

1 **Developing conceptual models that link multiple ecosystem services to ecological research to aid**  
2 **management and policy, the UK marine example**

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6 *Keywords: marine ecosystem services; conceptual model; expert workshop; trade-offs; management*  
7 *measures; indicators*

8 **Abstract**

9 Our understanding of ecological processes that lead to ecosystem services is still evolving but  
10 ecological research aims to understand the linkages between the ecosystem and services. These  
11 linkages can affect trade-offs between different ecosystem services. Understanding these linkages,  
12 by considering multiple ecosystem services simultaneously supports management of the  
13 environment and sustainable use of resources. The UK marine environment is relatively data rich,  
14 yet the links between ecosystem and several ecosystem services and linkages between services are  
15 poorly described. A workshop with 35 marine scientists was used to create a conceptual model that  
16 links ecosystem components and key processes to four services they provide and to highlight trade-  
17 offs between them. The model was subsequently further developed to include pressures and  
18 mitigating management measures. The models are discussed in terms of their application to marine  
19 data to facilitate evidence-based marine management and their usefulness to communicate  
20 management measures with managers and stakeholders.

21 **1. INTRODUCTION**

22 In recent years there have been significant changes in the focus of environmental policy. The first is a  
23 shift towards an ecosystem-based approach to management (EBM). The second is a move away  
24 from sector by sector management towards integrated management and planning, recognising that  
25 single sector management approaches do not always allow for interactive and cumulative effects or  
26 for trade-offs between sectors and their impacts (Knights et al. 2013, Cavanagh et al. 2016). Thirdly  
27 there is increasing recognition that an ecosystem service approach helps understanding the societal  
28 implications of management decisions (Daily et al. 2009, Börger et al. 2014, Cavanagh et al. 2016).  
29 Therefore ecosystem services are now included in legislation such as the EU's Biodiversity Strategy  
30 (COM/2011/0244), Regulation on Invasive Alien Species (REGULATION (EU) No 1143/2014) and  
31 Directive for Environmental Liability (2004/35/CE). The Common International Classification of  
32 Ecosystem Services (CICES) of the European Union (Haines-Young & Potschin 2013) defines  
33 ecosystem services as the contributions ecosystems make to human well-being while still being  
34 connected to the underlying ecosystem functions, processes and structures. Humans then create or  
35 derive ecosystem goods and benefits from final ecosystem services (Haines-Young & Potschin 2013).  
36 The ecosystem services approach is an appropriate way to link ecological research with  
37 sustainability, ecosystem benefits and human well-being (Mach et al. 2015, Van Wensem et al.  
38 2016).

39 Ecosystem services are created through interactions among numerous biotic (species groups) and  
40 abiotic components which create processes such as nutrient cycling or predator-prey relationships  
41 (MEA 2005, TEEB 2010). Ecological research developed over the past decades has aimed to  
42 understand these interactions as well as linkages between biodiversity and ecosystem functioning  
43 (Sutherland et al. 2013, Hyder et al. 2015, Strong et al. 2015).

44 Ecosystem service studies have tended to focus on the link between biodiversity and a single  
45 ecosystem service, yet this is likely to lead to an underestimation of biodiversity effects on services  
46 because species often carry out a number of ecosystem functions which may each contribute to  
47 several services (Cardinale et al. 2012, Balvanera et al. 2013). For example, in the marine  
48 environment fish catch as a measure of the food provision service is easily quantified compared to  
49 regulatory or habitat services and can be the focus of ecosystem service and valuation studies  
50 (Cavanagh et al. 2016, Barbier 2017). Turner et al. (2014) linked ecosystem services to ecosystem  
51 processes and components and this was an important step in linking ecological research with human  
52 well-being and economics while focussing on ecosystem services other than food provision. They  
53 also created conceptual models linking six ecosystem services with the ecosystem components and  
54 processes, but they created a model for each ecosystem service separately. However it is crucial  
55 that studies include multiple services to allow the capture of trade-offs amongst them and to  
56 explore the complexity of the system (Lester et al. 2013, Mach et al. 2015, Cavanagh et al. 2016).  
57 Additionally, knowledge and tools necessary to quantify and forecast changes to ecosystem services  
58 under different management measures need to be developed further (Daily et al. 2009, Mach et al.  
59 2015). Such tools would ideally help to understand if or why policy instruments aimed at halting  
60 biodiversity loss and decline of ecosystem services have failed or succeeded (Carpenter et al. 2009).

61 Trade-off analysis is an extremely difficult challenge (Bennett et al. 2009, Mach et al. 2015, Cavanagh  
62 et al. 2016). Construction of conceptual models around the biodiversity - ecosystem services  
63 relationships and the trade-offs between different ecosystem services help clarify thinking (Potschin-  
64 Young et al. 2018). Such an approach helps us understand the complexity of the ecosystems and  
65 focus attention to those parts of ecosystems that are important in the delivery of specific ecosystem  
66 services. A conceptual model can allow the generation of hypotheses and focus relevant research  
67 (Daily et al. 2009, Ostrom 2009, Potschin-Young et al. 2018). It can also serve as a first step towards  
68 developing dynamic models and tools to further strengthen evidence-based marine management.

69 Creating tools to understand ecosystem - ecosystem service relationships as well as trade-offs  
70 among them is particularly timely in the marine environment. Policy makers and marine managers  
71 need to make informed decisions to manage marine ecosystems sustainably even while the gap in  
72 our understanding of the relationships remains (Hyder et al. 2015, Mach et al. 2015, Van Wensem et  
73 al. 2016). The marine environment is heavily exploited for the goods and services it provides and  
74 also faces global pressures such as climate change (Jackson et al. 2001, Halpern et al. 2008, Knights  
75 et al. 2013). This adds uncertainty to the sustainable management as it is not clear how these  
76 pressures affect the ecosystem (Knights et al. 2013, Hyder et al. 2015) or the services it provides  
77 (Gattuso et al. 2015, Mach et al. 2015, Broszeit et al. 2016).

78 In this study, we develop a conceptual model that will help gain required understanding to support  
79 evidence-based approaches. We also show an extension of this model including examples that  
80 demonstrate by what pathways pressures and management measures can influence ecosystem

81 services. Abiotic chemical or physical processes support some ecosystem services but here we focus  
82 on those services provided by the living components of the marine ecosystem. The aims of this study  
83 were:

- 84 • To explore the complexity of the marine ecosystem and the services it provides by linking  
85 the interacting components with the processes they produce and ecosystem services they  
86 deliver
- 87 • To develop a conceptual diagram that incorporates key ecosystem services and includes  
88 ecosystem processes and species groups relevant to these services, as well as the links and  
89 feedbacks between them
- 90 • To include example pressures on the marine environment and how they affect ecosystem  
91 services as well as corresponding management measures that may alleviate such pressures

92 The conceptual model that we created can be used in many marine ecosystems but we have  
93 focussed on UK marine waters.

## 94 **2. METHODS**

### 95 **2.1 Identify ecosystem processes linked to services using a workshop**

96 To understand the complexity of the interlinkages between processes and services requires the  
97 expertise and knowledge from different marine science disciplines. To capture this understanding, a  
98 one-day workshop was organised to facilitate the development of a conceptual model that links  
99 services and processes. Four key ecosystem services plus seven additional services thought to be  
100 useful in supporting the key ecosystem services were to be addressed by the attendees. The four key  
101 ecosystem services were: food provision, leisure and recreation, bioremediation of waste and  
102 biological control – checks and balances. The aims of the workshop were:

- 103 • To assess among the researchers how these four services are dependent on the structure of  
104 the marine ecosystem and influenced by top-down and bottom-up processes
- 105 • To add services that may be of relevance to support the four key services to allow the  
106 development of a model that includes relevant services and processes without becoming too  
107 complex
- 108 • to identify useful indicators for the processes and components, find suitable methods of  
109 measuring such indicators through models or empirical research, and identify relevant data  
110 sources

111 Attending researchers were divided into four groups ensuring that researchers with different  
112 backgrounds worked together. Each group was asked to draw a conceptual model including up to 11  
113 marine ecosystem services (Table 1) important in the UK marine environment. The researchers  
114 connected relevant ecosystem processes and species groups (biotic components) to each of the  
115 services that they had chosen to include in their respective models. To avoid ambiguous terminology  
116 that could lead to false linkages between processes or misunderstandings between groups,  
117 participants defined each process that they included in their model during the workshop. Each group  
118 suggested potential indicators with measurement units for each process and service. Where  
119 possible, they identified relevant data sources for each of the indicators which could be either

120 empirical, derived from existing empirical data bases or modelling outputs. Their suggestions were  
 121 based on their expertise and understanding of indicators and processes.

122 Table 1: Eleven ecosystem services and their respective definitions (from Hattam et al. (2015)) that  
 123 were used in the expert workshop. \* indicate the ecosystem services that the workshop focussed on

<b>Service</b>	<b>Definition</b>
Food provision*	The availability of marine flora and fauna for human consumption that can be caught from the wild
Climate regulation	The contribution of the marine environment to the maintenance of a favourable climate
Disturbance prevention and coastal erosion prevention	The contribution of the marine ecosystem to the dampening of the intensity of environmental disturbances such as storm floods, tsunamis and hurricanes
Bioremediation (of waste)*	The removal of waste input by humans from the marine environment, e.g. excess nutrients
Biological control - checks and balances*	The contribution of marine ecosystems to the maintenance of population dynamics, resilience through food web dynamics, disease and pest control
Feeding habitat	Provision of habitats supporting enough food for marine species to participate in the trophic web
Migratory habitat	The contribution of a particular marine habitat for migratory species populations through the provision of safe passages for migration, resting and feeding areas
Nursery habitat	The contribution of a particular marine habitat to populations through the provision of critical habitat for juvenile maturation
Gene pool protection	The contribution of marine environments to the maintenance of viable gene pools through evolution. Processes which enhance adaptability of species to environmental change, and thereby the resilience of the ecosystem
Leisure and recreation*	The provision of opportunities for tourism, recreation and leisure that depend on a particular state of marine ecosystems
Aesthetic experience	The contribution of the marine environment to the existence of a landscape that generates a noticeable emotional response within an individual observer

124

125 **2.2 Development of a unified conceptual model**

126 All information gathered during the workshop was compiled and assessed. After the workshop a  
127 unified conceptual model was developed by combining the outputs created by all groups and  
128 incorporating the four key ecosystem services. All processes and species groups deemed important  
129 by workshop participants were included in the diagram as well as potential data sources and  
130 relevant ecosystem models. The diagram was then extended to incorporate examples of pressures  
131 that occur in the UK marine environment as well as management measures that would alleviate  
132 these example pressures.

### 133 **3. RESULTS**

#### 134 **3.1 Linking processes and components using a workshop**

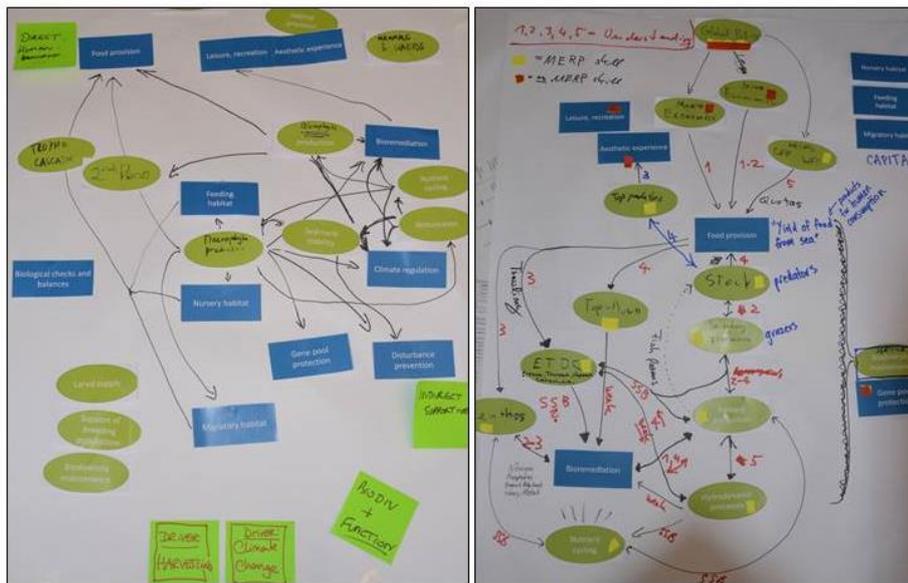
135 Thirty-five UK marine researchers with backgrounds in the following disciplines: mathematical  
136 ecosystem modelling, empirical and experimental ecology, interdisciplinary ecosystem service  
137 research and environmental economics, attended the workshop. They created four distinct  
138 conceptual diagrams linking ecosystem services to the ecological components and processes  
139 necessary to create them (Figure 1). They also gave information on potential data sources for these  
140 processes and components.

#### 141 **3.2 Generation of a unified conceptual model**

142 Based on the information gathered during the workshop a list was created of all the processes and  
143 components involved in the creation of the four services and contained information on potential  
144 data sources to use the conceptual diagram (Table 2). Definitions of all processes were  
145 comprehended if they differed among groups and list of example data sources was created  
146 (Appendix Table 2). The authors of this manuscript then firstly created a unified conceptual diagram  
147 based on all the information gathered during the workshop (Figure 2). Second, they extended the  
148 thus created diagram (Figure 2) to include example pressures and management options (Figure 3).

#### 149 **3.3 Description of ecosystem services contained in the conceptual diagram**

150 Four key ecosystem services were addressed during the workshop along with seven  
151 additional/potentially relevant ecosystem services. The key ecosystem services are derived from  
152 biotic ecosystem functions (as opposed to some services such as flood protection that can have a  
153 large abiotic component) and are subject to top-down and/or bottom-up processes of marine food  
154 webs. The four services were food provision, leisure and recreation, bioremediation of waste and  
155 biological control - checks and balances (from now on 'biological control'). The latter two were  
156 redefined to focus on aspects of these services that are strongly linked to the ecosystem structure  
157 and trophic interactions. The conceptual models developed by workshop attendees (examples in  
158 Figure 1) focussed on cycling of nutrients in the system as an example of bioremediation of waste,  
159 based on their particular expertise in this area and to reflect the interest in nutrient cycling through  
160 the structure of marine ecosystems. We therefore redefined the service 'bioremediation of waste' to  
161 'bioremediation of excess organic nutrients' (from now bioremediation). To define, measure and  
162 analyse resilience was considered beyond the scope of this study and therefore the definition of  
163 biological control – checks and balances was narrowed down to concentrate on the control of pest  
164 species such as harmful algal blooms and jellyfish blooms and their interactions on the ecosystem  
165 structure.



166

167 **Figure 1:** Two examples of diagrams created during the workshop by workshop attendees. Notes and  
 168 other information were written onto the flip chart paper during information collection

169

170 **3.3.1 Food provision**

171 The food provision service is driven by species groups rather than by processes, because the species  
 172 groups contribute to this service as goods that can be fished or harvested for human consumption.  
 173 Food provided by the marine environment in the UK consists of commercial fish and shellfish  
 174 (crustaceans and molluscs) but also to some extent macrophytes. The critical process leading to all  
 175 but macrophyte food provision was identified as secondary production which includes any  
 176 production of biomass that is not based on autotrophy, for example larval fish production.

177 **3.3.2 Leisure and recreation**

178 The marine environment can be enjoyed by humans for the benefit of leisure and recreation in  
 179 several ways such as swimming, angling and wildlife watching (above water through boat- or shore-  
 180 based observations or in water through sub-aqua diving and snorkelling). For this study, the leisure  
 181 and recreation service was largely linked to the presence of charismatic megafauna (or top  
 182 predators) that can be observed by participating in boat trips or visiting nesting colonies, such as  
 183 those of seabirds or seals. In addition, this service includes provision of resources for angling, sub-  
 184 aqua diving and snorkelling for example fish and invertebrate species (such as crustaceans collected  
 185 during rock pooling) and macrophytes (kelp forests, seagrass beds) for sub-aqua diving and  
 186 snorkelling. Clean water supply for swimming was also included and therefore leisure and recreation  
 187 is linked to both, bioremediation and biological control. as Some processes such as excessive primary  
 188 production can have a negative effect on leisure and recreation for example when a large biomass of  
 189 opportunistic macrophytes is produced, which may wash up on beaches reducing perceived  
 190 environmental quality for beach goers; or when harmful algal blooms occur that can reduce bathing  
 191 water quality to such an extent that beaches are closed to visitors.

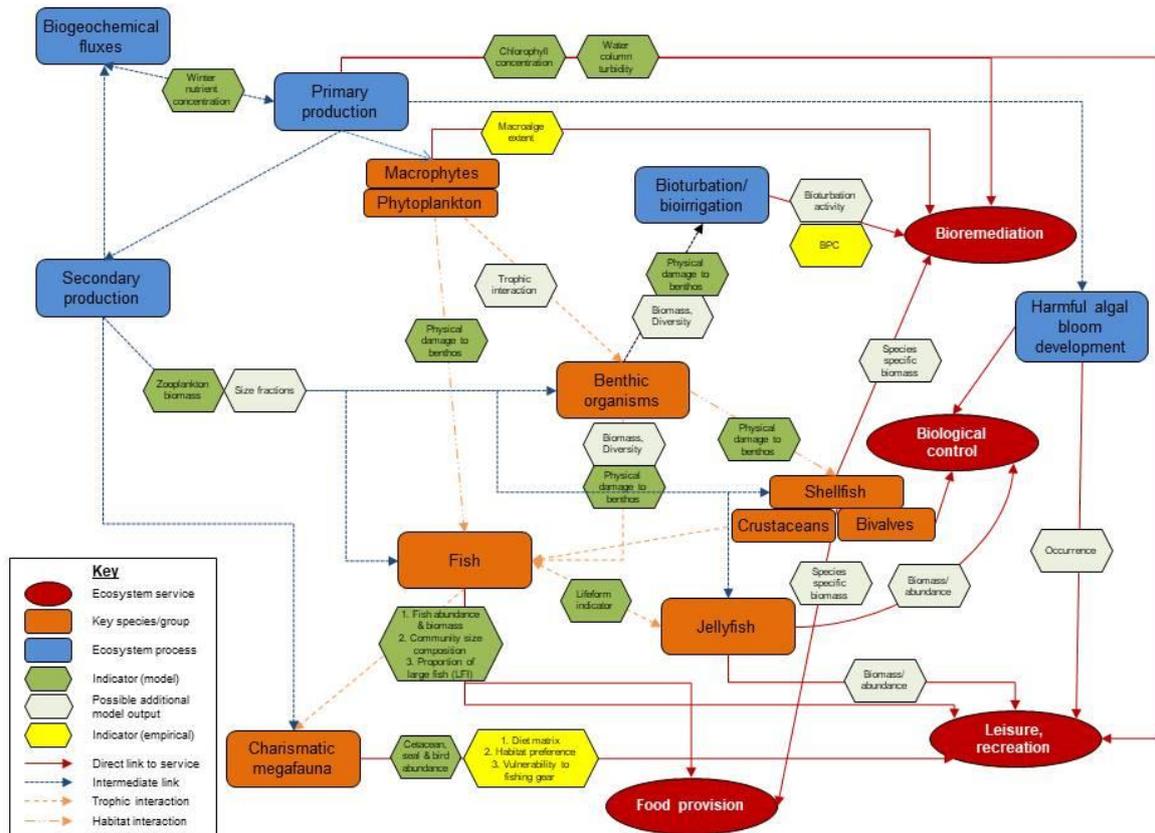
192 **3.3.3 Bioremediation (of waste)**

193 The service bioremediation involves many benthic organism groups because of the processes they  
194 carry out such as filter feeding or bioturbation which aid the cycling of nutrients through the  
195 ecosystem (e. g. Gray & Elliott 2009, Queirós et al. 2013). Macrophytes and phytoplankton remove  
196 excess organic nutrients from the water column (e.g. Riebesell 1989, Heip 1995, Diaz & Rosenberg  
197 2008). Filter feeders help to remove such nutrients and also some particulates from the water  
198 column by either using energy derived from ingested phytoplankton for growth and reproduction or  
199 excreting the digested phytoplankton in faecal pellets which sink to the sea bed (e. g. Lindahl et al.  
200 2005, Riisgård et al. 2011). Soft sediment infauna may contribute to this service through bioirrigation  
201 and bioturbation helping to draw organic matter, such as dead plankton and faecal pellets into the  
202 sediment and this temporarily, or sometimes permanently, removes excess nutrients from the  
203 ecosystem (e.g. Gray & Elliott 2009). Abiotic processes such as photochemical interactions, thermal  
204 degeneration, and abiotic transport including dilution and dispersion are also important processes  
205 for this service but were not addressed in this study. Nor were biotic transformations and  
206 bioaccumulation addressed because such processes are quite specific to the type of waste involved  
207 and the chemical transformations that take place within specific organisms.

#### 208 *3.3.4 Biological control – checks and balances*

209 Biological control is a service that can be difficult to define and in this study, Biological control –  
210 checks and balances has been defined as: the contribution of marine ecosystems to the maintenance  
211 of population dynamics, resilience through food web dynamics, disease and pest control. It can also  
212 be difficult to find suitable indicators for, but useful information is available concerning the  
213 occurrence and frequency of occurrence of jellyfish, opportunistic macrophytes or harmful algal  
214 blooms and these were retained in the conceptual model. These species can change the ecosystem  
215 and affect services negatively when occurring in high abundance. Harmful algal blooms (HABs) can  
216 lead to reduced water quality with consequences for bathing water quality and aquaculture,  
217 reducing both, the recreation and leisure as well as the food production services (e.g. Fleming et al.  
218 2006, Anderson 2009). Opportunistic macrophytes may develop large deposits on beaches and in  
219 the surf zone of beaches, with deleterious effects on underlying sediment processes (Raffaelli 2000,  
220 Cardoso et al. 2005) making access to the beaches unsafe and reducing the leisure and recreation  
221 service (e. g. Scanlan et al. 2007). Jellyfish can form blooms which also reduce bathing water quality  
222 and access to beaches (Ghermandi et al. 2015). Also they can destroy fish aquaculture if large  
223 smacks (swarms or blooms) of jellyfish drift into aquaculture nets, harming fish (Baxter et al. 2011).  
224 Filter feeding by bivalves and other benthic invertebrates can control opportunistic species such as  
225 harmful algal blooms by filtering them out of the water column. Predation on jellyfish through fish  
226 may reduce the abundance of such species helping to keep the ecosystem in balance.

227 All information gathered during the workshop was incorporated into one conceptual model to  
228 connect the four ecosystem services and the processes and biological components that aid in the  
229 development of those services (Figure 2).



230

231 **Figure 2:** Conceptual model for four marine ecosystem services incorporating ecosystem processes,  
 232 biotic components (species groups) and linkages between them. See legend and text for further  
 233 information.

234 **3.4 Indicators and data sources**

235 The key processes and species groups involved in the four chosen ecosystem services are listed in  
 236 Table 2. This table also includes examples of indicators, relevant models and potential relevant data  
 237 sources for each process and species group where they could be identified during the workshop.

238 **Table 2:** (a) Species groups and (b) Processes identified in this study that are involved in the delivery of ecosystem services. References for models and data  
 239 sources that are UK specific given in appendix Table 2

240 a)

<b>Species groups</b>	<b>Ecosystem services reliant on the component</b>	<b>Ecological function contributing to ecosystem services</b>	<b>Example species/groups</b>	<b>Indicators</b>	<b>Relevant models and example empirical data sources (in the UK)</b>
Microphytes	Bioremediation (nutrients), biological control, leisure and recreation	Nutrient removal from water column for growth, can improve water quality	Numerous phytoplankton species	Chlorophyll <i>a</i> concentration in seawater, biomass measures of species groups	ERSEM, Ecopath with Ecosim, Western Channel Observatory, SAHFOS
Macrophytes	Bioremediation, biological control, leisure and recreation	Nutrient removal from water column for growth, can improve water quality	Kelp, Seaweeds	Chlorophyll <i>a</i> measures, biomass measures of species groups	ERSEM, Ecopath with Ecosim, MarClim

<b>Species groups</b>	<b>Ecosystem services reliant on the component</b>	<b>Ecological function contributing to ecosystem services</b>	<b>Example species/groups</b>	<b>Indicators</b>	<b>Relevant models and example empirical data sources (in the UK)</b>
Benthic organisms	Bioremediation	Feed on detritus, bioturbation	Polychaetes, sediment-dwelling invertebrates	Abundance/biomass measures of species groups	ERSEM, Ecopath with Ecosim
Crustaceans	Food provision, Leisure and recreation, bioremediation of waste	Provide valuable protein, can be collected for recreational purposes	Edible crabs, prawns, amphipods, copepods	Abundance/biomass measures of species groups	Ecopath with Ecosim, International Council for the Exploration of the Sea
Bivalves	Food provision, Leisure and recreation	Provide valuable protein, can be collected for recreational purposes	Blue mussels, oysters, scallops	Abundance/biomass measures of species groups	Ecopath with Ecosim, International Council for the Exploration of the Sea
Jellyfish	Biological control, Leisure and recreation	Provide valuable protein, can be collected for recreational purposes	Compass jellyfish, moon jellyfish, Portuguese man-o-war	Abundance/biomass measures of species groups	Ecopath with Ecosim, ERSEM, SAHFOS, Western Channel Observatory, Marine Conservation Society

Species groups	Ecosystem services reliant on the component	Ecological function contributing to ecosystem services	Example species/groups	Indicators	Relevant models and example empirical data sources (in the UK)
Harmful algal blooms	Biological control, Leisure and recreation	Increase of harmful algae to such an extent as to cause ill health or death to humans, and marine animals, lead to decreased water quality	Microphytes	Chlorophyll <i>a</i> concentrations in seawater	ERSEM, SAHFOS, Western Channel Observatory
Fish	Food provision, Leisure and recreation	Provide valuable protein, angling, diving, snorkelling	Cod, haddock, anglerfish, some sharks	Abundance/biomass measures of species groups	Ecopath with Ecosim, StrathE2E, MIZER, FishSUMS, International Council for the Exploration of the Sea
Charismatic megafauna	Leisure and recreation	Ecotourism	Whales, dolphin, seals, birds, basking sharks	Abundance measures of species groups	Ecopath with Ecosim, StrathE2E, Seawatch Foundation

241

242 b)

243

Process name	Service it feeds into	Definition	Species groups involved in the process	Indicators	Relevant models and example empirical data sources
Biogeochemical fluxes	Bioremediation	Nutrients are cycled through the food web	Shellfish: crustaceans, bivalves, primary producers	Shellfish abundance, Chlorophyll <i>a</i> concentrations in seawater	ERSEM
Bioturbation	Bioremediation	Transport processes carried out by animals that directly or indirectly affect sediments	Shellfish, crustaceans, bivalve	Community bioturbation potential	ERSEM
Primary production	Food webs	Generation of biomass through (in photic zones) photosynthesis	Micro- and macrophytes	Chlorophyll <i>a</i> concentrations in seawater, macrophyte biomass	ERSEM, Ecopath with Ecosim, Strath E2E
Secondary production	Food provision	Turnover of biomass	Fish, Charismatic megafauna, jellyfish		Ecopath with Ecosim, Mizer, StrathE2E, FishSUMS

244 **3.4 Pressures and management measures**

245 Sustainable management should aim to maintain the an ecosystem capable of providing ecosystem  
246 services into the future (Elliott et al. 2014, Scharin et al. 2016). There are numerous anthropogenic  
247 pressures on the marine environment and much research has been carried out to improve our  
248 understanding the effects of such pressures and how human activities link to ecosystems (Elliott  
249 2011, Patrício et al. 2016, Elliott et al. 2017). Our conceptual model was extended to include the  
250 pressures: habitat degradation, eutrophication and overfishing and to add relevant example  
251 management measures. This links our framework to the widely used DPSIR (Drivers, Pressures, State  
252 change, Impact Response) framework which has now been extended to DAPSI(W)R(M) (Scharin et al.  
253 2016, Elliott et al. 2017). According to (Elliott et al. 2017) DAPSI(W)R(M) stands for: “Drivers of basic  
254 human needs require Activities which lead to pressures. The Pressures are the mechanisms of State  
255 change on the natural system which then leads to Impacts (on human Welfare). Those then require  
256 Responses (as Measures)”.

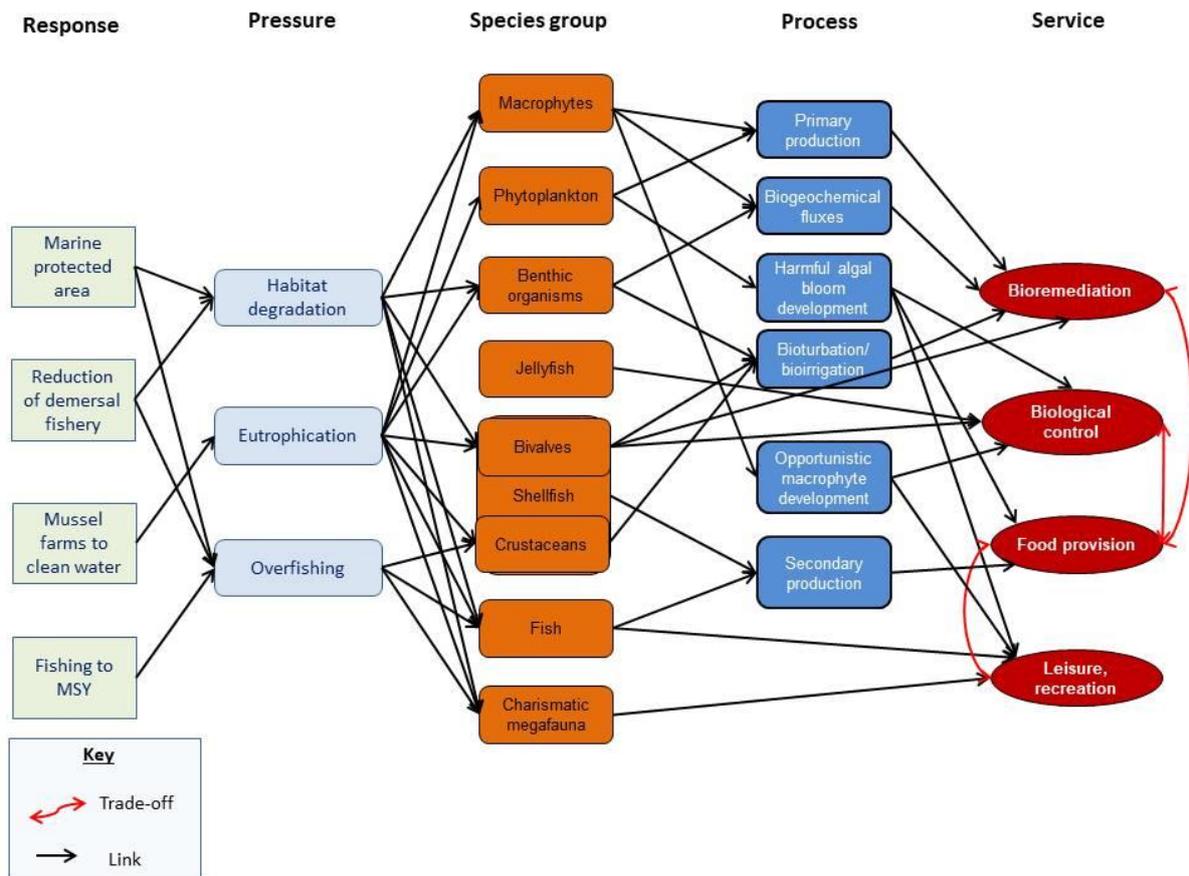
257  
258 The example pressures used in this study were chosen because they are relevant at regional  
259 management scales as opposed to global or exogenic pressures (sensu Elliott 2011, Elliott et al.  
260 2017) such as climate change. Figure 3 indicates the trade-offs between the ecosystem services that  
261 might arise from introducing management measures to address the pressures.  
262

263

264

265 **3.5 Trade-offs between ecosystem services**

266 Trade-offs between services occur when the components involved in one service are also part of  
267 another service or where accessing one service alters another. Several trade-offs between services  
268 were recognised in this study and all involved food provision (Figure 3). Bioremediation and food  
269 provision may be in trade-off if filter feeders that could be harvested for food take up pollutants and  
270 can then no longer be eaten. Trawling for demersal species for food provision disturbs the benthos  
271 and can interrupt processes necessary for the bioremediation service that are largely carried out by  
272 benthos. Shellfish filtering HABs out of the water column can no longer be consumed by humans,  
273 implying a trade-off between biological control and food provision. Leisure and recreation can be in  
274 a trade-off with food provision because an abundance of marine top predators such as mammals or  
275 birds may reduce the abundance of fish available for human consumption.



276

277 **Figure 3:** Conceptual model extended to include example pressures and management measures.  
 278 Colours as in Figure 2.

279 **4. DISCUSSION**

280 In this study a conceptual diagram was created linking ecosystem processes and components to four  
 281 selected ecosystem services. Inputs of 35 marine scientists attending a workshop were used as a  
 282 basis from which to create this model. It focuses on key processes and components involved in  
 283 delivering these ecosystem services and it thereby helps to reduce the complexity of the marine  
 284 ecosystem. The experts used the diagram creation process to identify data and indicators that may  
 285 be helpful for measuring ecosystem services. The model has subsequently been extended to include  
 286 example pressures and ameliorative management measures that are relevant to the UK and other  
 287 seas. This extended model (Figure 3) demonstrates how pressures are linked to ecosystem services  
 288 and develop understanding of trade-offs under different management options. It may help in the  
 289 communication between marine scientists and environmental managers and stakeholders by  
 290 clarifying and visualising the linkages between ecology and ecosystem services. Additionally, it  
 291 complements other conceptual frameworks for example those based on the DIPSR concept (Patrício  
 292 et al. 2016, Elliott et al. 2017) by linking the ecology to ecosystem services which can be integrated  
 293 into the broader DIPSR frameworks. Within the UK marine environment, the list of models and data  
 294 collections can also help to locate relevant data that may be useful in management decisions.

295 Environmental managers face the large challenge of assimilating complex information, and then  
 296 reaching an understanding of the information from which they can draw suitable management

297 actions (Lester et al. 2013, Fletcher et al. 2014, Holt et al. 2016). An approach similar to the current  
298 study was taken to link water quality to human well-being and to improve assessment of ecosystem  
299 services. Keeler et al. (2012) linked water quality parameters to changes in water quality (for  
300 example increased nitrogen leading to algal blooms). These were then connected to affected  
301 ecosystem services such as changes in recreational fishing due to abundance changes of fish. Like in  
302 the current study, the authors then elected appropriate biophysical models to be able to move the  
303 conceptual model towards a quantitative approach of ecosystem service assessment.

304

305 Understanding the complexity of marine ecosystems and the way they provide ecosystem services is  
306 crucial to support management, but this must not come at the cost of accuracy and understanding  
307 of how ecosystems and exploitation of their services can be managed sustainably and effectively.  
308 The trade-offs between food provision and the other services addressed in this study provide a good  
309 example of this. Fish and shellfish harvested for human consumption also fulfil other roles in the  
310 ecosystem. This indicates that one route by which the marine environment should be managed to  
311 achieve long-term, sustainable use of all services is by managing fisheries and doing this with these  
312 other services in mind, rather than only considering the size of stocks needed for sustaining fisheries.  
313 A comparable situation has recently been highlighted for arable lands. Holt et al. (2016) argue that  
314 policies influencing agronomic decisions rarely take account of the trade-offs between food  
315 production, biodiversity conservation and ecosystem service provision. The authors therefore  
316 suggest an approach that can reveal these trade-offs and thereby help to make appropriate policy  
317 and management decisions. Their approach linked the effects of different types of pesticides with  
318 the effects they may have on different animal groups and the ecosystem services they provide. This  
319 allows policy makers to assess the trade-offs they are facing when aiming to support biodiversity and  
320 ecosystem service provision at the same time as regulating agriculture (Holt et al. 2016).

321

322 Using marine ecosystem experts to create a conceptual diagram containing information on services,  
323 processes and components was an approach that helped understand complexity by focusing on key  
324 links in the system, without losing accuracy. Data required to model ecosystem services are often  
325 scarce (Townsend et al. 2014, Cavanagh et al. 2016). The outputs of the workshop demonstrate that  
326 within UK marine waters, data are already available either through modelling outputs or empirical  
327 data collections. Gathering information on relevant and available datasets means that it is possible  
328 to take development of the conceptual model further, possibly into a numerical model which can be  
329 used as a tool to support marine planning, licensing decisions and development of management  
330 measures in the future. The conceptual models can be used in the communication between scientists  
331 and environmental managers and policy makers. Table 2 containing indicators and data sources for  
332 processes and species groups provided in this study should be considered as a living document that  
333 can adapted and extended when new data are created either empirically or through modelling at  
334 relevant spatial and temporal scales. Likewise, the conceptual diagram presented here will need to  
335 be adapted to include new scientific outputs as well as information specific to different regions.

#### 336 **4.1 Conclusions**

337 The aim of this study was to create a conceptual model that brings together a holistic view of the  
338 ecosystem, its processes and multiple ecosystem services, using UK marine waters as a case study.  
339 This enables the assessment of trade-offs that arise between these services under different  
340 management scenarios. The conceptual models, which consider four different ecosystem services,

341 are a step from conceptual to evidence-based marine science. They can be used to communicate  
342 with policy makers and regional managers to support them to take sustainable management  
343 decisions. Ecologically, the models are an important step towards improving our understanding of  
344 how the regulation of key ecosystem services are affected by top-down and bottom-up processes.  
345 They will also help to integrate this knowledge and understanding into existing ecosystem models.

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