not a direct output of any of the nodes.	
Any categories used to assess service provision. The aquaculture sector relies on various ecosystem services that support its productivity, including: the physical environment; chemical cycling/ water purification; biological	

productivity (Saunders, 2010)		
1 Regional to Global Drivers		Confidence
Climate	Mediates (High): temperature mediates plant growth rates and other processes such as reproduction (see water chemistry and temperature). Climate also influences storminess, wave exposure and may therefore determine habitat suitability (see sections below). Increased temperatures related to anthropogenic climate change may impact the structure of kelp forests and the ecosystem services they provide (Smale <i>et al</i> 2016).	High
Depth	Mediates suitability for operations.	Low
Geology	Not relevant. Most macroalgal culture is likely to be long-line and independent of the substratum.	Low
Propagule supply	Not relevant.	
Water currents	Mediates suitability for operations.	Low
Wave exposure	Mediates suitability for operations.	Low
2 Water Column Processes		
Evidence		
Dissolved oxygen	Mediates suitability for operations.	Medium
Primary production	Mediates suitability for operations.	Medium
Suspended Sediment	Mediates suitability for operations.	Medium
Light Attenuation	Mediates suitability for operations.	Medium
Water Chemistry and temperature	Mediates suitability for operations.	Medium
3 Local Processes/Inputs at the seabed		
Evidence		
Food Sources	Not relevant	
Grazing and predation	Mediates: control of local grazers will support biomass production of algae. Confidence is Medium.	
Seabed Mobility	Not relevant. Most macroalgal culture is likely to be long-line and independent of the substratum.	
Recruitment	Aquaculture unlikely to rely on propagules supplied by the environment.	
4. Habitat and Biological assemblages		
CICES 1.1.2.1 Plants cultivated by in- situ aquaculture grown for nutritional purposes;	Requires updating	
CICES 1.1.2.2 Fibres and other materials from in-situ aquaculture for direct use or processing (excluding genetic materials); and	Kelps can grow very quickly (up to 50 cm per day), are rich in polysaccharides, and do not compete with land-based crops for space, fertilizers, and water (Smale <i>et al</i> 2013).	
CICES 1.1.2.3 Plants	Within the UK and Ireland, the potential for kelp biomass to be	

cultivated by in- situ aquaculture grown as an energy source.	used for conversion to biofuels has reignited interest in large scale kelp production. In Ireland, for example, the EnAlgae project enalgae.eu is cultivating macroalgae in and around Strangford Lough for biofuel development, and similar projects are underway in Scotland (Smale <i>et al</i> 2013). A realistic contribution to energy markets through bioethanol production may require more kelp than can be harvested from natural habitats, prompting efforts to develop methods of farming kelp (Burrows <i>et al</i> 2014). A recent cradle-to-grave analysis of the carbon footprint of the production of biofuels (ethanol and methane) from seaweeds, however, indicated that production of biofuels from other sources (e.g., corn, wheat, sugar cane) is more efficient (Fry <i>et al.</i> 2012, cited from Smale <i>et al</i> 2013).
5. Output processes relevant to ecosystem service	
Evidence	
Biodeposition	Not relevant. Most macroalgal culture is likely to be long-line and independent of the substratum.
Bioengineering	Not relevant. Most macroalgal culture is likely to be long-line and independent of the substratum.
Hydrodynamic flow	Not relevant.
Bioturbation	Not relevant. Most macroalgal culture is likely to be long-line and independent of the substratum.
Primary production	Not relevant, the service relates to primary production by cultivated rather than wild plants.
Secondary production	Supports: secondary production by filter and suspension feeders may reduce suspended sediments supporting primary production.
Habitat modification	Not relevant. Most macroalgal culture is likely to be long-line and independent of the substratum.
Supply of propagules	Not relevant.
6. Local ecosystem functions	
Biogeochemical cycling	Support: biogeochemical cycling may support in-situ primary production.
Control of algal growth	Support: may be beneficial where this relates to epiphytes or negative where the cultivated algae is grazed.
Food resource	Not relevant.
Habitat provision	Not relevant. Most macroalgal culture is likely to be long-line and independent of the substratum.
Microbial activity	Support: may support in-situ primary production
Nutrient cycling	Mediates: The availability of nutrients is a key component in controlling the abundance and diversity of marine flora which produce provisioning ecosystem services. A reduction in nutrient availability is therefore likely to reduce the delivery of any ecosystem services produced, and a total absence of nutrients is likely to result in non-delivery of any ecosystem service (Alexander <i>et al</i> 2016). Nutrients are transported by water movement and in-situ primary production may not rely on nutrient cycling within the biotope.
Population control	Mediates: control of local grazers will support biomass production of algae. Confidence is Medium.
Sediment stability	Not relevant. Most macroalgal culture is likely to be long-line and independent of the substratum.
7 . Regional to global ecosystem functions	

Not relevant. Cultivated plant biomass is likely to be removed and the functions are not relevant to this service.

Knowledge Gaps

Although seaweeds are cultivated this sector was considered to be relatively under developed in comparison with the more mature fish and shellfish aquaculture sectors. Previous reports have found that quantitative information on aquaculture of seaweed (e.g. locations and amounts) was difficult to source (eftec 2014).

Proforma 9

Proforma 10

Proforma 10	CICES 1.1.5 Wild plants (terrestrial and aquatic) for nutrition and materials Intermediate service primary production
<p>The CICES group 1.1.5 Wild plants (terrestrial and aquaculture for nutrition and materials contains three classes:</p> <ul style="list-style-type: none"> • CICES 1.1.5.1 Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition • CICES 1.1.5.2 Fibres and other materials from wild plants for direct use or processing (excluding genetic materials) • CICES 1.1.5.3 Wild plants (terrestrial and aquatic, including fungi, algae) used as a source of energy <p>The provision of Food (wild and farmed) represents a good/benefit that is derived from an ecosystem and is directly linked to final (provisioning) ecosystem services and intermediate (supporting) services. This final ecosystem service is supported by the following intermediate services: Primary production, Nutrient cycling, Formation of Species Habitat and Larval and Gamete Supply.</p> <p>The intermediate service: the rate of primary production determines the potential level of the final ecosystem services by determining the biomass of macroalgae present. Macroalgae play further roles in supporting final ecosystem services within the CICES classification. Macroalgae may capture sediment particles (biodeposition) reducing erosion and dense beds reduce wave strength through friction providing a role in natural hazard regulation. Mucilage produced by MPB also stabilises benthic sediments. Macroalgae also contribute to nutrient cycling, bioremediation (proforma xx), produce genetic material (proforma xx), propagules (xx) accumulate and store wastes (proforma xx)</p>	
<p>Specific node in model, added to models or based on existing nodes?</p> <p>This final ecosystem service is supported by the following intermediate services: Primary production, Nutrient cycling, Formation of Species Habitat and Larval and Gamete Supply (eftec, 2014).</p> <p>The CEM do not include seagrass and within the existing CEM models this service is represented by the biomass or standing stock of macroalgae present within the following model biological assemblages:</p> <p>Sand: Submodel 4: Biological assemblage: kelp Mud: None Mixed:None Coarse: None Reef: Submodel 1 Kelp, brown, red and green algae.</p>	
<p>Any categories used to assess service potential:</p> <p>Service provision was assessed based on a three-point scale:</p> <p>None: Animal is not known to be commercially targeted</p> <p>Medium: Animal is targeted, it may be sparse in the habitat under consideration OR it may be a species that is only targeted in parts of its range or sporadically.</p> <p>High: Species has high commercial value and is targeted across most or all of the range.</p>	
<p>Comments</p>	

Notes:		
Regional to global drivers		
Evidence		
Climate	Mediates: temperature mediates plant growth rates and other processes such as reproduction (see water chemistry and temperature). Climate also influences storminess, wave exposure and may therefore determine habitat suitability (see sections below). Increased temperatures related to anthropogenic climate change may impact the structure of kelp forests and the ecosystem services they provide (Smale <i>et al</i> 2016).	High
Depth	Mediates: through light attenuation and habitat suitability for macroalgae with changes in community at different depths (Markager & Sand-Jensen, 1992; Laffoley and Grimsditch 2009).	High
Geology	Mediates: through habitat suitability, requirements for attachment vary for macroalgae.	High
Propagule Supply	Mediates: through provision of macroalgal spores.	High
Water Currents	Mediates: through habitat suitability for biological assemblages that provide this service. Nutrient limitation related to low water flow can limit growth (Mann, 1982 cited in Scottish Government, 2016). Primary producers also alter hydrodynamic output processes by attenuating water flow (Blight and Thompson 2008).	High
Wave Exposure	Mediates: through habitat suitability for species including kelps (Birkett <i>et al</i> 1998), for example, <i>Laminaria hyperborea</i> density, biomass, morphology and age are generally greater in exposed sites (Smale <i>et al</i> 2016). At high levels of exposure (EUNIS A3.1) kelp may be replaced by more robust animal communities, and at lower levels of exposure (EUNIS A3.3) turbidity and sediment abrasion may reduce productivity (eftec, 2014).	High
2 Water Column Processes		
Evidence		
Primary production	No- primary production in the water column does not support primary production in the benthic habitat.	
Suspended Sediment	Mediates (High): through light attenuation (see below). Suspended Particle Matter (SPM) concentration has a positive linear relationship with sub surface light attenuation (Kd) (Devlin <i>et al</i> 2008) and controls the photic zone (Cloern, 1987)	
Light Attenuation	Mediates (High): Light availability and water turbidity are principal factors in determining depth range at which macro-algae can be found (Birkett <i>et al</i> 1998) and is a key factor influencing ecosystem services based on marine primary producers (Alexander <i>et al</i> 2016). Kelp canopy biomass and the standing stock of carbon are positively correlated with large-scale wave fetch and light levels and negatively correlated with temperature (Smale <i>et al</i> 2016).	
Water Chemistry and temperature	Direct water chemistry and temperature will influence rates of primary production. Smale <i>et al</i> (2016) found that kelp canopy biomass and the standing stock of carbon were positively correlated with large-scale wave fetch and light levels and negatively correlated with temperature. Water chemistry also affects nutrient availability, with nutrient limitation identified as a limiting factor for growth (Mann, 1982 cited in Scottish Government, 2016). Alterations to features such as dissolved oxygen, pH, and dissolved compounds caused by a poor state of the environment are likely to have knock-on effects on marine	

	flora and fauna (Alexander <i>et al</i> 2016).
3 Local Processes/Inputs at the seabed	
Evidence	
Food Sources	Not relevant
Grazing and predation	Mediates (Low): Grazing as a pressure mediates the supply of primary production. Excessive grazing by sea urchins can denude entire kelp forests. However, in more persistent stands grazers typically consume only a small fraction of the kelp that is produced (Reed and Brzezinski 2009). Herbivory is generally low in kelp forests, with less than 10% of live kelp biomass thought to be consumed by grazers (Norderhaug and Christie, 2011), and 80% being exported as detritus (Burrows <i>et al</i> 2014; Wernberg and Filbee-Dexter, 2018).
Seabed Mobility	Mediates habitat suitability. In the natural environment, values for maximum productivity are 10 times higher for a seaweed stand than for a plankton population which is due to the fixed position of a seaweed on a substrate (Lüning 1990). This ecological advantage allows macroalgae to form a stable, multi-layered, perennial vegetation capturing almost every photon falling on a square metre of rocky bottom, as in a dense terrestrial forest, where almost no light reaches the forest floor (Lüning and Pang, 2003).
Recruitment	Mediates supply of primary producers. See larval and gamete supply (proforma 2).
4. Habitat and Biological assemblages	
Macroalgae	It is estimated that 2000–3000 dry tonnes (equivalent to 25,000–40,000 tonnes wet weight) of macroalgae is harvested from the wild per year in the United Kingdom to produce food and feed products as well as speciality chemicals and fertilisers (Schlarb-Ridley and Parker, 2013),
CICES 1.1.5.1 Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition	There is limited utilisation of specific wild harvested seaweeds as food, although exploitation is increasing, and seaweeds are also used as a source of chemicals for industries. Alginate, agar and carrageenan are gelatinous extracts that are used as food additives (Austen <i>et al</i> 2010). In coastal communities in the UK, nonkelp seaweeds have been consumed for at least 4000 years, particularly <i>Palmaria palmata</i> (“Dulse”), <i>Chondrus crispus</i> (“Carageen”), <i>Porphyra umbilicalis</i> (“Purple laver”), and <i>Ulva lactuca</i> (“Green laver”). Although all kelps in the UK and Ireland are edible, <i>Sachharina latissimi</i> is considered the most palatable due to its sweet taste. Kelps including <i>Alaria esculenta</i> and <i>Sachharina latissima</i> are being marketed as “sea vegetables” by health food companies, due to their high levels of vitamins and minerals and low levels of salt and digestible sugars (Jaspars and Folmer 2013). As such, some suppliers in Scotland and Ireland harvest kelps for human consumption, but these operations are currently fairly small scale (Smale <i>et al</i> 2013).
CICES 1.1.5.2 Fibres and other materials from wild plants for direct use or processing (excluding genetic materials)	Current harvesting of marine species for use as fertiliser is small scale and primarily based in Northern Ireland and some of the Scottish islands. A site-specific example of a species that is used as fertiliser is <i>Laminaria hyperborea</i> , which has been used historically and currently as a fertiliser on machair in Scotland (UK NEA, 2011). The Seaweed Industry Association (www.seaweedindustry.com) report that <i>Sargassum muticum</i> is often gathered from the shore or floating mats to be used as fertilizer or compost and that many coastal populations make use of <i>Sargassum muticum</i> as food source. A breed of sheep on North Ronaldsay (Orkney Islands, Scotland) feeds almost

	<p>entirely on beach wrack (principally <i>L. hyperborea</i>) for most of the year. Stable isotope analysis suggests that the North Ronaldsay breed has been consuming kelp since the fourth millennia BC, during which time it has adapted its rumen bacteria to facilitate the breakdown of laminarin (the storage glucan in brown algae) and adapted an unusual pattern of grazing and ruminating that follows the tidal cycle rather than the (more typical) diurnal cycle (Balasse <i>et al</i> 2005, cited from Smale <i>et al</i> 2013).</p> <p>Macro and microalgae may be used in the cosmetic industry by small businesses with innovative products based on raw materials (e.g., seaweed soaps from Rest and be Thankful or Irish Seaweeds) and multinationals. UK companies include Seaweed Organics, The Scottish Fine Soap Company, Rest and be Thankful and the Highland Soap Company (Schlarb-Ridley and Parker 2013).</p> <p>Kelp is exploited in a range of European and Asian countries for the production of alginate, food, biofuels, medicine and other chemicals (McHugh 2003). French and Norwegian kelp industries, for example, harvest 50,000 tonnes of <i>Laminaria digitata</i> and 200,000 tonnes of <i>L. hyperborea</i> annually for alginate production (Edwards & Watson 2011) (cited from Alexander <i>et al</i> 2016).</p>
CICES 1.1.5.3 Wild plants (terrestrial and aquatic, including fungi, algae) used as a source of energy	Large-scale harvesting of marine species for biofuel is not currently undertaken, however, some assessments of the potential resource have been undertaken for the UK and Ireland (Saunders <i>et al</i> 2010). The only contributing factor considered relevant to this project is macroalgae with the potential level of service based on the available biomass (cited from eftec 2014).
5. Output processes relevant to ecosystem service	
Evidence	
Biodeposition	Not relevant but macroalgae may trap sediments supporting biodeposition which in turn supports nutrient cycling (see proforma 3).
Bioengineering	Not relevant: primary producers do support bioengineering, (see proforma 4).
Hydrodynamic flow	Mediates? Macroalgae may alter hydrodynamic flows, (see proforma 5).
Bioturbation	Not relevant, however bioturbation supports primary production in the marine environment through nutrient cycling (see proforma 3).
Primary production	Provision. Marine primary producers contribute at least 50% of the world's carbon fixation and may account for as much as 71% of all carbon storage (Chung <i>et al</i> 2011). Primary production at the seabed occurs through microphytobenthos and macroalgae. Benthic algae contribute some 10% of the total marine primary production (Charpy-Roubaud and Sournia, 1990). Kelp may conservatively account for ~45% of primary production in UK coastal waters, and 12% of marine production in the entire UK EEZ. This estimate for annual UK kelp production does not include the extensive shallow subtidal rocky reef habitats found off England and Wales and will therefore be an underestimate. Although these coarse estimates should be interpreted with caution, it is clear that kelps make a substantial contribution to primary production in coastal waters off the UK and Ireland (Smale <i>et al</i> 2013).
Secondary production	Not relevant. Kelp detritus, as broken plant tissue, particles and dissolved organic material supports soft bottom communities outside the kelp bed itself

	(Stamp and Hiscock.
Habitat modification	Not relevant (but see geology above). Macroalgae primary producers create habitat (see proforma 4). Kelp forests are the primary habitat for many commercial and recreational fisheries that include a wide diversity of mollusks, crustaceans, and finfish (Laffoley and Grimsditch 2009 and references therein).
Supply of propagules	Not relevant to service but primary producers support propagules that may be transported to other habitats (see proforma 2).
6. Local ecosystem functions	
Biogeochemical cycling	Supports: primary production underpins marine food webs and supports biogeochemical cycling (see proforma 3).
Control of algal growth	Mediates: Control of algal growth by grazers could reduce the level of service.
Food resource	Not relevant to primary production. However, primary production provides food to other species. However, herbivory is generally low in kelp forests, with less than 10% of live kelp biomass thought to be consumed by grazers (Norderhaug and Christie, 2011), and 80% being exported as detritus (Burrows <i>et al</i> 2014; Wernberg and Filbee-Dexter, 2018). The flow of detritus between habitats is an important form of connectivity that affects regional productivity and the spatial organization of marine ecosystems. Kelps produce detritus through incremental blade erosion, fragmentation of blades, and dislodgement of whole fronds and thalli. Rates of detrital production range from 8 to 2657 g C m ⁻² yr ⁻¹ for blade erosion and fragmentation, and from 22 to 839 g C m ⁻² yr ⁻¹ for loss of fronds and thalli. The estimated global average rate of detrital production by kelps is 706 g C m ⁻² yr ⁻¹ , accounting for 82% of annual kelp productivity (Krumhansl and Scheibling, 2012) (see Nutrient Cycling proforma 3). Detrital production rates are regulated by current and wave-driven hydrodynamic forces and are highest during severe storms and following blade weakening through damage by grazers and encrusting epibionts. Detritus settles within kelp beds or forests and is exported to neighboring or distant habitats, including sandy beaches, rocky intertidal shores, rocky and sedimentary subtidal areas, and the deep sea. Exported kelp detritus can provide a significant resource subsidy and enhance secondary production in these communities ranging from tens of meters to hundreds of kilometers from the source of production. Loss of kelp biomass is occurring worldwide through the combined effects of climate change, pollution, fishing, and harvesting of kelp, which can depress rates of detrital production and subsidy to adjacent communities, with large-scale consequences for productivity (Krumhansl and Scheibling, 2012).
Habitat provision	Primary production indirectly supports habitat provision through the growth of algae that provide habitat for other species including photosynthesising epiphytes (see proforma 4). Beaches with wrack were associated with enriched benthic infauna (polychaetes) on the lower shore, and wrack mounds supported abundant macroinvertebrates (mainly Diptera larvae and oligochaetes). These fauna are valuable prey to shorebirds, as demonstrated by a strong positive relationship between wader abundances and the percentage cover of wrack on beaches (Orr 2013). the volume of drifting macroalgae inshore was a significant predictor (along with physical beach characteristics) for the abundance of decapods and fish (Orr 2013)
Microbial activity	Provision: where primary producers are maintained or enhanced.
Nutrient cycling	Mediates: The availability of nutrients is a key component in controlling the

	abundance and diversity of marine flora which produce provisioning ecosystem services. A reduction in nutrient availability is therefore likely to reduce the delivery of any ecosystem services produced, and a total absence of nutrients is likely to result in non-delivery of any ecosystem service (Alexander <i>et al</i> 2016). Nutrients are transported by water movement and in-situ primary production may not rely on nutrient cycling within the biotope.
Population control	Supports where grazers are controlled by higher trophic levels, e.g. otters feeding on urchins. Mesograzers feeding on macrophyte surfaces remove smaller epiphytes like diatoms and foliose algae and are thus important for keeping the larger macrophytes free from being overgrown by epiphytic competitors (Moksnes <i>et al.</i> 2008). However, in some cases the grazers increase in density to an extent that they start to overgraze the macrophytes which are then grazed to extinction (Christie <i>et al</i> 2009).
Sediment stability	Supports where sediment stability supports primary producers.
7 . Regional to global ecosystem functions	
Biodiversity enhancement	Supports where biodiversity increases support primary production.
Biotope maintenance	Supports where biotope maintained support primary production.
Biotope stability	Supports where stability refers to a biotope supporting primary production.
Carbon sequestration	Marine primary producers contribute at least 50% of the world's carbon fixation and may account for as much as 71% of all carbon storage (Chung <i>et al</i> 2011). Kelps are the major primary producers in UK marine coastal waters producing nearly 75 percent of the net carbon fixed annually on the shoreline of the coastal euphotic zone (Birkett <i>et al</i> 1998). Kelp plants produce 2.7 times their standing biomass per year. The kelps reduce ambient levels of nutrients, although this may not be significant in exposed sites, but increase levels of particulate and dissolved organic matter within the bed.
Export of biodiversity	Not relevant.
Export of organic matter	Not relevant to primary production within habitat. Mediates as part of marine food webs supporting nutrient cycling. Primary production may lead to the export of organic matter. The vast majority (>80%) of kelp-derived organic matter is typically exported from the kelp forest, rather than being consumed or remineralized within the source habitat (Krumhansl and Scheibling 2012).
Knowledge Gaps	

Proforma 11

Proforma 12

Proforma 13

Proforma 14 CICES 4.3.1 Mineral substances used for nutrition, materials or energy

Proforma 14		CICES 4.3.1 Mineral substances used for nutrition, materials or energy
Ecosystem Service-Description <ul style="list-style-type: none"> • Mineral substances used for nutritional purposes • Mineral substances used for material purposes • Mineral substances used for as an energy source <p>Salt (sodium chloride, NaCl), occurs naturally in the marine environment in solution. The extraction of sea salt from the surrounding marine waters occurs at two sites in England and one site in Wales. Salt extraction is therefore dependent on the following ecosystem services: Provision of water quality, and Tidal cycles (to supply salt pans – assuming this is the method of salt extraction).</p> <p>Aggregates: The mineral extraction sector includes the extraction of marine aggregates (sands and gravels) from the seabed</p> <p>Oil and Gas: UK production of oil and gas, principally from the UK continental shelf (UKCS), was equal to nearly two thirds of UK primary energy demand in 2008 (94% of oil demand and 74% of gas demand) (Saunders, 2010)</p>		
Specific node in model, added to models or based on existing nodes? This service is not delivered by the biota and no nodes within the CEM models represent the services.		
Any categories used to assess service provision. This service is not delivered by the biota and no nodes within the CEM models represent the services.		
1 Regional to Global Drivers		Confidence
Climate	Aggregate: Mediates suitability for operation. Possibility for increased storm and wave activity could reduce the calm weather windows available for dredging aggregates (Saunders, 2010). Oil and gas: Mediates suitability for operation. Resources are dependent on a physical environment in which to operate. The offshore oil and gas industry could be vulnerable to both changes in sea level and increases in waves and winds, leading to greater stresses on oil and gas structures in the marine environment (Saunders, 2010). Changes in storminess could also affect air and sea access to offshore installations and pose operational issues in terms of health and safety.	
Depth	Aggregate: The maximum depth that dredgers can practically operate in is around 50 m and is limited by available technology and vessel size (Saunders, 2010).	
Geology	Aggregate: The mining and quarrying sector relies on various ecosystem services that support its productivity, including: (1) physical environment; and (2) erosion-deposition cycles (of sediment) – although most aggregate resources are relict so fall outside of contemporary erosion/deposition cycles (Saunders, 2010). Primary aggregate is defined as a 50/50 blend on production suitable for use as concreting aggregates	

	and typically contains >20% gravel in-situ on the seabed. Sand is defined as a product suitable for use as concreting aggregates or concreting/building sand, typically composed of 0% to 40% gravel on production and containing 0% to 20% gravel in-situ on the seabed (Saunders, 2010). Oil and Gas: Oil and gas resources are considered relict features (Saunders, 2010).	
Propagule supply	Not relevant	
Water currents	Oil and Gas: Mediates suitability for operations: Changes to currents could result in changes to scour around the legs and supports of offshore installations (Rees, 2008).	
Wave exposure	Salt: Mediates suitability for use of tidal pans where this is the method of extraction. Oil and Gas: The offshore oil and gas industry could be vulnerable to both changes in sea level and increases in waves and winds, leading to greater stresses on oil and gas structures in the marine environment (Rees, 2008).	
2 Water Column Processes		
Evidence		
Dissolved oxygen	Not relevant	
Primary production	Not relevant	
Suspended Sediment	Not relevant	
Light Attenuation	Not relevant	
Water Chemistry and temperature	Salt: Mediates suitability- salt for food use cannot be extracted from highly contaminated environments. Oil and Gas: are dependent on chemical cycling/water purification to assimilate wastes (Saunders, 2010).	
3 Local Processes/Inputs at the seabed		
Evidence		
Food Sources	Not relevant	
Grazing and predation	Not relevant	
Seabed Mobility	Mediates (low) The mining and quarrying sector relies on various ecosystem services that support its productivity, including: erosion-deposition cycles (of sediment) – although most aggregate resources are relict so fall outside of contemporary erosion/deposition cycles (Saunders, 2010).	
Recruitment	Not relevant	
4. Habitat and Biological assemblages		
Not relevant.		
Habitat: Sublittoral sand, coarse sands, gravels	Provision of aggregates	High
5. Output processes relevant to ecosystem service		
Not relevant		
6. Local ecosystem functions		

Not relevant	
7 . Regional to global ecosystem functions	
Not relevant	
Knowledge Gaps	
Aggregate: Low	There are no significant knowledge gaps associated with this service.
Salt: High	Very little specific information exists regarding salt extraction from the marine environment and the information provided in Saunders (2010) was obtained through individual consultation with the three sea salt production companies in the UK.
Oil and Gas	There are no significant knowledge gaps associated with provision of this service.

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