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Making modelling count - increasing the contribution of shelf-seas community and ecosystem models to policy development and management


a. Centre for Environment, Fisheries & Aquaculture Science, Lowestoft Laboratory, Pakefield Road, Lowestoft, NR330HT, UK.
b. Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, UK.
c. Hadley Centre & National Centre for Ocean Forecasting, Met Office, Fitzroy Road, Exeter EX1 3PB, UK.
d. Animal & Plant Sciences, University of Sheffield, Alfred Denny Building, Western Bank Sheffield S10 2TN, UK.
e. School of Mathematics & Statistics, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, UK.
f. Institute for Marine and Antarctic Studies, University of Tasmania, 20 Castray Explanade, Battery Point, Tasmania 7004, Australia.
g. Scottish Association for Marine Science, Scottish Marine Institute, Oban, Argyll PA37
IQA, UK.

h. Imperial College London, Silwood Park Campus, Buckhurst Road, Ascot, Berkshire SL5
7PY, UK.

i. Department for Environment, Food & Rural Affairs, Nobel House, 17 Smith Square,
London SW1P 3JR, UK.

j. Estuarine & Coastal Monitoring & Assessment Service, Environment Agency, Manley
House, Kestrel Way, Exeter EX2 7LQ, UK.

k. Department of Mathematics and Statistics, University of Strathclyde, Livingstone Tower,
26 Richmond Street, Glasgow, G1 1XH, Scotland

l. National Oceanography Centre, Joseph Proudman building, 6 Brownlow Street, Liverpool
L3 5DA, UK.

m. School of Biological Sciences, Queen's University Belfast, Medical Biology Centre, 97
Lisburn Road, Belfast BT9 7BL, Northern Ireland.

n. National Oceanography Centre, University of Southampton Waterfront Campus, European
Way, Southampton SO14 3ZH, UK

o. Centre for Environment, Fisheries and Aquaculture Science, Weymouth Laboratory,
Barrack Road, Weymouth, Dorset DT4 8UB, UK

p. School of Environmental Sciences, University of East Anglia, Norwich Research Park,
Norwich NR4 7TJ, UK.

q. University of St Andrews, School of Biology, Scottish Oceans Institute, East Sands, St
Andrews, KY16 8LB, UK.
*Corresponding author:* Kieran Hyder, Centre for Environment, Fisheries & Aquaculture Science (Cefas), Lowestoft Laboratory, Pakefield Road, Lowestoft, NR330HT, UK. Tel: +44 (0)1502 524501, e-mail: kieran.hyder@cefas.co.uk
Abstract

Marine legislation is becoming more complex and marine ecosystem-based management is specified in national and regional legislative frameworks. Shelf-seas community and ecosystem models (hereafter termed ecosystem models) are central to the delivery of ecosystem-based management, but there is limited uptake and use of model products by decision makers in Europe and the UK in comparison with other countries. In this study, the challenges to the uptake and use of ecosystem models in support of marine environmental management are assessed using the UK capability as an example. The UK has a broad capability in marine ecosystem modelling, with at least 14 different models that support management, but few examples exist of ecosystem modelling that underpin policy or management decisions. To improve understanding of policy, and management issues that can be addressed using ecosystem models, a workshop was convened that brought together advisors, assessors, biologists, social scientists, economists, modellers, statisticians, policy makers, and funders. Some policy requirements that can be addressed without further model development were identified including: attribution of environmental change to underlying drivers, integration of models and observations to develop more efficient monitoring programmes, assessment of indicator performance for different management goals, and the costs and benefit of legislation. Multi-model ensembles are being developed in cases where many models exist, but model structures are very diverse making a standardised approach of combining outputs a significant challenge, and there is need for new methodologies for describing, analysing, and visualising uncertainties. A stronger link to social and economic systems is needed to increase the range of policy-related questions that can be addressed. It is also important to improve communication between policy and modelling communities so that there is a shared understanding of strengths and limitations of ecosystem models.
Keywords: ecosystem models; marine policy and management; UK environmental assessment, management, and monitoring.

Highlights (submit in a separate file – 3 to 5 bullet points):

- Ecosystem models have significant potential to support decision-making, but UK examples are limited.
- Ecosystem models would be more widely used if there was better awareness of model capabilities, documented quality assurance, and the uncertainties presented.
- Ecosystem modelling developments of high immediate value to policy makers and priorities to fill gaps in capability are identified for the UK.
- Multidisciplinary community of policy makers, modellers, statisticians, and data scientists are needed that co-develop ecosystem models.
1. Introduction

Marine legislation is becoming more complex as a consequence of increasing and more diverse use of the sea [1]. Commitments to marine ecosystem-based management that influence the UK are specified in national and regional legislative frameworks including the Marine Strategy Framework Directive (MSFD) [2], Common Fisheries Policy (CFP) [3], and the Water Framework Directive (WFD) [4]. However, the funding to provide the empirical evidence base that underpins monitoring, assessment, and management in support of these policies is decreasing in relative terms, requiring increasingly cost-effective decision tools for operational management and scenario planning. The key requirements for decision-makers are to understand links between human and environmental pressures and the state of the environment, to determine suitable management measures to meet objectives, to track progress in relation to those objectives, and to assess the performance of management options based on their environmental, social and economic consequences [5–7]. Shelf-seas community and ecosystem models (hereafter termed ecosystem models) can help to meet these requirements. Specific examples of contributions could include testing the sensitivity of indicators, increasing the cost-effectiveness of monitoring programmes, and supporting practical application of theoretical concepts like maximum sustainable yield (MSY).

Ecosystem models often differs fundamentally from models of physical systems because ecosystem dynamics are rarely only governed by physical laws and include biological feedbacks allowing for more complex dynamics. Thus, it is usually important to embrace model diversity to account for uncertainty about the most realistic structure of the model. Consequently, multi-model ensemble approaches similar to that used by the Intergovernmental Panel on Climate Change (IPCC) for climate projections [8] can be used to convey uncertainty that results from differences in structure; an approach is starting to be applied to advice on the management of fisheries [9].
Ecosystem models could make a much greater contribution to the evidence base that underpins policy development and decision-making, because they allow a-priori testing of policies and management scenarios and quantification of the risk and uncertainty. In most cases, it is impossible to assess the performance of policies and potential management measures without models. For models to fulfil a greater role in policy development and decision-making, and for the associated advice to be treated as credible, salient and legitimate, the modelling approaches used need to be more transparent, verifiable, and repeatable than they are at present.

Ecosystem models are increasingly used in support of marine environmental assessment, management, and policy development in other parts of the world including USA and Australia (e.g. [10,11]), but are not routinely used in the UK and Europe. In this paper, the prospects for increasing the contribution of community and ecosystem models to the evidence base that underpins assessment, management and policy support is assessed. Focussing on the UK shelf-seas community and ecosystem modelling capability, the range of models available are reviewed, actions expected to increase the uptake and use of these models in environmental management are identified, and priorities for model development, application and presentation are highlighted.

2. UK ecosystem modelling capability and its impact on policy

Many different global marine ecosystem models have been developed [12] and extensive intercomparisons have been made [13], but here the focus is on regional models (e.g. shelf-wide, regional sea) as these have the most direct relevance for application to UK marine environmental policy and management including regulation. UK institutes and universities already use many classes of models that represent different components of the ecosystem. These range from models of biogeochemistry and low trophic levels (e.g. [14]) to
size-based approaches (e.g. [15–18]) and models of the whole food web (e.g. [19,20]). Some
ecosystem models have been coupled to physical models and aim to represent the entire
system from physics to fishers [21]. Models vary in structure and parameterisation since they
have been developed to address different questions by researchers with different philosophies
and approaches. For example, ERSEM was originally developed as an end-to-end ecosystem
model to study nutrient cycling and planktonic ecosystem dynamics [14], the Population-
Dynamical Matching Model (PDMM) (e.g. [22,23]) was constructed to develop theoretical
understanding of food-web patterns and biodiversity [24,25], and Ecopath with Ecosim
(EwE) to assess the impacts of fisheries on food webs and consequences for fisheries (e.g.
[26]).

**INSERT FIGURE 1 HERE**

At least fourteen different marine ecosystem models are being used in the UK [Table 1 and
model summaries provided at http://www.masts.ac.uk/research/marine-ecosystem-
modelling/). Few of these models have directly influenced or routinely supported
management and policy development, but many are likely to have influenced societal and
scientific perceptions about the state of the marine environment and this has had an indirect
influence on the emphasis given to ecosystem considerations in contemporary policy (e.g.
[27–30]). As policy-making is normative and reflects societal values, alongside the evidence
base [31], it is often difficult to ascribe direct links between models and decisions. However,
there are some good examples including predicting harmful algal blooms, eutrophication, and
comparisons between targets for environmental legislation as explained below.

**INSERT TABLE 1 HERE**

Operational forecasting and monitoring of water quality enables timely interventions by both
stakeholders and the agencies responsible for public health. The AlgaRisk monitoring tool is
a prototype that provided warnings of algal blooms to support the statutory obligations of the
Environment Agency [32,33]. This tool combines data from an operational physical-
biological coastal model with satellite observations, and the results are available through an
internet portal where users can visualise both model output and observations
(http://www.neodaas.ac.uk/multiview/pa/). A demonstration AlgaRisk service was
implemented in 2008 to support the European Union Bathing Waters Directive.

Detection and diagnosis of eutrophication is required for a range of EU legislation (e.g.
MSFD [2], WFD [4]) and by the OSPAR Convention [34]. Following the first assessment of
eutrophication for OSPAR, the Netherlands and Germany identified eutrophication problem
areas in their marine waters and alleged that inputs of nitrogen from the UK made a
significant contribution. The OSPAR Eutrophication Committee tasked the Intersessional
Correspondence Group for Ecosystem Modelling (ICG-EMO) to undertake modelling based
on OSPAR riverine nutrient reduction scenarios and trans-boundary nutrient transport
[35,36]. This work involved the application of seven ecosystem models by different institutes
for pre-defined scenarios, using the same forcing, validation data, methods, and post-
processing procedures. The resulting multi-model ensemble was used to assess uncertainty,
which substantially enhanced the overall credibility of the results reported to the OSPAR
Eutrophication Committee. Their subsequent influence on OSPAR decision making was far
greater than would have been achieved by one national source. This modelling work was also
used as supporting evidence in a case where the UK successfully defended against the
European Commission in the European Court of Justice (Case C-390/07).

Advice on fisheries management is routinely supported by single-species modelling through
the UK contribution to the work of ICES assessment groups. Ecosystem models are less
widely used, but have been adopted to provide advice on the prospects for meeting single-
species management targets simultaneously and assessing the trade-offs between meeting
targets for fisheries management and conservation. For example, three different models have
been used to support advice on whether meeting MSY targets for fish in the North Sea under
CFP [3] would be sufficient to meet a proposed target for the Large Fish Indicator (LFI)
under Descriptor 4 of the MSFD [2,37]. It was found that, even though the rationale
underlying the two targets is very different, they were indeed compatible with each other
within the uncertainty of the combined model data (Axel Rossberg, pers. comm.).

3. Challenges for the uptake of ecosystem modelling by policy makers

3.1 Producing the right information from ecosystem models to inform policy

Policy questions are generally formulated much more broadly than scientific hypotheses [7],
so there can be a mismatch between policy needs and the specific outputs produced by
models. For example, the Defra Marine and Fisheries Evidence Plan [6] has the high level
policy goal “to secure healthy food supplies delivered by a more sustainable fishing industry”
that comprises of many different evidence needs including “reducing the adverse impact of
commercial fishing”. This particular evidence need is subdivided into research needs
including “developing an ecosystem approach to fisheries management through evaluating
the impacts of different management scenarios”. To maximise the utility of models, high
level policy goals need to be translated into evidence needs and matched against scientific
questions that can be addressed using models.

Model outputs also need to be expressed in a form that is meaningful to policy makers.
Knowledge of science, evidence, and policy is required to achieve this, so it is important that
policy makers work closely with modellers to ensure a common understanding of, and to
maximise the benefits from models. For example, policy questions are often framed in terms
of socio-economic consequences, but there is often no simple way to express ecosystem
model outputs in this way. Modification or development of models to allow assessment of the
impact of different management measures on ecosystems in biological, social and economic
value will increase the prospects for use (e.g. [38]).

3.2 Confidence in ecosystem model products

Lack of confidence in ecosystem model products may reduce their uptake by decision-
makers. In contrast, managers routinely accept results from single-species fish stock
assessment models, despite uncertainties. The contrast may exist because stock assessment
models are embedded in a well-established process, and there is international political
acceptance of their use as the basis of advice, a good understanding of the models, and
confidence in their outputs and their interpretation through quality assurance by scientific
experts (e.g. ICES). In many cases, expert judgement is required to interpret the range of
model outputs and these procedures can appear opaque to policy makers and lack legitimacy.
Expert groups are needed that provide impartial advice on the use of ecosystem models,
maintain quality standards for models, publish key validation runs, and provide clear output
that can be used by decision makers (e.g. ICES Working Group on Multispecies Assessment
Methods [39]). The UK Earth System Model 1 project builds on the iMARNET experience
[13] to provide a common framework for marine biogeochemistry models to sit within and,
as such, provides an example of how a community can be united around a common
framework with common standards.

3.3 Visibility and access to ecosystem model products

Models are often developed by the research community to answer scientific questions and are
then used by modelling experts to help decision-makers [10,11,40]. For ecosystem models,
this process is generally neither robust nor transparent due to the lack of visibility of existing
models, difficulties accessing model products, and absence of documentation of model
metadata. This contrasts with the current initiatives on data management and data standards
that provide public access to metadata catalogues and databases in order to maximise the use of existing data, and may be due to the volume and complexity of model products. However, this lack of visibility can lead to the false impression that models are not suitable for decision making.

Policy makers have often called for a “decision support toolbox” comprising models that can be used interactively to explore different options when negotiating and formulating policies [41,42]. Complex ecosystem models can be impractical in this context, as they generally have long runtimes, require trained operators, and produce 'big data.' It is therefore an important aim to increase transparency, and make model products available through web portals (e.g. Copernicus Prototype Marine Core Service - http://www.myocean.eu/, Marine OPEC - http://www.portaldev/marineopec.eu) and include model products in tools designed for use by evidence and decision-making communities (e.g. EMECO - http://www.emecodata.net/).

3.4 Development of ecosystem models and methods for understanding uncertainty

There are complex sets of challenges surrounding parameterisation, validation, data sets, uncertainty, visualisation, and ecosystem modelling methods that require further development. These challenges are significant, and a contrast to the physical components of earth system models that are based on well-understood physical laws and scalable processes (i.e. global predictions can be downscaled to regional seas), where the focus of development has shifted towards smaller scales, resolution, speed and numerical implementations. There is also a mismatch between the timescales associated with production of advice (weeks to months) and model development required where models do not produce the outputs needed (years to decades). Hence, there is need to anticipate how models might be used in future in order to produce advice on the timescales required.
New statistical methods are needed to analyse uncertainty in ecosystem (multi-)model ensembles that can be presented to decision-makers in order to understand the risk associated with a particular decision. The successful communication of uncertainties to decision-makers is important for transparency and robust decision-making, thus ensuring management efforts are not misplaced [43]. New visualisation methods are therefore needed to build trust and effectively communicate the outputs and associated uncertainty of ecosystem models to decision-makers and would increase the uptake of ecosystem models.

4. Increasing the use of ecosystem models in decision making

Here we address how to increase the uptake and use of community and ecosystem models used in the UK to support marine environmental management in the UK and Europe. The conclusions are based on discussions that took place at a two day workshop that brought together 55 people from 23 organisations across the UK that included advisors, assessors, biologists, social scientists, economists, modellers, statisticians, policy makers, and funders.

To understand how we might increase the contribution of the models to policy support, it was important to identify policy needs and match them against models that might support these needs. The outcomes included identification of potential quick wins and gaps in existing ecosystem modelling capability in the context of biological sustainability, social benefits, and economic value.

4.1 Understanding the policy and management drivers that can be addressed using ecosystem modelling

Climate change, biodiversity, and marine evidence needs have been identified by the UK Government [5,6,44,45] and were translated into tractable modelling questions. These were categorised into the following headings: natural variability and monitoring, management measures, ecosystem goods and services, Good Environmental Status (GES) targets under
MSFD [2] and pollution, and environmental change and climate adaptation [Table 2]. Since it is often unclear how models have and could be used to support policy, examples of the impact of models on policy and management were identified [Table 1]. A simple mapping exercise was then used to understand the potential contribution of ecosystem modelling in the policy and management arena through comparing available models against evidence needs. The utility (ranked qualitatively as “High”, “Medium”, or “Low”) and timescale for development (1 year, 5 years, 10 years) of each type of model to deliver policy relevant goals were then used to identify:

- Gaps - new models or long-term development required.
- Quick wins - short development time and high utility.
- Ensembles - many models and short development times.

A matrix of future ecosystem model impact was developed for the UK [Table 3]. This highlighted that there were a number of areas where we have many models that can be quickly developed to address questions (e.g. 3B – “What are the costs and benefits of MSFD/WFD/MSP implementation?”), some areas that few models can address (e.g. 5D – “What are the impacts of non-native species on ecosystem state from changes in the environment or transport opportunity?”), and some areas where it was difficult to assess if ecosystem models have any potential (e.g. 3F – “How are different ecosystem services and benefits coupled in a socio-economic system?”).

INSERT TABLES 2 & 3 HERE

4.2 Identifying potential quick wins, ensembles and gaps for ecosystem modelling

The quick wins, potential ensembles and gaps were identified for each theme, with the management measures and ecosystem goods and services themes combined for this purpose [Table 4]. A number of policy and management issues can be addressed immediately and are
brought together under the following general headings: 1. Attribution of change to underlying
drivers; 2. Integration of models and monitoring to develop more efficient monitoring
programmes; 3. Assessment of indicators and the interactions between legislative descriptors;
and 4. Cost-benefit of legislation [Table 4].

It was clear that multi-model ensembles could be used in some areas [Table 4], but the
methods for delivering multi-model ensembles for ecosystems still need to be developed. The
general methods for multi-model ensembles exist in the climate area [8], but ecosystem
model structures are very diverse (e.g. food-web, size-based, nutrient cycling) making a
standardised approach of combining outputs difficult. This is because it is difficult to relate
the variables from different models (e.g. relating functional types to size-based groups) and
this challenge increases at higher trophic levels. There are programmes underway to develop
these methods (e.g. Marine Ecosystem Research Programme – http://www.marine-
cecosystems.org.uk/) and includes the creation of a multi-model ensemble that build on the
ideas of Chandler [46]. The output are modelled using a hierarchical structure which
separates individual and shared model discrepancies. This approach allows models with
different outputs to inform one another through correlations and gives estimates of the true
output as well as robust measurements of uncertainty. Additionally, it is possible to introduce
a level to the hierarchical structure that groups models that have similar discrepancies, e.g.
size-based models. Some examples of model intercomparison also exist (e.g. ocean
biogeochemistry [13], nutrient transfer [35]), but more work is required before multi-model
ensembles can be used routinely to support policy development and management.

Potential gaps in existing ecosystem modelling capability were also identified including those
relating to non-native species, disease transmission, ocean acidification, coastal zone
management, marine protected areas, cumulative effects, socio-economics, and pollution and oil spills [Table 4]. However, this assessment was done in the context of existing ecosystem modelling capability in the UK, and other methods exist internationally (e.g. MARXAN - http://www.uq.edu.au/marxan/ - for marine protected areas, OSCAR - http://www.sintef.no/home/SINTEF-Materials-and-Chemistry/About-us/Departments/Environmental-Monitoring-and-Modelling/OSCAR-Oil-Spill-Contingency-and-Response/ - for oil spills).

4.3 Developing the link between biological, social, and economic drivers for ecosystem management

Policy questions are often framed in terms of socio-economic value (e.g. Policy Area 3 in Table 2), but few ecosystem models express the outputs in these terms. Moreover, there are significant challenges in valuation of the marine environment and there is often a mismatch between the complexity of biological and economic models. The workshop identified a need to develop methods that use the outputs from ecosystem models to drive the valuation of ecosystem services dynamically.

Ecosystem services are the direct and indirect contributions of ecosystems to human well-being, and are made up of tangible goods (e.g. food and raw materials) and less direct and often more intangible services (e.g. the regulation of our climate and the remediation of waste) [47]. The changes in an ecosystem and how this affects value are important for policy development, with changes in ecosystem services determined from empirical data or using models. Often it is the trade-offs among the different services under different policies or management strategies that determine the economic and social importance. The simplest way to use ecosystem models to help understand the changes in ecosystem services is to develop linkages between changes in ecosystem function and service. This has been done for Dogger...
Bank where indicators have been developed of changes in ecosystem services and the
changes in the underlying ecological function [48].

There are a number of more complex ecosystem service frameworks, with one good example
being the UK National Ecosystem Assessment Follow On (UKNEAFO [49]). UKNEAFO
describes a set of strategic principles based on the adaptive management approach together
with practical tools including models, to inform the sustainable management of coastal and
marine ecosystem services. A decision support system (DSS) was developed that adapted the
Drivers-Pressures-State-Impact-Response (DPSIR) approach to assess changes in ecosystem
services and their impact on human well-being as coastal zones are increasingly affected by
environmental change drivers and pressures [50]. This has highlighted key policy issues and
was adapted to include state changes and impacts specifically tailored to ecosystem services
and their human welfare effects. Four main marine based scenarios which deviated from a
baseline condition were explored and exposed to changes in selected environmental change
(e.g. climate, socio-economic development, political social and cultural drivers). A set of
ecosystem change indicators consistent with the implementation of the MSFD were derived
covering processes, intermediate and final ecosystem service delivery, in stock and flow
terms [51]. The data needed for these indicators were drawn from national level observations
and models. Given the uncertainty surrounding ecosystem functioning and the impact on
overall biodiversity of some ecosystem changes, a number of modelling approaches were
applied and tested. The UKNEAFO assessed formal models to quantify changes in ecosystem
service stocks and flows and in particular the practicality of coupling land use change,
estuarine and coastal and marine models.

The incorporation of feedback between biological, social, and economic systems can be
difficult in an ecosystem services framework. This is an issue because feedback loops are
important for making accurate predictions of the response of systems to management
measures and are inherent in the DPSIR approach. Systems dynamics is an alternative
approach that is gaining support in environmental economics and is used to model complex
non-linear systems including the design and analysis of policy. Current knowledge of how the
‘system’ functions has been used to develop a number of simple conceptual models that may
not always encapsulate the entirety of the system but include significant components (e.g. key
habitats, sub-systems, human uses for fishing or renewable energy). These simple conceptual
models can help to define information needs to build more information-rich systems models
that may be quantitative (stochastic or deterministic) or qualitative (narrative-rich models).
These enable exploration of the consequences of current or proposed policy for the delivery
of ecosystem services and for maintaining the integrity of the system as a whole, where
different models can be employed together and the approach is not prescriptive. Promising
‘wide spectrum models’ that can work across the natural-social science boundary include
extended Ecopath with Ecosim models [30], End-to-End models and Atlantis [10].

4.4 Methods for analysis and visualisation of model products

The complexity of ecosystem model and the treatment associated uncertainty has led to a
move from optimising parameter sets that fit observations [16] to finding a range of possible
solutions that support the management objective [52]. Standard methods of uncertainty
analysis (e.g. Markov Chain Monte Carlo [53]) are difficult to conduct due to the
computational power required. These problems are not unique to marine ecosystem models
and lessons can be learned from other disciplines including fitting models to observations
[54], examining structural uncertainty in decision models [55] and ensemble modelling [56].

There is an abundance of scientific literature assessing the methods used to resolve the
linguistic uncertainties in communicating model output [57–59], but there is little guidance
about visualising the outputs and uncertainty from complex models [60]. Many of the
techniques used for data visualisation ignore the presence of uncertainties or are only able to
depict one source of uncertainty at a time [61,62]. More recently methods have been
developed to depict multiple uncertainties within a single visualisation, although efforts have
been hindered by the presence of deep uncertainties and the challenges associated with
disentangling various sources of uncertainty [60].

5. Future challenges for ecosystem modelling that encompass natural,
social, and economic systems

A clear limitation to the development of policy-relevant ecosystem models is the maturity of
the underlying science. The link between biodiversity, ecosystem function and the flow of
ecosystem services is being addressed, but is not yet well enough understood or described to
fulfil the requirements for management and policy advice [63]. Concepts that are
underpinned by strong evidence are regularly questioned (e.g. global warming) and others
accepted before the science is resolved (e.g. ??) [63]. There is no absolute point at which a
model is sufficiently advanced to support management and policy advice, as this depends on
many political and societal factors as well as the development and presentation of the science.
Consequently, clear communications between scientists, modellers, statisticians, managers
and policy makers is important to build understanding of the capabilities of models and the
associated uncertainties.

Ecosystem functions are believed to be reliant on the organisms that inhabit the ecosystem,
but predicting the functionality and how it changes with different pressures is a significant
challenge. However, these uncertainties do not prevent the development of models that
include biodiversity or functionality based on knowledge of the species assemblages, but this
does require understanding of the limitations of scientific knowledge of the drivers of these
relationships. The relative uncertainty varies depending on the ecosystems service under
consideration; for example, primary production is easier to address than detoxification of xenobiotics, for which we have less specific knowledge. Progress is being made and mapping of biodiversity, habitat type and related functions and service provisions is becoming more common in terrestrial systems [64], with more information on coastal and marine systems emerging. The valuation of service in marine systems is also more problematic since the benefits of marine ecosystem services provision are less tangible than terrestrial system and methods of valuation (both monetary and non-monetary valuations) are more difficult to apply [65]. Hence, providing a common (comparable) currency across terrestrial and marine system can be difficult. However, the application of ecosystem models will help to focus on the most urgent issues to be addressed.

Much environmental decision-making assumes smooth cause-effect relationships, but there is increasing evidence of regime shifts at a number of different scales in both tropical and temperate marine ecosystems (e.g.[66–69]). Knowledge of ‘tipping points’ is empirical and conjectural, so their prediction is a huge challenge. Changes in global circulation will also affect shelf-models and represent another challenge over the next decade (e.g. [70]). Most models have to be constrained within defined spatial and temporal boundaries, and for natural systems focus on, for example, habitats, populations, or ecosystems. Social-ecological systems scales are more complex, partly because people who interact with marine systems live on the land, so operate on different scales than the natural systems they exploit. This scale mismatch presents a further challenge for modelling.

Coupled social-ecological systems suffer from ‘locked-in’ processes that have a profound effect on the potential options for their management. These factors can be modelled when they are properly understood but many feedback processes have not been identified as yet and can only be suspected from non-linear cause-effect behavior, making them very difficult to model. All systems have rate limiting steps or choke points that can simplify modelling.
Complex social-ecological system modelling has an added dimension however, the ‘on-off’
behaviour of the decision-making process. This provides a challenge for ‘stock and flow’
models for example. Modelling the factors affecting human decisions is complex and
culturally dependent, making predictions using models a significant challenge (e.g. fisher
behaviour [71]).

6. Conclusions

These conclusions have been developed from our assessment of UK ecosystem modelling,
but some of the challenges and solutions apply internationally. While some countries may at
present be more comfortable with deploying ecosystem models to guide management and
policy than others (e.g. Australia, USA), there is still a large gulf between modellers and
decision-makers, and the full utility of ecosystem models has not yet been realised.

To increase the uptake and use of ecosystem models and better support marine environmental
management and policy, it is important to:

- Ensure that decision-makers know where and how ecosystem models can be used in the
  context of the limited resources for evidence generation.
- Build multidisciplinary communities of policy makers, data collectors, modellers,
  statisticians, and socio-economists that speak a common language and work together to
  develop, apply, review and compare ecosystem models.
- Define and employ rigorous quality standards to satisfy legal challenge in policy and
  management decisions that ensure that model-derived products are available and robust.
- Put in place programmes to fill existing knowledge gaps that can only be addressed using
  contributions from models (e.g. linking biological sustainability, social benefits, and
  economic values, address the challenges of modelling dynamic systems).
• Maximise the pull-through of new modelling techniques to ensure that the latest science
  is being used to underpin decision-making.
• Encourage the development and use of new statistical methodology and visualisation
  techniques, for inference from model ensembles and for the propagation, management
  and communication of uncertainty in general.

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Science Coordination Committee (MSCC - https://www.gov.uk/government/groups/marine-
science-co-ordination-committee) in collaboration with the Marine Alliance for Science and
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References


[34] OSPAR. Convention for the Protection of the Marine Environment of the North-East Atlantic. 2007.


## TABLES

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<th>Name</th>
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<tr>
<td>EM1 European Regional Seas Ecosystem Model (ERSEM)</td>
<td>ERSEM is a lower-trophic level model designed to represent the biogeochemical cycling of carbon and nutrients (N, P, Si, O2, Fe) in an emergent property of ecosystem interaction.[14,72] It is coupled to a number of hydrodynamic models for the northeast Atlantic. It has been validated against in situ data (e.g. [73]) and satellite ocean color. In general predictions are reasonable for temperature, salinity, nutrients, oxygen, nutrients, but less good for chlorophyll and plankton, with predictions becoming less accurate at higher trophic levels.[73] Models capture seasonality well and can predict spatial scales of order ~100km².</td>
<td>ERSEM has been used to assess shelf seas water quality and climate impact, ocean acidification, eutrophication, trophic amplification and to assess potential climate impacts on harmful algal blooms, fisheries, fisheries economics and food security. For future use the model is being developed to quantify blue carbon, assess nutrient budgets, and simulate changes in ecosystem function and the consequences of such changes in the context of ecosystem services.</td>
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<td>EM2 GETM-ERSEM-BFM</td>
<td>This is a coupled hydrodynamic and biogeochemical model that is based on the cycling of carbon and nutrients. It represents phytoplankton, zooplankton, bacteria, macroalgae and filter feeder larvae, and has a coupled benthic system. It is available in a North Sea setup and a northwest European shelf setup that have been validated using chlorophyll, SPOM, temperature, and ship-based benthic data.[74].</td>
<td>The model has been used to investigate eutrophication and riverine nutrient transport, potential impacts of large-scale macroalgal farms, potential impact of climate change and trawling, ecosystem indicators, deep chlorophyll maximum production, Phaeocystis blooms, and potential impact of large-scale wind farms. In future it could be used to attribute causes of change, optimize monitoring programme, assess impacts of wind farms, tidal farms, macroalgal farms, nutrient reduction scenarios, trawling, and thermal plumes, within the context of a changing environment.</td>
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<td>EM3 Model of Ecosystem Dynamics, carbon Utilisation, Sequestration and Acidification (MEDUSA)</td>
<td>MEDUSA is an intermediate complexity model of lower-trophic level plankton ecosystem that is typically run within a global earth system model context to address the biogeochemical response to anthropogenic driven changes (including ocean acidification) in the oceans.[75] It has been evaluated at the global scale using observational nutrient, chlorophyll and carbon cycle fields. In general, simulations of nutrients, carbon and primary production are reasonable, though less accurate for chlorophyll. MEDUSA was selected from a UK-wide group of models to be the marine biogeochemical component of the UK Earth System Model (UKESM1) that will be used in IPCC AR6.[13].</td>
<td>The model is currently used at a range of resolutions (up to 1/12th degree) to study global-scale ocean biogeochemistry and marine productivity. It is also used to make future projections of ocean biogeochemistry and acidification at the global scale. In future, the model will provide regional predictions addressing policy issues relating to vulnerability, resilience, and adaptation to climate change. It will also be used (within UKESM1) across the suite of UK simulations submitted to IPCC AR6.</td>
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<td>EM4 Population Dynamical Matching Model (PDMM)</td>
<td>The PDMM is a simple theoretical ecosystem model that can represent typical temperate marine shelf communities, covering species of all sizes from phytoplankton to large fish. The model constructs complex and population-dynamically stable ecological model communities by mimicking the community assembly process of successive invasion. The model can reproduce size-abundance relations, distributions of species richness, species-size distributions, and key patterns in foodweb.[24].</td>
<td>The model has been used to understand mechanisms controlling size-abundance relationships, verify the theory of foodweb structure, assess the Large Fish Indicator (LFI), and study biodiversity-foodweb production relationships for fish. In future, the model could be used to assess the relationship between biodiversity and ecosystem function, and the long-term implications of fisheries management strategies to reach MSY for multiple interacting stocks.</td>
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<td>EM5 Strathclyde end-to-end ecosystem model (StrathE2E)</td>
<td>StrathE2E models the dynamics of nitrogen in ecosystem components including detritus, inorganic nitrogen in solution, plankton, benthos, fish, birds and mammals. Key physical, geochemical and biological processes which occur in the sea and seabed sediments are included.[76] Parameters were computationally fitted for a model of the North Sea to minimise the discrepancy between observed and modelled annual cycles and averaged abundances, production rates, and feeding fluxes.[76]</td>
<td>StrathE2E has been used to simulate fishery yields in relation to harvesting rates, trophic cascades, sensitivity of MSY to changes in trophic structure, and implementation of discard ban. In future, it could be used to assess sensitivity of fisheries to ocean acidification, disaggreate the effects of environment and fishing, compare observed fishery yields and MSY, project cumulative effects of harvesting and environmental change, and the ecological effects of the discard ban measures.</td>
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<td>EM6 Ecopath with Ecosim (EcE)</td>
<td>EcE is an ecosystem modeling framework that quantifies food web fluxes and habitat degradation, and allows fishing fleets to be described and information on landings, discards and economics can be included. The core of the model is determined by specifying who eats (or catches) who and how much. Models have been developed for specific regions and there is a strong research community with quality standards being established.</td>
<td>EcE has been used to evaluate the tradeoffs among fishing strategies in relation to sustainable fishing and mixed fisheries, assess relative impact of fisheries and climate impacts, and assessed ecosystem-based management. In future it could be used to assess the spatial impacts of</td>
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<td>EM7 Atlantis</td>
<td>A biophysical model that simulates the spatial and temporal dynamics of marine species population in terms of birth, death, growth and movement of fish [7]. The model is used to examine interactions between fisheries, wind farms, MPAs and climate change. The Atlantis framework has been used more extensively in other parts of the world for ecosystem based management (see [11]) for a general review.</td>
<td>Fisheries and climate on the structure and function of ecosystems, quantify the performance of different management strategies, and evaluate the benefits of spatial management policies (e.g. MPAs) and impacts of pressures (e.g. oil and gas) on ecosystems.</td>
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<tr>
<td>EM8 Strathclyde spatial population dynamics model (StrathSPACE)</td>
<td>Simulates the spatial and temporal dynamics of a single-species population in terms of birth, death, growth and movement of fish [7]. The model is used to examine interactions between fisheries, wind farms, MPAs and climate change. The Atlantis framework has been used more extensively in other parts of the world for ecosystem based management (see [11]) for a general review.</td>
<td>Fisheries and climate on the structure and function of ecosystems, quantify the performance of different management strategies, and evaluate the benefits of spatial management policies (e.g. MPAs) and impacts of pressures (e.g. oil and gas) on ecosystems.</td>
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<td>EM9 Coupled Community Size-Spectrum Model (CCSM)</td>
<td>Simulates the size and abundance of organisms in two coupled size-structured food chains, one based on predation and supported by primary production and one based on energy sharing and supported by detritus [15]. Species are not represented explicitly. Predictions of size-spectrum were validated in the North Sea by comparing model predictions with empirical data on the size structure of pelagic predators and benthic detritivores [15].</td>
<td>Applications of this model have included the assessment of fishing impacts on community size structure and abundance in the North Sea [15], the effects of coupling pelagic and benthic food webs on responses to fishing, and prediction of the medium- to long-term effects of climate change on fish production at regional and global scales [17].</td>
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<td>EM10 Species Size-Spectrum Model (SFSM)</td>
<td>Simulates the size and abundance of organisms in two coupled size-structured food chains, one based on predation and supported by primary production and one based on energy sharing and supported by detritus [15]. Species are not represented explicitly. Predictions of size-spectrum were validated in the North Sea by comparing model predictions with empirical data on the size structure of pelagic predators and benthic detritivores [15].</td>
<td>Applications of this model have included the assessment of fishing impacts on community size structure and abundance in the North Sea [15], the effects of coupling pelagic and benthic food webs on responses to fishing, and prediction of the medium- to long-term effects of climate change on fish production at regional and global scales [17].</td>
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<td>EM11 Multispecies size ecological modelling in R (MIZEr)</td>
<td>Simulates the size and abundance of organisms in two coupled size-structured food chains, one based on predation and supported by primary production and one based on energy sharing and supported by detritus [15]. Species are not represented explicitly. Predictions of size-spectrum were validated in the North Sea by comparing model predictions with empirical data on the size structure of pelagic predators and benthic detritivores [15].</td>
<td>Applications of this model have included the assessment of fishing impacts on community size structure and abundance in the North Sea [15], the effects of coupling pelagic and benthic food webs on responses to fishing, and prediction of the medium- to long-term effects of climate change on fish production at regional and global scales [17].</td>
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<td>EM12 Strathclyde length-structured partial ecosystem model (FishSUS)</td>
<td>Simulates the size and abundance of organisms in two coupled size-structured food chains, one based on predation and supported by primary production and one based on energy sharing and supported by detritus [15]. Species are not represented explicitly. Predictions of size-spectrum were validated in the North Sea by comparing model predictions with empirical data on the size structure of pelagic predators and benthic detritivores [15].</td>
<td>Applications of this model have included the assessment of fishing impacts on community size structure and abundance in the North Sea [15], the effects of coupling pelagic and benthic food webs on responses to fishing, and prediction of the medium- to long-term effects of climate change on fish production at regional and global scales [17].</td>
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<td>EM13 Fish community size-resolved model (FCSRSM)</td>
<td>Simulates the size and abundance of organisms in two coupled size-structured food chains, one based on predation and supported by primary production and one based on energy sharing and supported by detritus [15]. Species are not represented explicitly. Predictions of size-spectrum were validated in the North Sea by comparing model predictions with empirical data on the size structure of pelagic predators and benthic detritivores [15].</td>
<td>Applications of this model have included the assessment of fishing impacts on community size structure and abundance in the North Sea [15], the effects of coupling pelagic and benthic food webs on responses to fishing, and prediction of the medium- to long-term effects of climate change on fish production at regional and global scales [17].</td>
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<td>EM14 Length-based Multispecies Analysis by Numerical Simulation for the North Sea (LeMANS)</td>
<td>Simulates the size and abundance of organisms in two coupled size-structured food chains, one based on predation and supported by primary production and one based on energy sharing and supported by detritus [15]. Species are not represented explicitly. Predictions of size-spectrum were validated in the North Sea by comparing model predictions with empirical data on the size structure of pelagic predators and benthic detritivores [15].</td>
<td>Applications of this model have included the assessment of fishing impacts on community size structure and abundance in the North Sea [15], the effects of coupling pelagic and benthic food webs on responses to fishing, and prediction of the medium- to long-term effects of climate change on fish production at regional and global scales [17].</td>
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### Table 2: Policy questions derived from evidence plans [5, 6, 44, 45] split into 5 topics and reformulated for modellers.

<table>
<thead>
<tr>
<th>Policy Area</th>
<th>Modelling Questions</th>
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</table>
| 1. Natural variability & monitoring | A. What are the spatial and temporal scales that a particular model can address and do these match the policy requirements?  
B. How long would it take to quantify the uncertainty of model predictions?  
C. Can the model distinguish between relative performances of candidate environmental indicators?  
D. Can the model identify high risk areas?  
E. Can the model contribute to assessing the potential efficiency gains from redesigning monitoring programs?  
F. Does the model have a capacity to blend models and data to get best estimate of state of system e.g. data assimilation, parameter fitting, tuning?  
G. Can the model be used to inform engineering the ecosystem to reach the state that you require? |
| 2. Management measures             | A. What are the expected changes in habitat extent and condition resulting from environmental change for a given network of Marine Protected Areas (MPAs)?  
B. How effective are given networks of MPAs in achieving their management objectives?  
C. How will the network of MPAs deliver objectives and outcomes in relation to environmental impacts, ecosystem structure and function?  
D. What are efficient programs of measures to achieve Marine Strategy Framework Directive (MSFD) targets?  
E. Can the effects of changes (pressure and response) be attributed to individual and cumulative effects, and the risk (uncertainty) associated with this?  
F. What are the management strategies for exploitation of mixed fisheries to achieve Maximum Sustainable Yield (MSY)?  
G. What are the impacts of landing obligations on MSY objectives through e.g. food web interactions?  
H. What are the effects of changes in fisheries management on the environment, in particular through foodweb effects?  
I. What is the risk of population decline or regional extinction of valuable, endangered or vulnerable species from CFP reform? |
| 3. Ecosystem goods & services       | A. What are the socio-economic impacts of given networks of MPAs?  
B. What are the costs and benefits of MSFD/Water Framework Directive (WFD)/Marine Spatial Planning (MSP) implementation?  
C. What are the interactions between different sectors and ecosystem services?  
D. What are the marginal cost/values of changes in ecosystem services?  
E. How are different ecosystem functions and services dynamically coupled?  
F. How do different ecosystem services and benefits couple in a socioeconomic system? |
| 4. Good Environmental Status (GES) target and pollution | A. Can the model contribute to the ecosystem approach through interactions with other models?  
B. What is the response of indicators to specific management measures for MSFD descriptors?  
C. What are the effective MSFD indicators than those currently proposed in use?  
D. What are the impacts of pollutant dispersants in the marine environment, their impacts on marine ecosystems?  
E. How can efficiencies of pollutant dispersants be maximized?  
F. What are the effects of pollution on the marine environment?  
G. What are the interactions between biodiversity (Descriptor 1) and other descriptors of GES Status under MSFD?  
H. What are the interactions between commercial fish (Descriptor 3) and other descriptors of GES under MSFD?  
I. What are the interactions between food web structure (Descriptor 4) and other descriptors of GES under MSFD?  
J. What are the interactions between floor integrity (Descriptor 5) and other descriptors of GES under MSFD?  |
| 5. Environmental change & climate adaptation | A. What are the impacts of regional scale climate patterns on ecosystem state (GES), and can these be valued?  
B. Can a change in environmental status be attributed to a combination of drivers?  
C. Which aspects of environmental status are sensitive to climate change?  
D. What are the impacts of non-native species on ecosystem state (GES)?  
E. What are the impacts of harmful species on human and animal health?  
F. How are detailed local effects of local pressure captured?  
G. What are the impacts of ocean acidification on ecosystem state (GES)?  
H. What are the impacts of changes in shelf seas/biogeochemistry on ecosystem state (GES)?  
I. What is the impact on land/sea transition zone?  
J. Can the risk or impact from artificially introduced non-native species be modelled?  
K. What are the impacts of wind farms and other offshore structures? |

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Table 3: Scoring of ecosystem models (model names as in Table 1) and their ability to address policy questions (defined in Table 2). Scoring system: 0 = not possible, 1 = within ten years, 2 = within five years, 3 = within one year, and diagonal hashing is not possible to assess here.

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<th>Question</th>
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Table 4: Potential for use of ecosystem model-derived products in addressing policy needs in terms of quick wins, possible multi-model ensembles (italics), and gaps that cannot currently be addressed.

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<thead>
<tr>
<th>Theme</th>
<th>Quick Wins</th>
<th>Gaps</th>
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<tr>
<td>Natural variability and monitoring</td>
<td>• Distinguishing between the sensitivity and utility of different indicators.</td>
<td>• Improve the ability of models to capture inter-annual variability and long term trends.</td>
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<td>• Quantifying uncertainty.</td>
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<td>• Integration of models with monitoring to increase efficiency.</td>
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<td>• Identifying current system state.</td>
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<td>Management measures, goods and services</td>
<td>• Efficient programme of measures for achieving Good Environmental Status (GES).</td>
<td>• Assessing networks of Marine Protected Areas (MPAs) in terms of connectivity, achieving management objectives and socio-economics.</td>
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<td>• Impacts of landing obligations on Maximum Sustainable Yield (MSY) through food webs interactions.</td>
<td>• Cumulative effects.</td>
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<td>• Management strategies for achieving MSY in a mixed fishery.</td>
<td>• Risk of decline of endangered species from CFP reform.</td>
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<td>• Effects of fishery management on food webs.</td>
<td>• Coupling between ecosystem services and benefits in socio-ecological systems.</td>
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<td>• Cost-benefit of implementation of legislation (e.g. MSFD, Water Framework Directive – WFD, Common Fisheries Policy – CFP).</td>
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<td>• Marginal costs / values of changes in ecosystem services.</td>
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<td>• Links between ecosystem function and services.</td>
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<td>Good Environmental Status (GES) target and pollution</td>
<td>• Sensitivity of indicators to management measures and identification of better indicators.</td>
<td>• Impacts of pollutant dispersants.</td>
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<td>• Effects of pollution on the marine environment.</td>
<td>• Interdependencies between different descriptors within MSFD.</td>
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<td>• Interdependencies between MSFD descriptors.</td>
<td>• Model interoperability – modular approaches.</td>
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<td>Environmental change and climate adaptation</td>
<td>• Regional scale climate impacts and their value.</td>
<td>• Introductions and impacts of non-native species.</td>
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<td>• Atribing change in ecosystems to environmental drivers and the systems response.</td>
<td>• Animal and human disease.</td>
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<td>• Impacts of changes in shelf-seas biogeochemistry on ecosystem state function and services.</td>
<td>• Local effects of pressures.</td>
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<td>• Impacts of ocean acidification.</td>
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<td>• Impacts on the land-sea transition zone.</td>
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<td>• Impacts of geo-engineering.</td>
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<td>• Impacts of offshore structures.</td>
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FIGURES HEADING

Figure 1: Categories of ecosystem models and the parts of the ecosystem that they include.
Coupled Models = physical + biological (e.g. NEMO-ERSEM)