Marine Pollution Bulletin 141 (2019) 236–243

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

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

Stefanie Broszeit, Nicola J. Beaumont, Tara L. Hooper, Paul J. Somerfield, Melanie C. Austen*

Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, UK

A R T I C L E I N F O

Keywords:
Marine ecosystem services
Conceptual model
Expert workshop
Trade-offs
Management measures
Indicators

A B S T R A C T

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

1. Introduction

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

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

Ecosystem service studies have tended to focus on the link between biodiversity and a single ecosystem service, yet this is likely to lead to an underestimation of biodiversity effects on services because species often carry out a number of ecosystem functions which may each contribute to several services (Cardinale et al., 2012; Balvanera et al., 2013). For example, in the marine environment fish catch as a measure of the food provision service is easily quantified compared to regulatory or habitat services and can be the focus of ecosystem service and valuation studies (Cavanagh et al., 2016; Barbier, 2017). Turner et al. (2014) linked ecosystem services to ecosystem processes and components and this was an important step in linking ecological research with human well-being and economics while focussing on ecosystem services other than food provision. They also created conceptual models linking six ecosystem services with the ecosystem components and processes, but they created a model for each ecosystem service separately. However it is crucial that studies include multiple services to allow the

* Corresponding author.
E-mail address: mcva@pml.ac.uk (M.C. Austen).

https://doi.org/10.1016/j.marpolbul.2019.02.051
Received 4 September 2017; Received in revised form 11 January 2019; Accepted 23 February 2019
Available online 28 February 2019

Table 1
Eleven ecosystem services and their respective definitions (from Hattam et al. (2015)) that were used in the expert workshop.

Service	Definition
Food provision[a]	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)[a]	The removal of waste input by humans from the marine environment, e.g. excess nutrients
Biological control - checks and balances[a]	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[a]	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

[a] Indicate the ecosystem services that the workshop focussed on.

capture of trade-offs among them and to explore the complexity of the system (Lester et al., 2013; Mach et al., 2015; Cavanagh et al., 2016). Additionally, knowledge and tools necessary to quantify and forecast changes to ecosystem services under different management measures need to be developed further (Daily et al., 2009; Mach et al., 2015). Such tools would ideally help to understand if or why policy instruments aimed at halting biodiversity loss and decline of ecosystem services have failed or succeeded (Carpenter et al., 2009).

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

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

In this study, we develop a conceptual model that will help gain required understanding to support evidence-based approaches. We also show an extension of this model including examples that demonstrate by what pathways pressures and management measures can influence ecosystem services. Abiotic chemical or physical processes support some ecosystem services but here we focus on those services provided by the living components of the marine ecosystem. The aims of this study were:

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

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

2. Methods

2.1. Identify ecosystem processes linked to services using a workshop

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

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

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

2.2. Development of a unified conceptual model

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

3. Results

3.1. Linking processes and components using a workshop

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

3.2. Generation of a unified conceptual model

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

3.3. Description of ecosystem services contained in the conceptual diagram

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

3.3.1. Food provision

The food provision service is driven by species groups rather than by processes, because the species groups contribute to this service as goods that can be fished or harvested for human consumption. Food provided by the marine environment in the UK consists of commercial fish and

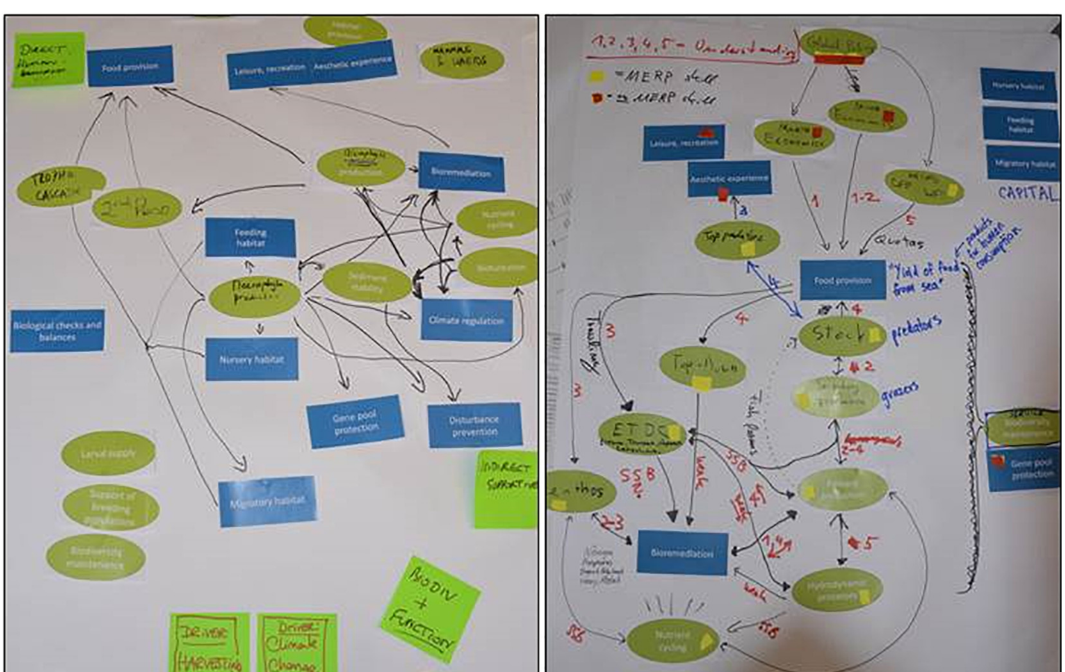

Fig. 1. Two examples of diagrams created during the workshop by workshop attendees. Notes and other information were written onto the flip chart paper during information collection.

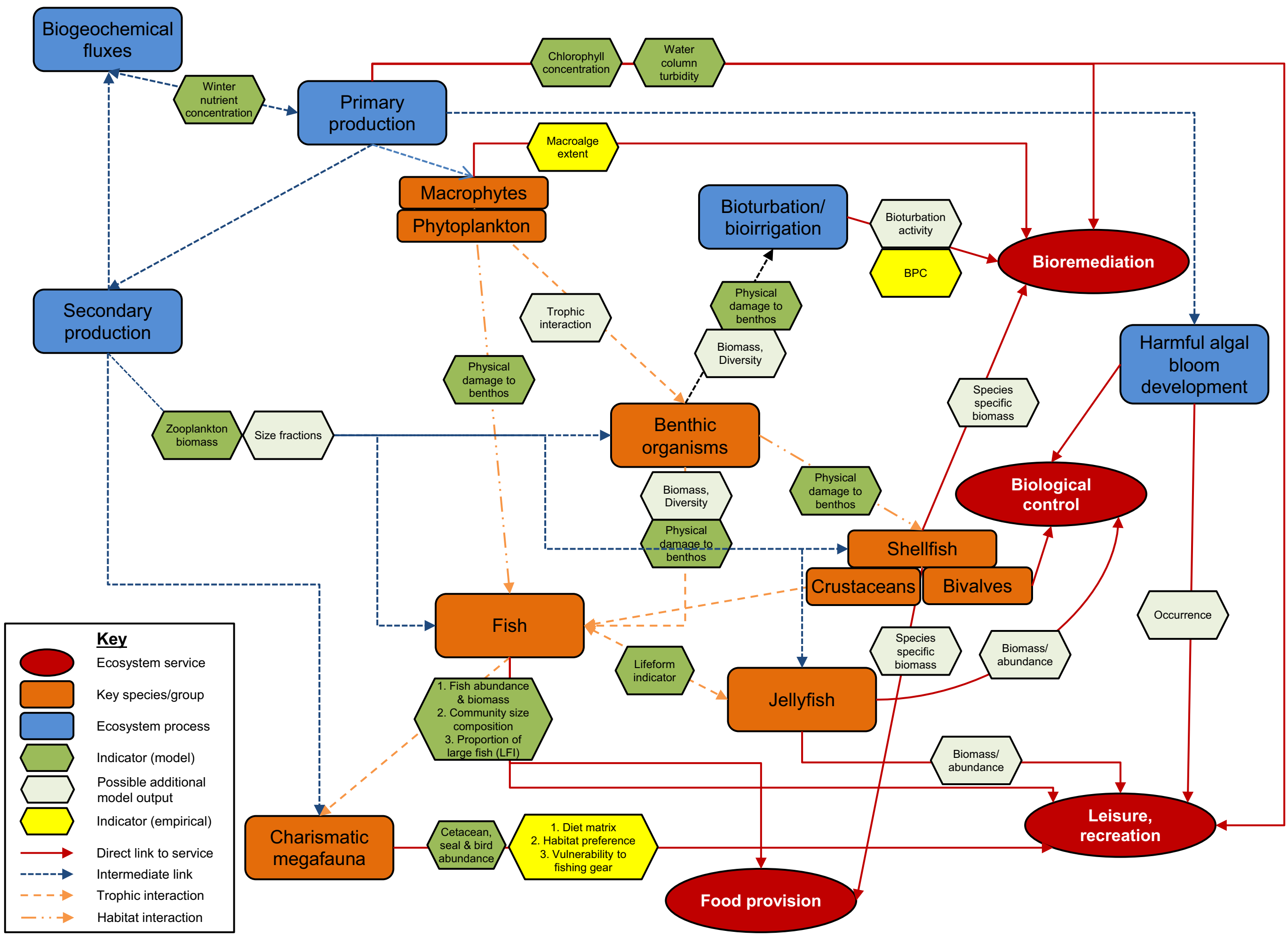

Fig. 2. Conceptual model for four marine ecosystem services incorporating ecosystem processes, biotic components (species groups) and linkages between them. See legend and text for further information.

shellfish (crustaceans and molluscs) but also to some extent macrophytes. The critical process leading to all but macrophyte food provision was identified as secondary production which includes any production of biomass that is not based on autotrophy, for example larval fish production.

3.3.2. *Leisure and recreation*

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

3.3.3. *Bioremediation (of excess organic nutrients)*

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

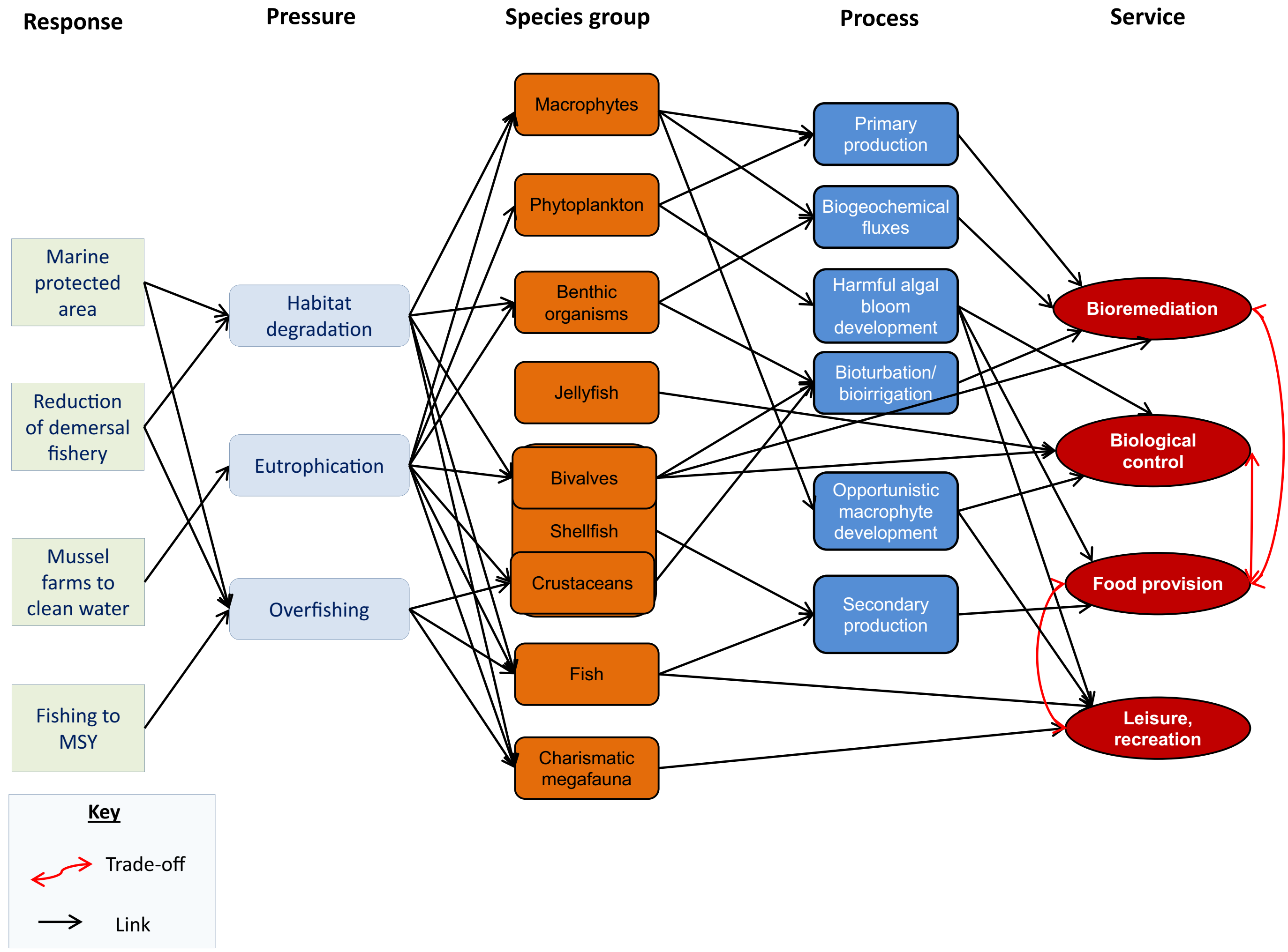

Fig. 3. Conceptual model extended to include example pressures and management measures. Colours as in Fig. 2.

3.3.4. Biological control – checks and balances

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

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

3.4. Indicators and data sources

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

3.5. Pressures and management measures

Sustainable management should aim to maintain an ecosystem capable of providing ecosystem services into the future (Elliott et al., 2014; Scharin et al., 2016). There are numerous anthropogenic pressures on the marine environment and much research has been carried out to improve our understanding the effects of such pressures and how human activities link to ecosystems (Elliott, 2011; Patrício et al., 2016; Elliott et al., 2017). Our conceptual model was extended to include the pressures: habitat degradation, eutrophication and overfishing and to add relevant example management measures. This links our framework

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 sources that are UK specific given in Supplementary Table 2.

a)

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)
Microphytes	Bioremediation (nutrients), biological control, leisure and recreation	Nutrient removal from water column for growth, can improve water quality	Numerous phytoplankton species	Chlorophyll *a* 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 *a* measures, biomass measures of species groups	ERSEM, Ecopath with Ecosim, MarClim
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
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 *a* 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

b)

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 *a* 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 *a* 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

to the widely used DPSIR (Drivers, Pressures, State change, Impact Response) framework which has now been extended to DAPSI(W)R(M) (Scharin et al., 2016; Elliott et al., 2017). According to (Elliott et al., 2017) DAPSI(W)R(M) stands for: "Drivers of basic human needs require Activities which lead to pressures. The Pressures are the mechanisms of State change on the natural system which then leads to Impacts (on human Welfare). Those then require Responses (as Measures)".

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

3.6. Trade-offs between ecosystem services

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

4. Discussion

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

Environmental managers face the large challenge of assimilating complex information, and then reaching an understanding of the information from which they can draw suitable management actions (Lester et al., 2013; Fletcher et al., 2014; Holt et al., 2016). An approach similar to the current study was taken to link water quality to human well-being and to improve assessment of ecosystem services. Keeler et al. (2012) linked water quality parameters to changes in water quality (for example increased nitrogen leading to algal blooms). These were then connected to affected ecosystem services such as changes in recreational fishing due to abundance changes of fish. Like in the current study, the authors then elected appropriate biophysical models to be able to move the conceptual model towards a quantitative approach of ecosystem service assessment.

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

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

4.1. Conclusions

The aim of this study was to create a conceptual model that brings together a holistic view of the ecosystem, its processes and multiple ecosystem services, using UK marine waters as a case study. This enables the assessment of trade-offs that arise between these services under different management scenarios. The conceptual models, which consider four different ecosystem services, are a step from conceptual to evidence-based marine science. They can be used to communicate with policy makers and regional managers to support them to take sustainable management decisions. Ecologically, the models are an important step towards improving our understanding of how the regulation of key ecosystem services is affected by top-down and bottom-up processes. They will also help to integrate this knowledge and understanding into existing ecosystem models.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2019.02.051.

Acknowledgements

This work and the workshop (held in May 2015) were supported by the Natural Environment Research Council and Department for Environment, Food and Rural Affairs [grant number NE/L003279/1, Marine Ecosystems Research Programme]. The authors would like to thank all the workshop attendees, listed in Supplementary Table 1 for their input into the model development. We would also like to thank one anonymous reviewer for valuable comments that helped to improve the manuscript.

References

Anderson, D.M., 2009. Approaches to monitoring, control and management of harmful algal blooms (HABs). Ocean Coast. Manag. 52, 342–347.
Balvanera, P., Siddique, I., Dee, L., Paquette, A., Isbell, F., Gonzalez, A., Byrnes, J., O'Connor, M.I., Hungate, B.A., Griffin, J.N., 2013. Linking biodiversity and ecosystem services: current uncertainties and the necessary next steps. BioScience 64, 49–57.
Barbier, E.B., 2017. Marine ecosystem services. Curr. Biol. 27, R507–R510.
Baxter, E.J., Sturt, M.M., Ruane, N.M., Doyle, T.K., McAllen, R., Harman, L., Rodger, H.D., 2011. Gill damage to Atlantic salmon (Salmo salar) caused by the common jellyfish (Aurelia aurita) under experimental challenge. PLoS One 6, e18529.
Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404.
Börger, T., Beaumont, N.J., Pendleton, L., Boyle, K.J., Cooper, P., Fletcher, S., Haab, T., Hanemann, M., Hooper, T.L., Hussain, S.S., Portela, R., Stithou, M., Stockill, J., Taylor, T., Austen, M.C., 2014. Incorporating ecosystem services in marine planning: the role of valuation. Mar. Policy 46, 161–170.
Broszeit, S., Hattam, C., Beaumont, N., 2016. Bioremediation of waste under ocean acidification: reviewing the role of *Mytilus edulis*. Mar. Pollut. Bull. 103, 5–14.
Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S., Naeem, S., 2012. Biodiversity loss and its impact on humanity. Nature 486, 59–67.
Cardoso, F., Baltazar, P., Bautista, J., 2005. The early development of the Patagonian squid *Loligo gahi* D'Orbigny, 1835 in Peruvian waters (Cephalopoda: Loliginidae). Rev. Peru. Biol. 12, 369–376.
Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFries, R.S., Díaz, S., Dietz, T., Duraiappah, A.K., Oteng-Yeboah, A., Pereira, H.M., Perrings, C., Reid, W.V., Sarukhan, J., Scholes, R.J., Whyte, A., 2009. Science for managing ecosystem services: beyond the millennium ecosystem assessment. Proc. Natl. Acad. Sci. 106, 1305–1312.
Cavanagh, R.D., Broszeit, S., Pilling, G., Grant, S.M., Murphy, E.J., Austen, M.C., 2016. Valuing biodiversity and ecosystem services – a useful way to manage and conserve marine resources? Proc. R. Soc. Lond. B Biol. Sci. 283, 20161635.
Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., Ricketts, T.H., Salzman, J., Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. Front. Ecol. Environ. 7, 21–28.
Diaz, R., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.
Elliott, M., 2011. Marine science and management means tackling exogenic unmanaged pressures and endogenic managed pressures – a numbered guide. Mar. Pollut. Bull. 62, 651–655.
Elliott, M., Cutts, N.D., Trono, A., 2014. A typology of marine and estuarine hazards and risks as vectors of change: a review for vulnerable coasts and their management. Ocean Coast. Manag. 93, 88–99.
Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., de Jonge, V.N., Turner, R.K., 2017. "And DPSIR begat DAPSI(W)R(M)!" - a unifying framework for marine environmental management. Mar. Pollut. Bull. 118, 27–40.
Fleming, L.E., Broad, K., Clement, A., Dewailly, E., Elmir, S., Knap, A., Pomponi, S.A., Smith, S., Solo Gabriele, H., Walsh, P., 2006. Oceans and human health: emerging public health risks in the marine environment. Mar. Pollut. Bull. 53, 545–560.
Fletcher, P.J., Kelble, C.R., Nuttle, W.K., Kiker, G.A., 2014. Using the integrated ecosystem assessment framework to build consensus and transfer information to managers. Ecol. Indic. 44, 11–25.
Gattuso, J.-P., Magnan, A., Billé, R., Cheung, W.W.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Pörtner, H.-O., Rogers, A.D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., Turley, C., 2015. Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. Science 349, aac4722.
Ghermandi, A., Galil, B., Gowdy, J., Nunes, P.A.L.D., 2015. Jellyfish outbreak impacts on recreation in the Mediterranean Sea: welfare estimates from a socioeconomic pilot survey in Israel. Ecosyst. Serv. 11, 140–147.
Gray, J., Elliott, M., 2009. Ecology of Marine Sediments: From Science to Management. Oxford University Press, Oxford.
Haines-Young R, Potschin M (2013) CICES V4.3 – Revised report prepared following consultation on CICES Version 4, August–December 2012. EAA.
Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., 2008. A global map of human impact on marine ecosystems. Science 319, 948–952.
Hattam, C., Atkins, J.P., Beaumont, N., Börger, T., Böhnke-Henrichs, A., Burdon, D., de Groot, R., Hoefnagel, E., Nunes, P.A., Piwowarczyk, J., 2015. Marine ecosystem services: linking indicators to their classification. Ecol. Indic. 49, 61–75.
Heip, C., 1995. Eutrophication and zoobenthos dynamics. Ophelia 41, 113–136.
Holt, A.R., Alix, A., Thompson, A., Maltby, L., 2016. Food production, ecosystem services and biodiversity: we can't have it all everywhere. Sci. Total Environ. 573, 1422–1429.
Hyder, K., Rossberg, A.G., Allen, J.I., Austen, M.C., Barciela, R.M., Bannister, H.J., Blackwell, P.G., Blanchard, J.L., Burrows, M.T., Defriez, E., Dorrington, T., Edwards, K.P., Garcia-Carreras, B., Heath, M.R., Hembury, D.J., Heymans, J.J., Holt, J., Houle Jennifer, E., Jennings, S., Mackinson, S., Malcolm, S.J., McPike, R., Mee, L., Mills, D.K., Montgomery, C., Pearson, D., Pinnegar, J.K., Pollicino, M., Popova, E.E., Rae, L., Rogers, S.I., Speirs, D., Spence, M.A., Thorpe, R., Turner, R.K., van der Molen, J., Yool, A., Paterson, D.M., 2015. Making modelling count - increasing the contribution of shelf-seas community and ecosystem models to policy development and management. Mar. Policy 61, 291–302.
Jackson, J.B., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293, 629–637.
Keeler, B.L., Polasky, S., Brauman, K.A., Johnson, K.A., Finlay, J.C., O'Neill, A., Kovacs, K., Dalzell, B., 2012. Linking water quality and well-being for improved assessment and valuation of ecosystem services. Proc. Natl. Acad. Sci. 109, 18619–18624.
Knights, A.M., Koss, R.S., Robinson, L.A., 2013. Identifying common pressure pathways from a complex network of human activities to support ecosystem-based management. Ecol. Appl. 23, 755–765.
Lester, S.E., Costello, C., Halpern, B.S., Gaines, S.D., White, C., Barth, J.A., 2013. Evaluating tradeoffs among ecosystem services to inform marine spatial planning. Mar. Policy 38, 80–89.
Lindahl, O., Hart, R., Hernroth, B., Kollberg, S., Loo, L.-O., Olrog, L., Rehnstam-Holm, A.-S., Svensson, J., Svensson, S., Syversen, U., 2005. Improving marine water quality by mussel farming: a profitable solution for Swedish society. Ambio 34, 131–138.
Mach, M.E., Martone, R.G., Chan, K.M.A., 2015. Human impacts and ecosystem services: insufficient research for trade-off evaluation. Ecosyst. Serv. 16, 112–120.
MEA, 2005. Millennium Ecosystem Assessment - Ecosystems and Human Well-being. vol. 5 Island Press Washington, DC.
Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. Science 325, 419–422.
Patrício, J., Elliott, M., Mazik, K., Papadopoulou, K.-N., Smith, C.J., 2016. DPSIR—two decades of trying to develop a unifying framework for marine environmental management? Front. Mar. Sci. 3.
Potschin-Young, M., Haines-Young, R., Görg, C., Heink, U., Jax, K., Schleyer, C., 2018. Understanding the role of conceptual frameworks: reading the ecosystem service cascade. Ecosyst. Serv. 29, 428–440.
Queirós, A.M., Birchenough, S.N., Bremner, J., Godbold, J.A., Parker, R.E., Romero-Ramirez, A., Reiss, H., Solan, M., Somerfield, P.J., Colen, C., 2013. A bioturbation classification of European marine infaunal invertebrates. Ecol. Evol. 3, 3958–3985.
Raffaelli, D., 2000. Interactions between macro-algal mats and invertebrates in the Ythan estuary, Aberdeenshire, Scotland. Helgol. Mar. Res. 54, 71–79.
Riebesell, U., 1989. Comparison of sinking and sedimentation rate measurements in a diatom winter/spring bloom. Mar. Ecol. Prog. Ser. 54, 109–119.
Riisgård, H.U., Egede, P.P., Barreiro Saavedra, I., 2011. Feeding behaviour of the mussel, *Mytilus edulis*: new observations, with a minireview of current knowledge. J. Mar. Biol. 2011.
Scanlan, C.M., Foden, J., Wells, E., Best, M.A., 2007. The monitoring of opportunistic macroalgal blooms for the water framework directive. Mar. Pollut. Bull. 55, 162–171.
Scharin, H., Ericsdotter, S., Elliott, M., Turner, R.K., Niiranen, S., Blenckner, T., Hyytiäinen, K., Ahlvik, L., Ahtiainen, H., Artell, J., 2016. Processes for the sustainable stewardship of marine environments. Ecol. Econ. 128, 55–67.
Strong, J.A., Andonegi, E., Bizsel, K.C., Danovaro, R., Elliott, M., Franco, A., Garces, E., Little, S., Mazik, K., Moncheva, S., 2015. Marine biodiversity and ecosystem function relationships: the potential for practical monitoring applications. Estuar. Coast. Shelf Sci. 161, 46–64.
Sutherland, W.J., Freckleton, R.P., Godfray, H.C.J., Beissinger, S.R., Benton, T., Cameron, D.D., Carmel, Y., Coomes, D.A., Coulson, T., Emmerson, M.C., Hails, R.S., Hays, G.C., Hodgson, D.J., Hutchings, M.J., Johnson, D., Jones, J.P.G., Keeling, M.J., Kokko, H., Kunin, W.E., Lambin, X., Lewis, O.T., Malhi, Y., Mieszkowska, N., Milner-Gulland, E.J., Norris, K., Phillimore, A.B., Purves, D.W., Reid, J.M., Reuman, D.C., Thompson, K., Travis, J.M.J., Turnbull, L.A., Wardle, D.A., Wiegand, T., 2013. Identification of 100 fundamental ecological questions. J. Ecol. 101, 58–67.
TEEB (2010) The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations. Earthscan, London and Washington.
Townsend, M., Thrush, S.F., Lohrer, A.M., Hewitt, J.E., Lundquist, C.J., Carbines, M., Felsing, M., 2014. Overcoming the challenges of data scarcity in mapping marine ecosystem service potential. Ecosyst. Serv. 8, 44–55.
Turner K, Schaafsma M, Elliott M, Burdon D, Atkins J, Jickells T, Tett P, Mee L, van Leeuwen S, Barnard S, Luisetti T, Paltriguera L, Palmieri G, Andrews J (2014) UK National Ecosystem Assessment Follow-on. Work Package Report 4: Coastal and marine ecosystem services: principles and practice. UNEP-WCMC, LWEC, UK.
Van Wensem, J., Calow, P., Dollacker, A., Maltby, L., Olander, L., Tuvendal, M., Van Houtven, G., 2016. Identifying and assessing the application of ecosystem services approaches in environmental policies and decision making. Integr. Environ. Assess. Manag. 9999, 1–10.