Marine Ecosystems Research Programme

Final Programme Report

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Marine Ecosystems Research Programme

Executive Summary

Co-funded by Defra, the Marine Ecosystems Research Programme (MERP) directly related to the delivery of the NERC Biodiversity theme. The programme aimed to improve our understanding of how marine ecosystems are being impacted by on-going environmental change, to develop more realistic marine ecosystem models and to test potential management solutions. The overarching objectives of the Marine Ecosystems research programme were to:

1. Improve our understanding of how the regulation of key ecosystem services such as food production, macronutrient cycling and cultural values by marine are affected by the relative roles of 'top down' and 'bottom up' processes, scale-dependence in these processes and functional diversity at different trophic levels.

2. Integrate the improved knowledge and understanding of how the regulation of key ecosystem services are affected by 'top-down' and 'bottom-up' processes with existing ecosystem models, in order to explore the impact of environmental change on the structure, function and services associated with marine across scales.

3. Apply the new model developments to test the impact of potential management solutions, such as marine conservation zones, on the structure and function of marine across scales, and explore the efficacy of specific indicators of good environmental status.

For management and coordination purposes the work was divided into a number of modules. Work Package 1 was divided into 5. These were: 1. Marine ecosystem data toolbox and application of macroecology; 2. Fieldwork to measure poorly known processes; 3. Ecological processes and their representation in models; 4. Simulating and predicting ecosystem changes using a model ensemble; 5. Linking macroecology and models to ecosystem services. Work Package 2 contributed module 6. Developing a model-based understanding of ecosystem service regulation. Work Packages 1 and 2 were funded from the outset. Work Package 3 was funded 2.5 years into the programme and contributed modules 7. *Understanding trade-offs to maximise benefits from living marine natural capital*, and 8. *Cumulative impacts and the management of marine ecosystems*.

A full science report was delivered in September 2017. The majority of the programme's work was completed early in 2018. Stakeholder materials were developed using MERP science with a focus on impact, and these were presented at a Stakeholder Symposium held at the Royal Society, London, in May 2018. This symposium was followed by the programme's final Annual Science Meeting. Module 6 is funded until 2019. Some elements of the programme, especially much of the work in WP3, could not be completed for the scheduled finish of the programme in 2018 and have been continued under no-cost project extensions to programme partners.

This report delivers the final reports from modules 7 and 8, with an update of the 2017 science report from modules 1 to 6 giving examples of completed research. A great deal of progress was made during the programme. Existing knowledge was brought together in new ways, and tools were developed to do so. Examples of new data syntheses include sediment maps, seasonal cetacean distributions, seabird diets and foraging areas and kelp distributions. A key tool developed in MERP is the Trait Explorer, which uses existing knowledge to predict the traits of species using information about their relationships to other taxa. Diverse fieldwork focused on processes known to be poorly understood or quantified in ecosystem models. Examples include work showing how demersal size-spectra vary interactively with differences in productivity and fishing pressure, the importance of gelatinous organisms in pelagic food webs, the importance of coastal algae as a source of primary production for offshore benthic systems, and how energy flows through the pelagic food web vary seasonally. Advances were made in understanding how perturbations propagate through the marine ecosystem, and how different models capture those perturbations. Novel ensemble methods were developed to combine different ecosystem model outputs to better understand uncertainty in predictions. Various models, including ERSEM, were greatly developed and enhanced. Finally, elements of the work considered how scientific knowledge about ecosystems, how they operate and how they change in response to different bottom-up and top-down pressures, could be linked to answering questions about managing marine ecosystems from the perspective of maintaining or enhancing ecosystem services and natural capital.

In addition to nearly 100 scientific publications (to date), elements of the programme's work are already having impact, having been used for national (e.g. Defra, Scottish Government) and international (ICES, WFD) purposes. MERP products, including a web-based interactive which aims to help policy-makers to find appropriate information and leads, are to be found on the programme's updated website www.marine-ecosystems.org.uk.

MERP Partners

1. Plymouth Marine Laboratory (PML)

2. Glasgow University (GU)

3. Sir Alister Hardy Foundation for Ocean Science (SAHFOS) through PML

4. Bangor University (BU)

5. Sheffield University (SU)

6. University of Strathclyde (UoS)

7. Queen Mary, University of London (QMUL)

8. Queens University, Belfast (QUB)

9. Centre for Ecology and Hydrology (CEH)

10. Scottish Association for Marine Science (SAMS)

11. Centre for Environment, Fisheries and Aquaculture Science (Cefas)

12. National Oceanography Centre (NOC)

13. Sea watch Foundation (through BU)

14. Royal Society for Protection of Birds (through CEH)

15. British Oceanographic Data Centre (BODC)

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Introduction

Over a decade ago, the Millennium Ecosystem Assessment drew attention to the importance of the direct and indirect contributions of ecosystem services in supporting human well-being. Since then, the scientific community has amassed powerful evidence that human actions are leading to declines in many ecosystem services. As a result, the protection of ecosystem services now forms an important part of environmental management practice, designed to ensure ecosystem services are conserved for human benefit. When some classes of these services are used by humans at an unsustainable rate, the stocks of resources which generate ecosystem services (i.e. Natural Capital) may be depleted.

Bringing ecosystem services into the active management of marine ecosystems requires an understanding of the key processes which couple the ecological state of ecosystems with the provision of goods and services valued by society that ultimately determine Natural Capital. The focus of MERP lay in understanding marine , and in particular how interactions and changes in feeding relationships amongst organisms affect the delivery of ecosystem services. MERP scientists integrated environmental, social and economic dimensions of this understanding to define options for the sustainable use (present and future) of aquatic living and non-living resources and related processes.

This £6m programme was co-funded by NERC (~ 85 %) and Defra (~ 15 %). Overall it was active for 5 years, concluding in April 2019. Consistent with the scientific aims of the programme, it comprised three major elements: 1) to deliver scientific understanding of how changes in drive changes in ecosystem service provision at different scales of space and time, 2) developing and improving NERC's marine ecosystem modelling capability, 3) addressing how different management scenarios may influence the sustainable provision of ecosystem services. The work was delivered by a consortium of over 50 scientists working in 15 organisations from across the UK.

This report provides key highlights from the Marine Ecosystem Research Programme with a focus on the activities funded through Work Package 3 of the programme (referred to as WP3). Two additional projects were funded to look at how management scenarios may influence the sustainable provision of ecosystem services: Understanding trade-offs to maximise the benefits from living marine natural capital (Module 7), and cumulative impacts and the management of marine ecosystems (Module 8). Summaries of the achievements of these areas of work are followed examples of scientific progress and application delivered in rest of the programme (Modules 1 to 6).

Module 7. Understanding trade-offs to maximise the benefits from living marine natural capital

The expected deliverables from Module 7 were:

1. Advances in the valuations of living marine natural capital, and its response to management interventions, taking account of ecological, economic and social feedbacks.
2. A scientific framework for conducting virtual experiments on the integrated social-economic-ecological system to test the effectiveness of management scenarios at attaining alternative outcomes.
3. A participatory scheme for engaging stakeholders in virtual experiments on the marine social-economic-ecological system, to test alternative management scenarios.
4. Models and outputs to support strategic decisions on the sustainable use of the marine environment and understanding of cultural values, and support for MSFD assessments.

The Module achieved its ambitions for all four of these deliverables. This was achieved through five main tasks, and a brief summary of the outcomes for each task is provided below.

Task 1: Goal setting and scoping of management options with stakeholders.

Sub-Task 1.1: Regional stakeholder analysis. A comprehensive analysis of the stakeholder landscape of MERP was completed. This involved mapping 278 stakeholders in terms of their interest in MERP, their power and influence over policy, and their potential as funders of future work. Separate classifications have been produced for the west of Scotland, Cardigan Bay, and the southwest approaches. The results were used to guide a stratification of stakeholders who were invited to participate in subsequent stages of the project to try to ensure balanced perspectives.

Sub-Task 1.2: Scoping and scenarios workshop. Three stakeholder 'scenario defining' workshops were held during April-May 2017, for the North Devon, Cornwall and West of Scotland regions. Each workshop was attended by a range of fishing industry, NGO and policy-related representatives. The aim was to document stakeholders' expectations and ambitions for the direction of change of a range of attributes describing the state and exploitation of their marine regions, under 4 different macroscopic 'worldviews' of socio-political systems. These worldviews provided a framework, or justification, for assembling suites of realistic management measures that might be deployed under differing social and political conditions. The definitions of world-views were a subset of those described by the UK National Ecosystem Assessment, namely **Nature@Work, World Markets, National Security** and **Local Stewardship**.

Based partly on summaries of the stakeholder workshops, and partly on a detailed assessment of the background descriptions of each of the worldviews in National Ecosystem Assessment reports, the team developed detailed narratives for the shelf sea regions west of the UK in terms of a set of fisheries, conservation and aquaculture management measures, reflecting the contrasting societal and political ethos expressed in the worldviews, e.g. protectionism vs globalisation. These measures were then translated into quantitative driving conditions of decision control rules which could be implemented in our ecosystem models. This whole process took many iterations before an agreed set of measures and model driving conditions was achieved. Detailed narratives for each of the worldviews and how they were translated into driving conditions and model rules are provided in Appendix 1, and the description of the management measures and, in general terms, in Appendix 2.

Task 2: Set-up of MERP ecological model for each case study.

Two of the MERP suite of ecosystem models were used in this module to explore the ecological and economic consequences of the measures deployed under the four worldviews. Both had strengths and weaknesses in terms of their ability to represent the full range of measures invoked by the worldview narratives.

Ecosim simulated a food web comprising a set of individual species spanning the range to fish, benthos and top-predators found in the real-world systems, but did not represent biogeochemistry, nutrient inputs, seabed impacts of trawling, or spatial dimensions. StrathE2E represented the food web only by coarse groupings of biomass based on broad feeding categories such as 'planktivorous fish' and did not resolve individual species. On the other hand, the model contained a coarse representation of spatial processes, biogeochemistry, nutrient inputs and seabed abrasion. A great deal of work went into ensuring that the management-measure driving conditions for the two models were comparable for each of the worldviews scenarios.

Environmental driving data for both models was provided by post-processed outputs from ERSEM. In the case of Ecosim, these were annual rates of primary production and temperature for years 1985-2016. In the case of StrathE2E, these were monthly temperatures, transport rates of water, nutrient and particulate organic material across the external boundaries of the model region, and between the internal spatial compartments for two periods: 1980-1999, and 2003-2013. Additional environmental drivers for StrathE2E were monthly turbidity data, wave heights and natural seabed disturbance, and river and atmospheric inputs of nutrient.

'Baseline' data on fishing gears, fishing effort, and for each gear and their species selectivity and discarding rates were derived for each model from the EU STECF database. Our baseline or reference period, against which all of the worldview scenario model results were compared, was 2003-2013.

The greatest amount of time and effort was spent on configuring Ecosim and StrathE2E to represent the west of Scotland ecosystem. It proved extremely challenging to implement the contrasting management-measure driving conditions in the models because they reflected condition far outside the range under which they had been developed and calibrated. An Ecosim model of the Celtic Sea was obtained from Cefas, but proved too burdensome to adapt and deploy for the purposes of these challenging scenarios. StrathE2E models of the Celtic Sea and English Channel were configured and preliminary runs completed and reported on, but lack of time and resources meant that we were unable to attempt simulations of the worldviews with these models.

Task 3: Valuation models and their coupling to the ecology

Sub-Task 3.1: Provisioning service valuation. Digital data on first-sale market prices of fish species in the UK by ports, gears and months extend back only to the early 2000's. This is too short a period to derive price flexibility relationships by statistical analysis. So, we digitised print-published annual statistical reports of fish species landings, revenue and where available, prices to recover a UK-wide data asset of annual mean prices for 81 fish and shellfish species back to 1965. When corrected by the Consumer Price Index or Gross Domestic Product Deflator, these provided time series for estimating flexibilities. At a UK-wide level, some species showed own-price supply-drive flexibilities – that is their prices varied in inverse relation to their quantity landed. Others showed group price flexibilities – other substitute species influenced prices. In the case of pelagic fish there were indications of demand-driven price fluctuations correlated with the price of e.g. chicken. However, for each of our individual case study regions, the scale of local variations in supply (landings) compared to the overall UK landings was small and hence any local influence on flexibilities was correspondingly attenuated. So, we derived a standard set of prices for each of the species in Ecosim, and each of the harvested groups in StrathE2E, and used these in our simulations.

First-sale market prices for harvested seaweeds were estimated from an extensive survey of the seaweed industry in France and Norway, as part of a review of the potential for growth of such an industry in Scotland.

Marginal valuations for salmon aquaculture output in Scotland were developed from market analysis.

Sub-Task 3.2: TLR service valuation. The aim of this task was to develop contingent valuations for three classes of Tourism, Leisure and Recreation activity dependent on living marine resources - wildlife watching, sea angling and diving – i.e. the change in participation rate and money spent per unit change in the abundance of the relevant resource in the sea e.g. whales, seals, fish etc. We accomplished this from a set of Stated-Preference Choice Experiments conducted in Scotland and the Southwest of the UK. Choice Experiment attributes focused on the chance of viewing relevant species and other relevant trip characteristics (e.g. duration, interpretation, comfort). The revealed and stated preferences were input to contingent behaviour models which predicted changes in participation and values in response to the outputs of fish and wildlife biomasses predicted for each of the worldview scenarios for our two ecosystem models.

Sub-Task 3.3: Cultural values, experiences, identities and capabilities. To assess non-monetary values and benefits we applied state-of-the art Community Voice methodology, in which ethnographic interviews from specific stakeholder groups (aquaculture/seaweed producers, fishermen, tourism operators, residents inter alios) were undertaken across a range of local community stakeholders in the west of Scotland and the southwest of Britain, to discuss cultural values, places, practices and identities, experiences and capabilities, and how these may be affected by projected changes under different worldview scenarios. Participants were presented with a map of their area to record the places they visit most often and their experiences of environmental changes. Interviews were transcribed and analysed using a thematic coding approach, and representative extracts of different positions around key themes were selected for inclusion in a 40-minute documentary film, which fed into the regional MCA workshop (Task 5.2). The film is available to view on the [MERP Website]() and at http://sharedvaluesresearch.org/merp-marinevalues/

This brings the stakeholders' views alive for viewers.

Sub-Task 3.4: Coupling of valuation and ecology models through management measures. Both StrathE2E and Ecosim combine sub-models of ecology and fishing fleets. Typically, the coupling between these sub-models is one-way, i.e. the fishing fleet model provides input to the ecology model. There is no return feedback by which the simulated ecological conditions and fishery landings and discards affect the subsequent activities of the fishing fleets. The purpose of this task was to develop this two-way connection between the ecology and fleet models, through a set of rules governing how the activity rates of gears should change over time in response to simulated revenues, costs, and catches relative to management targets such as quotas.

It proved impossible to develop this feedback process in Ecosim since the model is a compiled package and we do not have access to the raw code. However, StrathE2E was developed by researchers within the project so we were free to develop new approaches.

The outcome of the task was a dynamic coupling between the ecology and fishing fleet sub-models of StrathE2E, in which:

- Costs of individual gear types (up to 12) increase with their activity, their operating distance from shore, and the density of other competing gears.
- Revenues of individual gears increase with landings
- Individual gears redistribute their effort dynamically in space so as to be proportional to their recent profitability (revenue/costs) subject to any spatial exclusions (mimicking protected areas)
- Various options are available to dynamically control the overall level of activity by each gear:
    - If recent profit proportion ((revenue-costs/costs) is positive then activity increases, and vice versa. If this control alone is used to regulate activity then this represents a so-called 'open access' fishery in which participation is driven purely by market forces.
    - If recent biomass of each resource group is greater than a threshold representing a management target, then the activity of all gears in which each resource represents more than a given fraction of their catch (e.g. 15%) can increase, and vice versa.
    - A range of alternative regulatory controls of individual gears are possible, governed by, for example, activity limits (mimicking days-at-sea regulations), and intensity of seabed abrasion, or by-catch of non-target groups such as birds or cetaceans.

Runs of the model with any given set of prices for each resource group, cost-scalings for each gear, and management targets, converge to stable solutions in terms of gear activity rates and distributions in space, and simulated ecological states, which are emergent solutions and not easily predictable.

The two-way coupled StratheE2E was used to simulate each of the worldview scenarios.

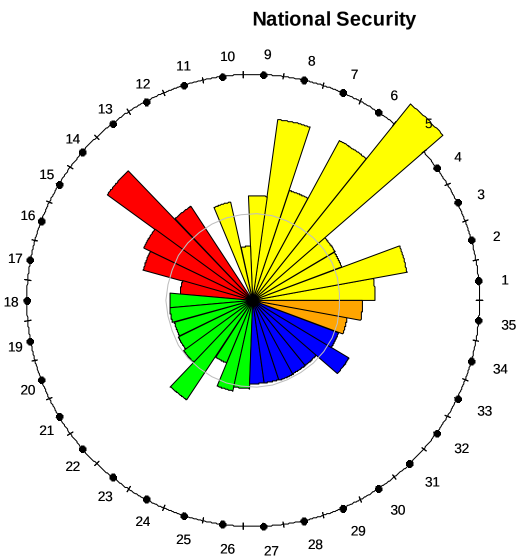
Task 4: Validation, sensitivity, optimisation and scenario simulation.

A standard set of model outputs was generated from both Ecosim and StrathE2E for a baseline state of the west of Scotland ecosystem and economy, representing the actual environmental, fishery and aquaculture systems during 2003-2013. Then each of the four worldview management and economic conditions was simulated with both models. 2003-2013 climate (temperature and ocean conditions) was used for all four worldviews.

The model outputs were delivered to the TLR contingent valuation model, to generate data on participation rates and revenue flows.

Finally, ecological, fishery, economic and wellbeing indicators from all the models were combined into a single visual display for each worldview, which compared the scenario values with the equivalent measures generated by the baseline simulation.

The results of these model simulations, along with an accompanying narrative for each worldview are shown for the west of Scotland in Appendix 1. This document was used in the subsequent Multi-Criteria Analysis workshop. An example of changes compared with baseline values for the National Security scenario is shown in Figure 1.



Label	Description	Label	Description
1	Mobile pelagic effort	18	Winter surface nitrate
2	Mobile demeral effort	19	Mud porewater ammonia
3	Static gear effort	20	Total PP inc kelp
4	Shellfish landings	21	Benthos biomass
5	Demersal fish landings	22	Finfish biomass
6	Planktivorous fish landings	23	Planktivorous/total fish biomass
7	Migratory fish landings	24	Seal biomass
8	Fishery revenue	25	Bird and cetacean biomass
9	Fishery profit margin	26	Top-predator prodn/Primary prodn
10	Fishery profits	27	Number of anglers
11	Seaweed profits	28	Number of divers
12	Total discards	29	Number of wildlife watchers
13	Cetacean catch ratio	30	Welfare of anglers
14	Seal catch ratio	31	Welfare of divers
15	Bird catch ratio	32	Welfare of wildlife watchers
16	Seabed abraded area ratio	33	TLR consumer suplus change
17	Inshore/total area abraded	34	Consumption of aqua products
		35	Aquaculture profits

Figure 1. Segment lengths are proportional to the ratio of scenario : baseline values. Inner grey circle represents the baseline (scenario:baseline ratio = 1).

Task 5: Synthesis, Knowledge Exchange and Impact

Sub-Task 5.1: Probabilistic Graphical Network Model (PGM) synthesis of scenario and optimisation runs

It was proposed that work using probabilistic graphical models based on conceptual models linking ecosystem structure and processes to services, developed in modules 4 and 5, would be used in this task to explore how different management decisions could influence changes in ecosystem configuration and hence trade-offs among services. Significant delays and changes in personnel and institutional responsibilities meant that, although progress on PGMs was made in modules 4 and 5 (described elsewhere in this report), this progress was neither sufficient nor adequately focused to allow the models or their results to be used as originally intended in this subtask.

Sub-Task 5.2: Regional Case Study Multi-Criteria Analysis (MCA) workshops. A Multi-Criteria Analysis workshop for the west of Scotland case study was held on 26 October 2018, supported by the worldview narratives, simulation model outputs and monetary valuations, the Community Voice film and a qualitative analysis of the non-monetary values expressed by the interviewees. The output of the workshop was a set of stakeholder preferences for the different management measures featuring in the model simulations, based on both their individual values, and the evidence of the model simulations. These results are in the process of being written up for publication as a policy briefing and as a peer-reviewed paper.

Regular interaction with the southwest case study stakeholders was undertaken via another NERC impact project (SWEEP) during which the MERP project progress was also regularly discussed. SW stakeholders made constructive and considerable contributions to the materials to be used in MCA workshops. These stakeholders indicated that although they were interested in the broader MERP approaches they did not feel that an equivalent workshop, based on worldview scenarios and the management measures to implement them, was particularly relevant to them at the time. Consequently only one MCA workshop was held, in West of Scotland, although the views expressed in the SW did contribute to the outcomes of that workshop.

Sub-Task 5.3: Synthesis workshop. The synthesis workshop for module 7 was subsumed into the main MERP stakeholder and science conference held and the Royal Society, London, 25-26 April 2018. Progress-to-date was presented on the module as a whole, and on several of the sub-tasks was presented at the science day.

Sub-Task 5.4: Pathway to Impact on MSFD and OSPAR assessments. Indicators derived from the outputs of StrathE2E, Ecosim, contingent monetary valuation models, and the non-monetary valuation data analysis are being incorporated into the developing Cefas CefMAT web application, a tool which will allow users to interrogate integrated data and generate visualisations corresponding to scenarios of their own construction. These will be geared to aiding decision making in relation to MSFD and OSPAR assessments. The full suite of module 7 data outputs will be available for the west of Scotland ecosystem. TLR contingent valuation model results and non-monetary assessments will also be available for the southwest of Britain, and Strathe2E results for the North Sea.

Module 8: Cumulative Impacts and the Management of Marine Ecosystems

This project encompassed a number of diverse topics, under five tasks: Indicators and pressures in space and time; Impact chains, CEA and risk analysis; Modelling management systems; Cumulative effects of management actions; and Communication and Uptake. Considerable progress has been made within most of these tasks, as documented below, although elements continue under no-cost contract extensions (to April 2019). The focus of some tasks changed owing to significant personnel changes over the course of the project, but the progress relating to indicators of ecosystem state, risk mapping of top predators based on multiple anthropogenic and environmental stressors, further development of MERP ecosystem modelling approaches, and integrating these multiple sources of evidence and information into a risk-based approach to assessing cumulative effects is resulting in important outputs. These are fully documented below:

Indicators and Pressures in Space and Time

A new size-based indicator has been developed, based on the observation that small species are more frequent than large species, formalised in the 'diversity spectrum'. The precise shape of this relationship, derived from food web theory and empirically tested over species encompassing fish, marine mammals and seabirds, and a range of invertebrates throughout the UK's seas, is proposed as an indicator of fishing pressure (figure 2). This work is described in a manuscript *The marine diversity spectrum power law: robustness and the impact of fishing* led by QMUL involving MERP collaborators from Sheffield and PML (to be submitted to *Ecology* in early 2019), and the potential of this indicator was presented by Co-I Rossberg to Healthy & Biologically Diverse Seas Evidence Group (HBDSEG) in March 2018.

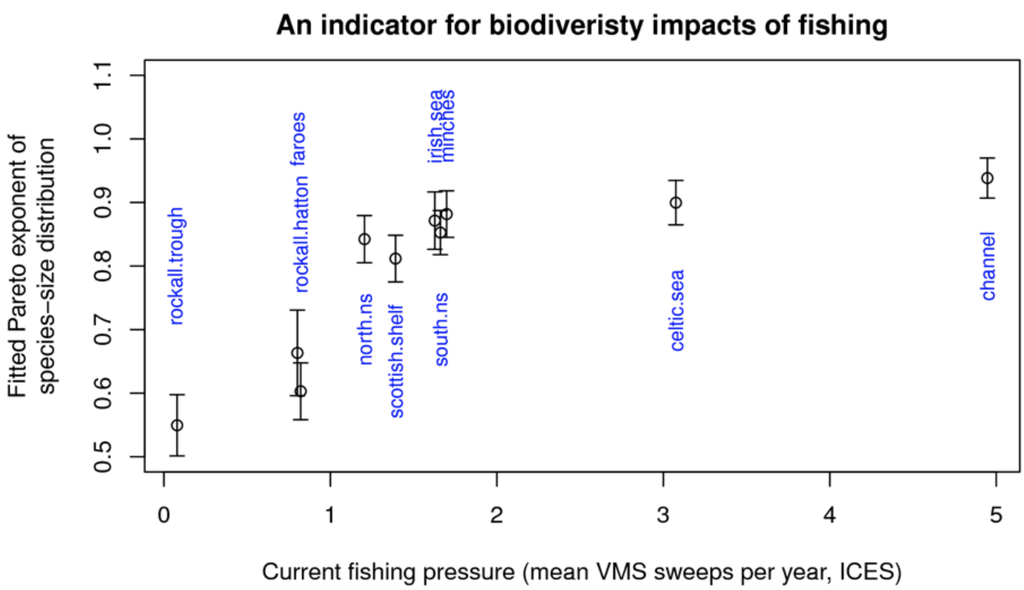


Figure 2. Fitted exponent of the marine diversity spectrum as a function of fishing pressure for UK regional seas, showing that the exponent increases with fishing pressure.

Work in M8 on top predators involved developing an energetics modelling framework that translates estimates of breeding seabird distribution throughout UK waters and around seabird protected areas (SPAs) into the amount of prey removed from the marine system by five seabird species (black-legged kittiwake, common guillemot, razorbill, European shag and northern gannet) comprising more than three-quarters of the seabird breeding biomass in the UK. These predation pressure maps are spatially resolved to approximately 1km, and represent the state-of-the-art in quantitatively estimating seabird distributions from GPS tracking data. These maps allow for observed individuals in a given area of sea to be linked back to their colony of origin, in contrast to methods that use at-sea survey data where the provenance of an individual cannot be explicitly known.

These distribution and predation pressure maps relate to the breeding populations of seabird species at SPAs, which are key components of marine planning activities in the UK, including the Cardigan Bay and South West case studies. In both these areas there are important seabird SPAs and reserves attracting large numbers of local and visiting tourists.

This research has contributed to MERP objectives by providing novel baseline understanding of the spatial habitat use and predation pressure of ecologically important marine top predators. This knowledge may be combined with other data and models to better understand how ecosystem processes and the services they support, such as wildlife tourism, operate against the background of environmental change both now and into the future. We anticipate this work, once published, will have strong relevance to stakeholders (including statutory nature conservation bodies) responsible for understanding and assessing the responses of top predator populations to multiple human activities impinging upon predator populations and behaviour (e.g., offshore renewable energy developments, commercial fishing).

The work on four species has been completed (black-legged kittiwake, common guillemot, razorbill, European shag) and a manuscript is in preparation (Fig. 3): Searle, K. R., A. Butler, M. Bogdanova, E. Wakefield, M. Bolton, S. Wanless and F. Daunt. Predation pressure of breeding seabirds in UK nearshore waters: changes over the last two decades. In prep. To be submitted to Journal of Applied Ecology.

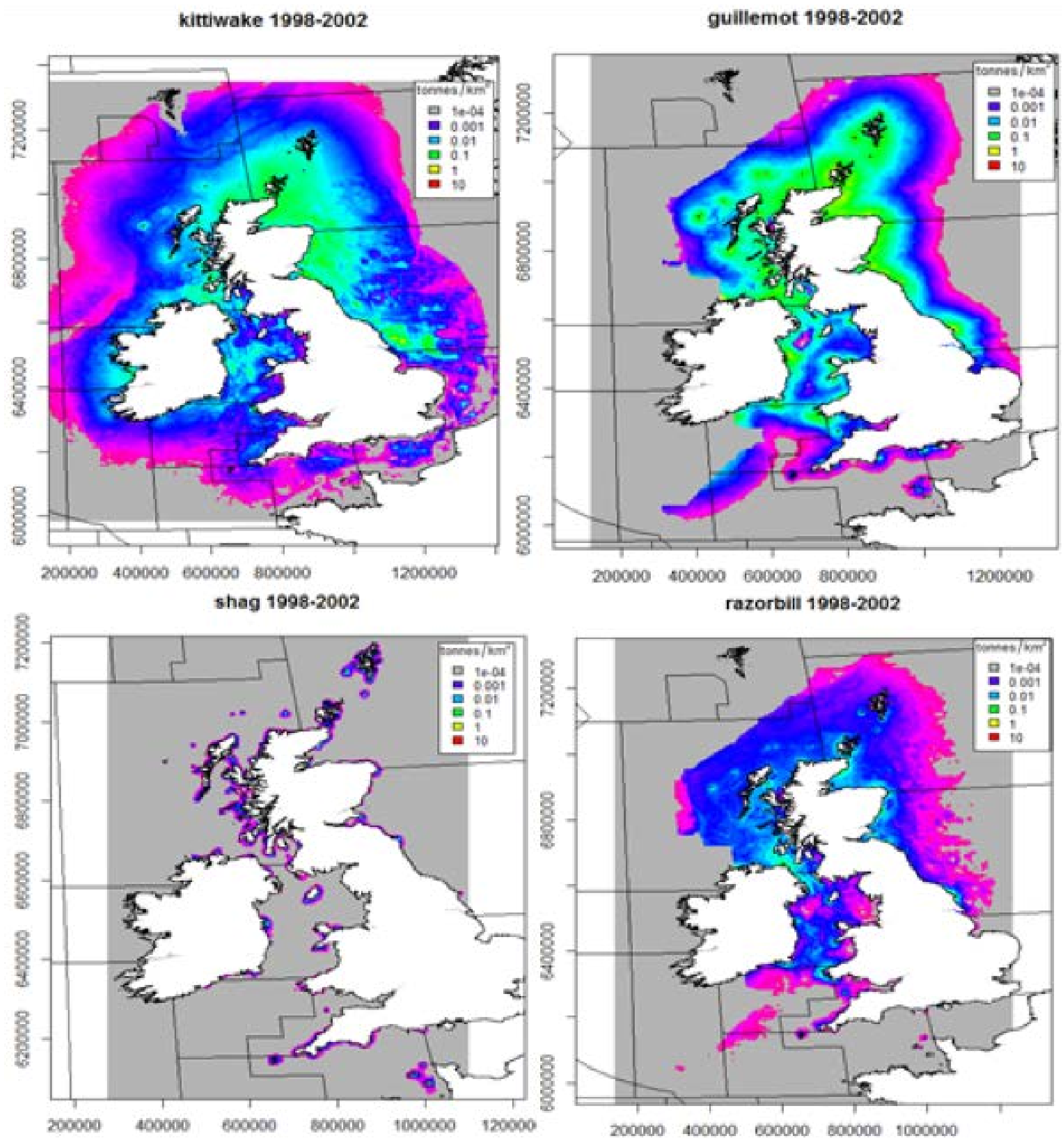


***Figure 3**. Mapped estimated prey consumption (tonnes per km^2) for four species of seabird breeding in UK waters (black-legged kittiwake, common guillemot, razorbill and European shag).*

The second piece of work focuses on northern gannets, drawing together all available GPS tracking data for this species and applying models to map the habitat use of this iconic species around all major colonies occupying UK waters (Fig. 4). These models provide spatially explicit estimates of habitat usage and derived prey consumption around the UK for this ecologically important species. This work is a direct outcome of collaboration between MERP partners (CEH, RSPB, University of Glasgow) and other external partners (Centre D'ecologie Fonctionnelle & Evolutive, University of Leeds, University of Liverpool, University of Exeter).

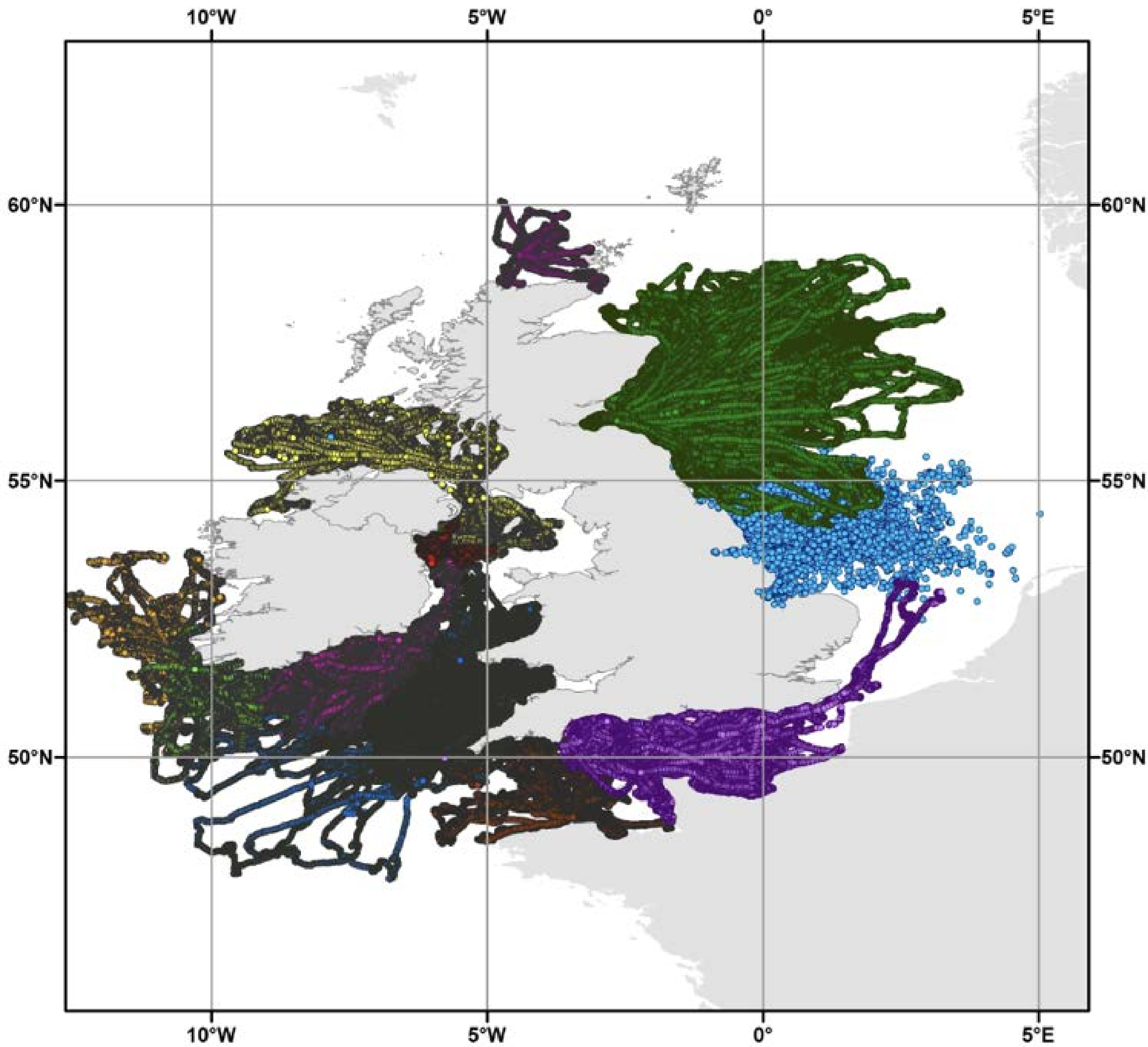


Figure 4. *GPS tracks for breeding northern gannets from all major UK breeding colonies, derived from seven partner organisations.*

A manuscript is in preparation: Searle KR, A. Butler, M Bogdanova, E Wakefield, M Bolton, S. Bearhop, J Green, D Gremillet, K Hamer, S Votier, F Daunt and S Wanless. Regional distribution and predation pressure of breeding northern gannets in UK waters. In prep. To be submitted to Journal of Animal Ecology, Spring 2019.

More general risk mapping of top predators has seen considerable progress on various fronts. The first stage was to continue to refine the models produced in M1 to improve the temporal and spatial resolution of distributions of seabird and cetacean species, as robust monthly distribution maps and maps with resolution <10km are particularly relevant for mapping risk for activities having a localised footprint - e.g. effects of offshore renewables. The focus then switched to mapping primary risk factors including fisheries conflicts (notably bycatch), vessel strikes (primarily through shipping), and noise disturbance (both continuous and pulsed sounds):

- Fishing activities were processed and mapped by gear type and by month using two different data sets (one from ICES, the other from Global Fishing Watch). These rely upon either AIS or VMS data. Neither method was comprehensive and both had other limitations, resulting in different conclusions. The causes of these discrepancies, and strategies for effectively combining the two sources, were examined in collaboration with Mike Heath and Robert Wilson (Strathclyde), with the aim of mapping fishing effort by gear type, by month, and by target fish species using as comprehensive and representative a data set as possible. Preliminary maps have been produced of bycatch risk of different gear types on cetaceans and seabirds (by species). Refinements are ongoing to improve the quantification of fishing effort, identify target fish species of different fisheries for more detailed mapping of risk, and identify country of origin of fishing effort by gear type.

- Estimating risk of vessel strike requires good data on shipping resolved by vessel speed since those travelling above 10 knots have a significantly higher probability of causing lethal injury. Vessel data rely upon AIS or VMS, and these data were secured, allowing characterisation of vessel movements at high resolution. These are now being classified by vessel type and speed to derive maps of risk of ship strike for different cetacean species.

- The third area of risk mapping that we hoped to address was effects of noise (both continuous and impulsive noise) upon cetaceans. ICES has been working on this, particularly for pulsed sounds, and is building maps for the OSPAR region and to satisfy EU MSFD noise descriptors. Continuous noise comes primarily from shipping so, again, the use of AIS/VMS data will help address this sound source. Deriving detailed risk maps from these data is dependent upon the progress of acousticians that are attempting to monitor both forms of noise and produce soundscapes for MSFD. There are several groups (notably from Denmark, The Netherlands, France, and the UK) developing noise propagation models for different sources. We are engaging with them as necessary collaborators.

Outputs are planned to include separate publications on each of the three main stressors, together with a fourth considering multiple stressors and their interactions.

Models of Management Systems

Development of the MERP model ensemble and the BBN approach to modelling has been very closely allied to work in other modules within MERP, in part due to staffing changes towards the beginning of WP3 work. Thus although specific outputs are more directly relevant to other MERP work, the methodological development has much wider applications. This work is reported in modules 4 and 5.

There has also been further development of individual ecosystem models, specifically the top-down and bottom-up Ecospace coupling for the West Coast of Scotland, including much improved covering of top predators. This model has been used to derive indicators for ecosystem state, highlighting how Ecosystem Based Fisheries Management, informed by food web models which incorporate multiple interacting drivers, are necessary for effective achievement of Good Environmental Status (Baudron, Serpetti, Fallon, Heymans, Fernandes (2019) Can the common fisheries policy achieve good environmental status in exploited ecosystems: The west of Scotland demersal fisheries example. Fisheries Research, Volume 211: 217-230. https://doi.org/10.1016/j.fishres.2018.10.024). Similar work is in progress for the Celtic Sea model, which is expected to be submitted for publication in 2019. Both of these models have been implemented with ECOIND providing key information on indicators of GES (Table 1), derived from biomass and/or catch data which are available for most species in the relevant ecosystems, which can be linked to MSFD indicators as shown in table 2. Temporal trends of these indicators have been analysed to identify potential shifts in the ecosystems (e.g. Fig 5).

Table 1. Ecosystem indicators produced using ECOIND for both the West Coast of Scotland and the Celtic Sea Ecopath models.

A. Biomass-based	B. Catch-based	C. Trophic-based	D. Species-based
Total B ($t{\cdot}km^{-2}$)	Total C ($t{\cdot}km^{-2}{\cdot}year^{-1}$)	TL catch	Intrinsic Vul. Index
Commercial B ($t{\cdot}km^{-2}$)	Fish C ($t{\cdot}km^{-2}{\cdot}year^{-1}$)	MTI	Endemics B
Fish B ($t{\cdot}km^{-2}$)	Invertebrate C ($t{\cdot}km^{-2}{\cdot}year^{-1}$)	TL community	Endemics C
Invertebrates B ($t{\cdot}km^{-2}$)	Invertebrates / Fish C	TL community 2	IUCN species B
Invertebrates / Fish B	Demersal C ($t{\cdot}km^{-2}{\cdot}year^{-1}$)	TL community 3.25	IUCN species C
Demersal B ($t{\cdot}km^{-2}$)	Pelagic C ($t{\cdot}km^{-2}{\cdot}year^{-1}$)	TL community 4	Mammals, birds & reptiles B
Pelagic B ($t{\cdot}km^{-2}$)	Demersal / pelagic C		Mammals, birds & reptiles C
Demersal / Pelagic B	Predatory C ($t{\cdot}km^{-2}{\cdot}year^{-1}$)		
Predatory B ($t{\cdot}km^{-2}$)	Discards ($t{\cdot}km^{-2}{\cdot}year^{-1}$)		
Kempton's Q			
Shannon diversity			

Table 2. Links between outputs of Ecopath with Ecosim (temporal) and Ecospace (spatio-temporal) and MSFD indicators, showing that temporal and spatial trends in many MSFD indicators can be successfully resolved using this modelling framework.

2. MSFD indicators			Ecopath	Ecosim	Ecospace
GES descriptors	Assessment criteria	Indicators	Static	Temporal	Spatio-temporal
1. Biological Diversity	Species distribution	Distributional range/pattern	✗	✗	✓
	Population size	(1) abundance and/or (2) biomass	✓	✓	✓
	Population condition	(1) body size; (2) age class structure; (3) sex ratio; (4) fecundity rates; (5) survival/ mortality rates; (6) other	✓	✓	✓
	Habitat distribution	Distributional range/pattern	✗	✗	✓
	Habitat condition	Condition of the typical (1) species and (2) communities	✗	✓	✓
		Relative (1) abundance and/or (2) biomass	✓	✓	✓
	Ecosystem structure	Composition of ecosystem components: (1) habitats and (2) species	✓	✓	✓
		Relative proportions of ecosystem components: (1) habitats and (2) species	✓	✓	✗
	Ecosystem processes & functions	Interactions between structural components	✓	✓	✗
		Services provided	✗	✓	✓
4. Food webs	Productivity (production per unit biomass) of key species or trophic groups	Performance of (1) key predator species determined from their productivity; (2) other trophic group	✓	✓	✗
	Proportion of selected species at the top of food webs	(1) Large fish (by weight); (2) other species	✓	✓	✓
	Abundance/distribution of key trophic groups/species	(1) groups with fast turnover rates; (2) groups/species that are targeted by human activities or that are indirectly affected by them; (3) habitat-defining groups/species; (4) groups/species at the top of the food web; (5) long distance anadromous and catadromous migrating species; (6) groups/species that are tightly linked to specific groups/species at another trophic level	✓	✓	✓
6. Sea floor integrity	Substrate characteristics - physical damage	(1) type; (2) abundance; (3) biomass; (4) areal extent	✓	✓	✓
		Extent of seabed significantly affect by human activities for the different substrate types	✓	✓	✓
	Condition of benthic community	Presence of particularly sensitive and/or tolerant species	✓	✓	✓
		(1) species diversity and (2) richness, (3) proportion of opportunistic to sensitive species	✓	✓	✓
		Proportion of (1) biomass or (2) number of individuals in the macrobenthos above some specified length/size	✓	✓	✓

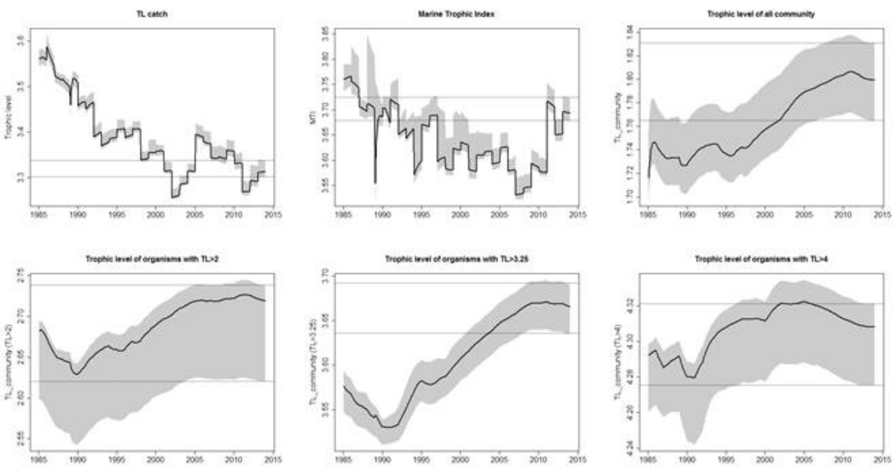


***Figure 5**. Temporal trends in a range of ecological indicators of GES calculated from the Celtic Sea Ecopath ECOIND model.*

Impact Chains, CEA, and Risk Analysis

'Evidence Chains', closely linked to Impact Chains, have been produced for seabirds using a range of evidence. Evidence chains provide a description of the linkages and interactions between natural capital assets and ecosystem services and human benefits, and are a useful step to link together the multiple impacts and outcomes required in cumulative effects assessment. We have established a conceptual framework for linking natural capital assets to human well-being, identifying and providing an evidence base for each step along the chain. We have collated information and assessed the strength of evidence for impacts of offshore renewable energy on seabirds (Fig. 6). This information will be made available to stakeholders through the NERC CEH Natural Capital Portal and the MERP website, which should be online by early 2019.

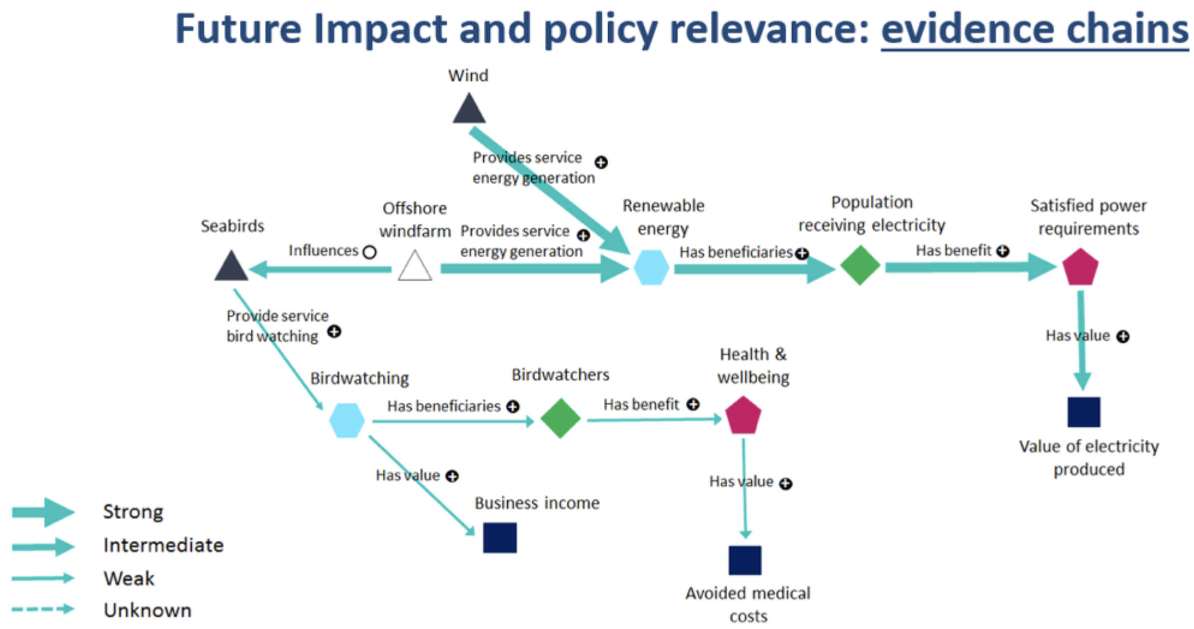


Figure 6. *Evidence chain linking natural capital assets (seabirds) to ecosystem services (offshore renewable energy) and benefits (human health and well-being).*

Cumulative Effects of Management Actions

This work has been developed in the framework of Bow Tie Analyses. A methodological paper describing the use of BTA for cumulative effects assessment is planned for submission. This paper contains case studies on pollution from plastics, TBT and contaminants affecting seabirds, and will provide a demonstration of the practical implementation of methodologies developed in M8. We have also run two live trials of using BTA for stakeholder engagement, and incorporating stakeholder expert knowledge into BTA for cumulative effects assessment. The M8 Cardigan Bay Stakeholder Workshop in November 2017 is fully reported in the Cefas report (Judd & Wood 2018 Cardigan Bay Stakeholder Report, Cefas technical report, available in the reports section of the website), but in brief it involved convening a range of stakeholders, using pre-workshop questionnaires to define issues or activities of concern in the Cardigan Bay area, and then running three exercises for each issue: identifying the consequences (impacts) of these issues; identifying the threats or causal factors associated with these issues; and identifying the preventative or remedial management actions that are applied, together with their effectiveness. These constitute the key information required to build Bow-Ties for each issue, and these draft Bow-Ties produced ‘on the fly’ during the workshop itself were then refined post-workshop. The lessons and outputs from this workshop directly informed a second stakeholder workshop in Norway for OSPAR, which has expanded the MERP work from a local level out to the OSPAR regional level. The work flow has gone from a local level to feeding into the cumulative effects assessment of the OSPAR region(s) for the 2023 Quality Status Report.

In addition, BTA was trialled separately during the second Marine Pioneer stakeholder workshop in Bideford, Devon on 6 February 2018 (attended by 50 representatives from a range of sectors). We coordinated a session in which bow-ties were developed for two locally important contexts: declining bird populations and poor water quality. Participants identified pressures, impacts, management measures and the benefits of mitigation in both contexts. The 'nested' nature of the problems was also demonstrated, with poor water quality identified as an impact on bird populations, and with broader overlap around issues of pollution impacts and the benefits offered by recreation. This stakeholder input was then used to construct Bow-ties (e.g. fig 7).

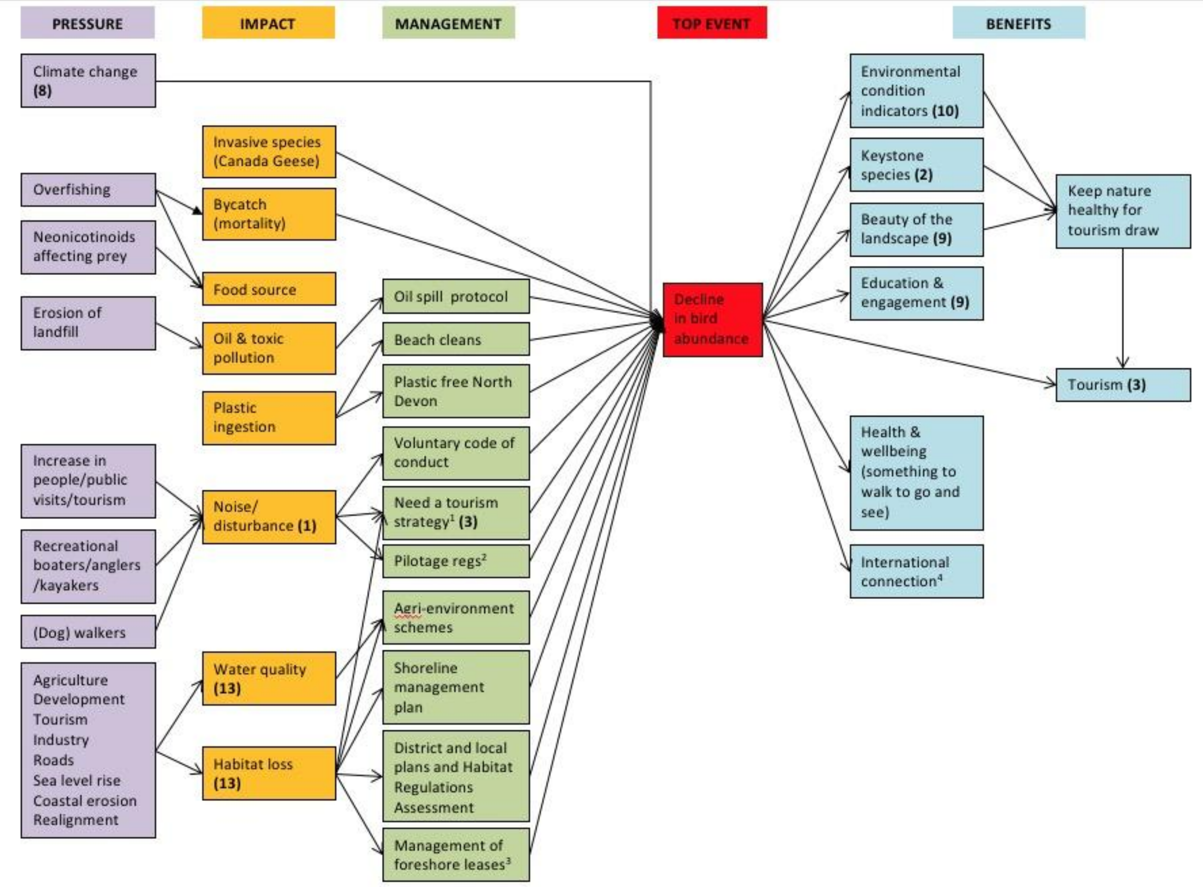


Figure 7. *Example Bow-Tie focused on declines in bird abundance produced 'on the fly' during the second SW Marine Pioneer stakeholder workshop, Feb 2018.*

Communication, Uptake, and Synthesis

Communication and uptake has been documented throughout this report where possible, however some specific activities are worth highlighting. In particular the Cardigan Bay Stakeholder Workshop was, to our knowledge, the first time that Bow Tie Analysis has been used in a live situation to collate stakeholder knowledge and experience, and so it was a valuable exercise from a methodological best-practice standpoint. A number of lessons were learnt from the process that can inform further events, including the need to define the top event well before starting a stakeholder workshop - if the top event is loosely defined, it forms a topic for discussion rather than being a specific unwanted scenario. In addition, and as with all stakeholder events, it is difficult to get complete stakeholder representation. This can lead to a skewed perception within the results. Within this workshop there was no representation from the scallop dredging industry. Some NGOs and local businesses were also missing. However, overall, we had broad representation from most stakeholders. We plan to write up these methodological insights as a paper presenting bow tie analysis as a stakeholder tool, with a planned submission date of February 2019.

Whilst BTA is an exercise in simplifying complex chains of events for stakeholder consumption, interactions with stakeholders throughout MERP, and specifically within M8, has stimulated research into examining how we communicate complex information more generally. University of Sheffield PhD student Hayley Bannister worked closely with the MERP scientific and stakeholder communities to try to understand the factors that make for effective graphical communication of model uncertainty. A large online survey was designed to assess various aspects of effectiveness of different graphics, including the accuracy with which respondents were able to extract information, as well as their overall preferences for different types of graphic. This work was presented at the November MCCIP meeting, is written up as a thesis chapter, and will be submitted as a paper in early 2019.

More generally, in an attempt to synthesise the different methods adopted to address the complex questions posed in M8, and to show how the empirical, ecosystem modelling, risk-based, and stakeholder-driven approaches complement each other, a paper Triangulating the Evidence on Cumulative Impacts and the Management of Marine Ecosystems is in preparation, led by Webb and Grace (Sheffield) but involving the entire M8 team. This concept was presented at the MERP Science Meeting in April 2018, and the first draft is complete. The next stage is gathering specific contributions from team members, some of which will be dependent on completion of other outputs. Target submission date is Feb 2019.

Marine ecosystem data toolbox & application of macroecology (Module 1)

This work specifically addresses the need to improve our understanding of how marine ecosystems may respond to specific "bottom up" and "top-down" changes through the novel combination of existing data with recent theoretical advances from marine and terrestrial ecology.

Existing marine ecosystem data records from a wide range of sources will be rearranged according to species traits (body size, habitat, feeding mode). This resource will be used to conduct a range of comprehensive regional macroecological analyses.

Bringing diverse data together (Ecoinformatics)

New data and R tools developed in the programme are now accessible through the Marine Ecosystems Research Programme GitHub repository (https://github.com/MarineEcosystemResearchProgramme). This provides a simple 'research-grade' interface to access, manipulate, and display UK marine biodiversity data. The data accessed via these tools involved input from multiple MERP partners. With additional work from software developers this output may be useful beyond academic audiences. A Research Software Engineer has been engaged to finalise data products, including working with MERP partners in Glasgow to prepare the seabird diet database (currently in GitHub repository https://github.com/annakrystalli/seabirdPrey while final quality control is completed, after which it will be made public) for publication and producing a new R Shiny app (https://sheffield-university.shinyapps.io/sedmap_shiny/) that serves gridded MERP data with functionality allowing the user to extract data for a given region of interest (e.g. a regional sea, a marine plan area, etc.). Currently this works with the gridded MERP sediment map (see below, fig 7), with additional MERP gridded data products in the process of being added.

Work was also progressed on enriching occurrence data with biological traits and environmental data (aided by additional funding to TJW from EMODnet biology to develop data products for a European Atlas of Marine Life, see https://github.com/EMODnet/EMODnet-Biology-thermal-traits). This gridded data product on thermal tolerance of European marine species will be accompanied by a manuscript describing the workflow and comparing experimentally-derived and occurrence-derived thermal tolerance (target journal: Ecology Letters). The library of code associated with this work is a MERP legacy, some of which is already publicly available on GitHub via EMODnet (see above) and via TJW's own site (e.g. this generic function to assign functional groups to marine species: https://github.com/tomjwebb/WoRMS-functional-groups). The remainder will be released alongside accompanying publications.

Utilising meta-analytic methods, papers exploring the body mass-scaling of key metabolic and life history rates have been completed, encompassing both benthic and pelagic invertebrate species. This work allows for a better ability to predict rates of many diverse biological processes, as well as demonstrating profound differences between how organismal rates and body mass vary in these two habitat types (Hirst et al. 2017 Limnol Oceanogr 62: 311-319. doi: 10.1002/lno.10396; Lilley et al. near submission).

R tools and training

Having better and more transparent methods for processing such data was of benefit to the programme. Understanding where things are, and making best use of empirical data, is a key component of spatial planning. Working in collaboration with European partners, tutorials on working with marine biodiversity data in R were made available (http://www.iobis.org/2016/11/22/sorbycollection/ and https://ropensci.org/blog/blog/2017/01/25/obis. These posts provide step-by-step guides to accessing, enriching, manipulating and visualising marine biodiversity data using R. In particular, they show how to subset biodiversity records by taxon or by region, and how to match occurrences to environmental variables. This workflow is very general and ongoing work is adapting it to incorporate more sources of both biodiversity and environmental data, documented in the extensive readme on the EMODnet site (https://github.com/EMODnet/EMODnet-Biology-thermal-traits). This work has benefited from discussions with a range of MERP colleagues.

This work was used for training purposes within the international marine biodiversity community by OBIS. The version on the OBIS website has been accessed 900 times, and the ROpenSci version has been viewed 500 times and was reposted on the popular r-bloggers site (https://www.r-bloggers.com/extracting-and-enriching-ocean-biogeographic-information-system-obis-data-with-r/) and was a featured tutorial on R-weekly (https://rweekly.org/2017-5.html). In addition, rOpenSci tweeted it to ~12,000 followers. Thus, it exposed a wide range of stakeholders to the kind of marine biodiversity data work that we are undertaking within MERP.

As with the GitHub repository, we expect this work to form the basis of a more professional, packaged set of tools for accessing and working with marine biodiversity data. Collaboration with Research Software Engineers in Sheffield to this end is ongoing, with the prototype shiny app (https://sheffield-university.shinyapps.io/sedmap_shiny/), designed with researcher and stakeholder needs at heart, an initial output.

Accessing Cefas data

Assessing the state of (or their components) against specified targets (e.g. GES under the MSFD), and understanding factors driving the distribution of food web components and their interaction in space and time with pressures and environmental variables, are key policy-relevant applications of MERP science. Cefas are a key partner in MERP, and are custodians of relevant data that are extensive spatially and temporally. Relevant data was made available to MERP via the Cefas Data Hub (www.cefas.co.uk/cefas-data-hub/).

Cefas has been conducting policy-relevant studies enabled by the integration of existing data within MERP and more widely. Existing faunal, environmental and pressure data collected in the North Sea were combined to establish key characteristics of benthic communities in response to natural environmental drivers (physical and hydrodynamic environment), climate drivers (temperature) and anthropogenic drivers (fishing pressure). Over 650,000 records from the Ocean Biogeographic Information System (OBIS) have been assembled, corresponding to occurrences of benthic genera in the North Sea between 1985-2015 and historic beam and otter bottom trawling pressure has been reconstructed. This data set is currently being used by Cefas to advise Defra on the level at which each stressor causes significant shifts in community composition and to develop scenarios under which shifting, rather than static, baselines and targets are appropriate for management. A summary of key results was presented at the 4th World Conference on Marine Biodiversity (Montréal, Québec, Canada, 13-16 May 2018) and at a recent Defra biodiversity science briefing on 15 October 2018.

Making use of scripts and data resources developed at Sheffield University, Cefas has been combining species distribution data in the Exclusive Economic Zone (EEZ) with spatial information on environmental and anthropogenic pressures to (i) identify key stressors (e.g. climate, fishing, pollution) on marine species diversity, (ii) highlight locations where environmental and anthropogenic threats to marine species diversity are greatest and (iii) highlight locations that are accepted priorities for marine conservation/management measures. This information is being used to advise Defra on where biodiversity may be particularly vulnerable to human pressures and to identify areas where management measures may be particularly effective. Key aspects of this study were presented at JNCC's conference on the future of our offshore marine environment, “Beyond the Coast 2018” (Hull, UK, 26-27 June 2018) and at a Defra biodiversity science briefing on 15 October 2018.

Cefas data was combined with other relevant freely accessible data and new observations from MERP cruises to provide a more complete picture of how food web components are distributed and how they interact in space and time with pressures and environmental variables. New maps and other data products and indicators underpin advice on the state of and the environmental conditions required to maintain them. Further integrating data has direct relevance to investigate species distributions and interactions. Of particular relevance to Defra are questions including: How can we define and describe biodiversity hotspots? How are populations of vulnerable species (cetaceans, seabirds, elasmobranchs etc.) distributed in space and time? What are the effects of changes in fisheries management on the environment, in particular through food web effects? Cefas continue to use the combined and integrated data from MERP to address such questions, and the strategic relationship between MERP partners is secured by a new funded PhD studentship within the NERC-funded ACCE DTP, led by the University of Sheffield (Webb) with MERP co-supervisors from the University of Liverpool (Hirst) and PML (Bruggeman), and with Cefas as CASE partner. Over the next 3.5y this studentship will build on MERP's data legacy to further address these core, policy-relevant questions, with a focus on the macroecology of biological traits.

Accessing CPR data

SAHFOS collaborated with the University of Sheffield and University of Bangor, providing processed time series of relative abundance and biomass of key zooplankton taxa, and of the phytoplankton colour indicator (PCI) index, for MERP's focal regions (the western seas of the UK, including the Western Channel, Celtic Sea, Irish Sea, and seas of the West of Scotland), as well as data on key biological traits of major zooplankton taxa. Other raw data was sent to Bangor for all North East Atlantic regions (DOI: Plankton Abundance data for: Total Small Copepods, Total Eyecount Copepods, *Calanus finmarchicus*, *Calanus helgolandicus*, Euphausiacea Total For Standard Areas: B1, B2, B4, C1, C2, C3, C4, C5, D1, D2, D3, D4, D5 DOI:10.7487/2016.21.1.947 URL to DOI: http://doi.sahfos.ac.uk/doi-library/merp-raw-data.aspx. These data were used in work submitted for publication (Serpetti, N. Baudron, A.R., Burrows, M.T., Payne, B.L., Helaouët, P., Fernandes, P.G., Heymans, J.J. (Submitted). Ocean warming could jeopardise sustainable fisheries management). This work improves our understanding of how marine are affected by 'top down' and 'bottom up' driven cascades and scale- dependence in the underlying processes over space and time. It provides evidence for long-term biological changes around the British Isles and how these effect sustainable fishery management, how the various trophic levels interact over decadal periods, the long-term and spatial behaviour of primary producers, and provides data that can be used to test and develop models.

MERP Trait Explorer

For many applications we need to know the traits of marine species. This is crucial for understanding ecosystem function and building ecosystem models. We are still a long way away from complete characterization of every species, but the MERP Trait Explorer (http://www.marine-ecosystems.org.uk/Trait_Explorer) addresses this issue. Trait Explorer is publicly available, was announced on the MERP's ResearchGate page, was an item in the MERP newsletter, and has already been used in various presentations including at http://deb.akvaplan.com/symposium.html. Trait Explorer represents a step-change in estimating traits for species. It can estimate traits for any species through a form of "automated expert judgement" that combines large datasets with published trait values and the latest taxonomic information. It takes into account taxonomic relationships between species (related species tend to have similar traits) and power law-like relationships between traits (e.g., organism mass is a good predictor for many physiological traits). It relies in part on trait datasets provided by other MERP modules. Outputs of the Trait Explorer were used in MERP, for example to determine body-size distributions in UK waters, and to assess functional diversity in MPAs. It was also used to convert species wet weights to carbon mass to facilitate comparison with ERSEM, both within MERP and SSB (John Aldridge; paper accepted). Trait

Explorer enables us to reconstruct functional diversity from the most common type of observation - species abundances or presence/absence - and thus contributes to understanding the link between functional diversity and ecosystem services. It also supports the integration of existing and new knowledge [datasets] into models by inferring quantitative traits (e.g., DEB parameters) for any species from sparse datasets with observed trait values. As a publicly available resource Trait Explorer has received > 800 queries (requests for the traits of one or more specific species) from 101 unique IP addresses from 20 different countries since January 2017. Users include many institutes not in MERP, e.g., AWI and NIOZ. It can serve as a point where data generated within MERP comes together. The more trait datasets are integrated in the server, the more useful it becomes. Integrating data sources in the server does not publish the underlying data themselves, so it does not preclude the separate publication of the dataset. A new NERC ACCE PhD studentship will both use and help to further develop Trait Explorer over the next 3.5 years.

Trait Explorer was updated with new datasets on length and mass recently. A spin-off (http://server1.pml.ac.uk/traitexplorer/deb.shtml) built on the same infrastructure has been developed to infer Dynamic Energy Budget (DEB) model parameters for any of the > 1.6 million species – marine and terrestrial – present in the Catalogue of Life (http://www.catalogueoflife.org). This spin-off was presented at the Fifth international symposium on Dynamic Energy Budget theory (Tromsø, Norway).

Working with ICES using MERP products

In collaboration with scientists from various ICES countries, MERP scientists have been using traits-based data, brought together through MERP (e.g. Trait explorer) and other nationally- and internationally-funded initiatives, to support activities of the ICES Working Group on Biodiversity Science (WGBiodiv). The group met in Copenhagen from 5-9 February 2018 to progress the development of life-history-trait-based biodiversity indicators for benthic invertebrates. A traits-based physical disturbance indicator has been developed, combining functional characteristics of benthic species, including their sensitivity to physical perturbations (i.e. their response through injury or death) and their recoverability (i.e. the self-sustainability of a population when damaged and/or its recolonisation potential following mass mortality). The report (ICES CM 2018/EPDSG:01. 82 pp.) is available from ICES. WGBioDiv has proposed new Terms of Reference for 2019-2021 to the ICES Science Committee. These include testing and wider application of the benthic indicator.

New large-scale sediment data

In order to derive the average properties of seabed sediment in the spatial habitat domains of improved StrathE2E models we needed data on continuous variables associated with the sediment. Indeed, for a range of purposes within and beyond MERP spatial data on the nature and composition of the seabed are crucial. All the published compilations to date are of sediment categories, from which it is very hard to interpret these continuous variable. Following the MERP strategy of bringing together existing data and merging them with models to improve our understanding of large-scale patterns and processes, University of Strathclyde compiled international data sets on individual sample-by-sample measurements of sediment composition, grain size, and carbon and nitrogen content. The combined international raw data set covered a large part of the NW European shelf from the Bay of Biscay to the northern limits of the North Sea and the Faroe Islands with reasonable sample density. However there were also large gaps with no or few samples. They used a combination of gridding where the data density was high, and a machine-learning algorithm to predict the sediment data in the voids where there were no samples, to produce an integrated atlas of a range of continuous properties of the seabed. The machine-learning algorithm used inputs on bathymetry and bed-shear stress due to current and wave action derived from the most recent UK shelf seas hydrodynamic model simulations. These digital data, gridded at ⅛-degree resolution, are open access and available to download, along with a full description of the methods used (Wilson, R.J., Speirs, D.C., Sabatino, A. and Heath, M.R. A synthetic map of the northwest European Shelf sedimentary environment for applications in marine science. Earth System Science Data 10, 109-130, 2018, doi: 10.5194/essd-10-109-2018).

The gridded data products available are maps of:

- mud, sand and gravel percentages by weight of the sediment,
- median grain size of the whole sediment and separately for the sand and gravel fractions,
- porosity and permeability of the sediment,
- mean and maximum depth-averaged tidal velocity and wave-orbital velocity at the seabed,
- monthly mean natural disturbance rates of the whole sediment

Of particular note is the mapping of exposed and thinly covered bedrock. Previously maps of seabed rock outcrops were in some cases based on more-or-less ad-hoc shapes enclosing clusters of raw data points alluding to seabed rock outcrops, rather than by any quantitative statistical analysis. To resolve this they downloaded and analysed, for example from BGS, the hand-written deck-logging sheets from the original surveys to get back to the raw data on estimated locations of shallow or exposed bedrock. Then they produced continuous data combing directly gridded and machine-learning predicted area-proportions of grid cells classed as exposed or thinly covered rock. In some regions, e.g. west of the Outer Hebrides, the results give a very different perception of the extent of exposed rock comparted to the traditional maps. While assembling seabed sedimentology data was required to better configure StrathE2E for regions around the UK, the data will have much wider applicability. For example, so-called habitat maps are widely used in spatial management and conservation planning, and suffer the problems that the new data are designed to address. The data on natural seabed disturbance are already proving of interest to Defra as providing context for analyses of fishing disturbance, and have been used as an exemplar gridded dataset for the prototype MERP shiny app (https://sheffield-university.shinyapps.io/sedmap_shiny/).

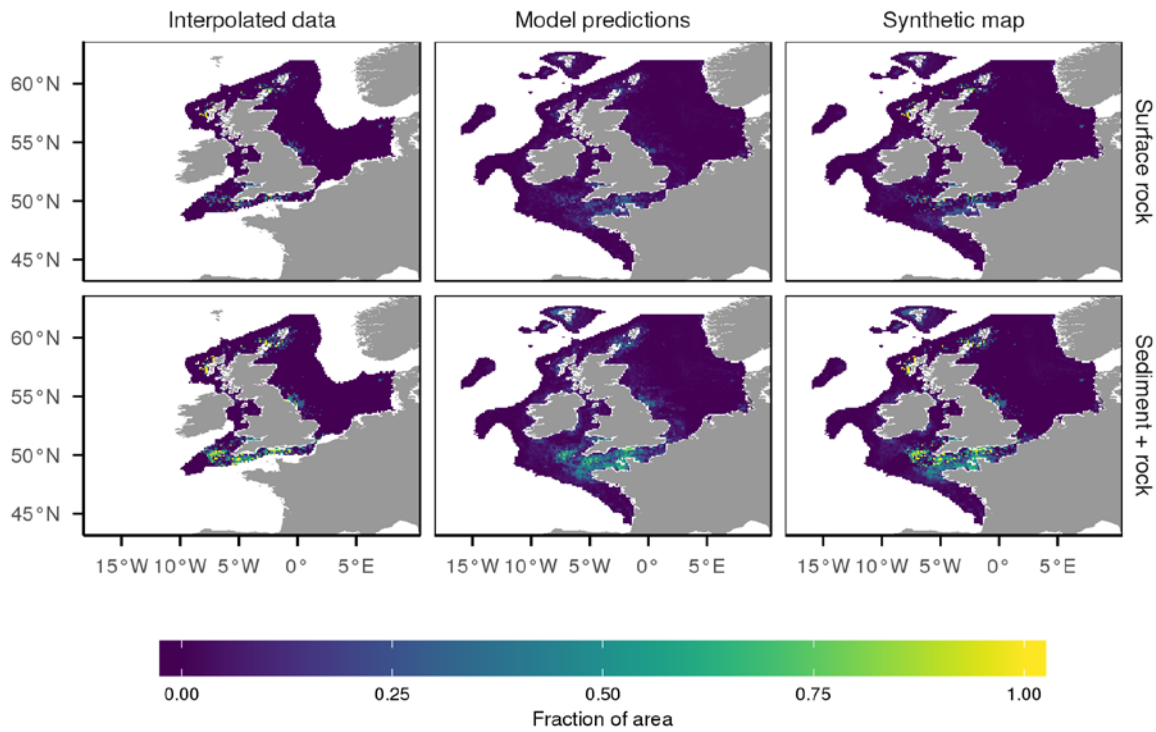


Figure 8. *Derivation of the synthetic maps of area-proportions of exposed bedrock, and of rock covered by up to 5cm of sediment. The interpolated map uses bilinear spline interpolation of sediment data over the region. The model prediction map shows the rock area proportions using a random-forests machine learning algorithm which relates the percentage to the bed shear stress and the distance to the coast. The synthesized map merges the two, using spatial interpolations where we have data and the predictions where we do not.*

Environmental and sediment conditions, infaunal benthic communities and biodiversity in the Celtic Sea

One of the stated aims of MERP was to work with our partners in other NERC/Defra programmes. MERP scientists analysed data collected during the Shelf Seas Biogeochemistry (SSB) programme, and the resulting paper (Somerfield et al. 2018 Continental Shelf Research doi: 10.1016/j.csr.2018.09.002) is in a dedicated SSB special issue. While it is recognised that the nature of the sediment is a major driver of benthic macro-infaunal community structure, it is also true that diverse environmental factors determine the distribution and composition of sediments. Among those factors are depth, tidal stress and seasonal stratification of the water column. In the Celtic Sea an area of seabed approximately 20 km wide and 125 km long was selected in which variation in water depth, stratification, primary production and current velocity were minimised, but which contained sediments ranging from fine muds to coarse gravelly sands. 55 stations were sampled across the area using a box-corer. At each station a comprehensive suite of sediment and biogeochemical measurements were made. Macrofauna were identified and weighed. Of the stations sampled, four had been chosen by SSB as focal sites for a study of relationships between benthic biogeochemistry and sediment type. Relationships between variation in environmental and sediment variables and macrofaunal community structure were analysed using a range of non-parametric multivariate techniques. Environmental variables were discriminated into situational variables that broadly encapsulate potential drivers of spatial heterogeneity in the benthos such as depth and fishing effort, and in-situ variables that were measured at each site concurrently with the sampling of the macrobenthos, such as sediment properties and biogeochemical measurements. Among the former, analyses tended to identify the importance of average shear stress and depth in explaining observed variation in benthic community structure, even though the area had been chosen to minimise variation in those factors. Analyses using in-situ measurements of sedimentary conditions at each site identified very fine sand content (correlated with average shear stress) as the most important explanatory variable. Most of the measured biogeochemical variables varied with sediment structure, particularly reflecting differences between finer-grained sediments with higher organic content (generally from deeper areas) and coarser sediments with lower organic content. While clear spatial heterogeneity in sediments and associated biogeochemical variables could be demonstrated, spatial variation in benthic abundance and biomass was less clear. Benthic community structure varied significantly with sediment type, but did not vary closely with the in-situ environmental variables measured at the same sites. This may indicate that the samples collected were too small to accurately characterise the benthic assemblage at each site, or that most species inhabiting the area inhabit a range of sediment types, or that processes which are not reflected in sediment or biogeochemical measurements are also important determinants of benthic community structure.

Hotspots of UK Marine Biodiversity: Linking data to the marine conservation zone network

To protect marine ecosystems and their biodiversity the biodiversity hotspot approach offers a solution by efficiently allocating conservation action to the most biodiverse areas, hence maximising benefits from limited conservation resources. However, the success of the approach needs to be assessed, so that its usefulness can be determined. The Ocean Biogeographical Information System (OBIS) marine record database was used to investigate the location of marine biodiversity hotspots within UK waters. Hotspots for species richness and taxonomic diversity were located and compared to assess congruence between different taxonomic groups and measures of diversity. There was considerable overlap in the hotspots of 10 major taxa, with 84.2% of hotspots overlapping with at least one other taxonomic hotspot, and 50.2% overlapping with 4 or more. Positive correlations were recorded for species richness distribution across invertebrate taxa, but relationships between invertebrates and vertebrates were negative or non-existent. The diversity within the UK marine protected area network was also assessed, with 2,942 species (45.9% of total) recorded within the network, and a mean taxonomic diversity of 0.861. Randomised sampling of UK waters revealed that the existing network represented more species and hosted significantly greater mean taxonomic diversity than if the network was randomly allocated across the UK exclusive economic zone. The research helped to identify hotspots within UK waters, as well as offering a new insight into the distribution of UK marine biodiversity, and the taxonomic coverage of the existing protected area network. The work (Josh Parker, 2016, MBiolSci thesis, Sheffield) will be written up for publication.

Factors affecting the location of UK Marine Biodiversity Hotspots

Conservation action in the marine environment is vital for the maintenance of ecosystem services. Hotspots are areas with especially high levels of biodiversity, allowing the conservation of diversity through the protection of a relatively small area. A study (Laura Abels, 2017, MBiolSci thesis, Sheffield) focused on the United Kingdom Exclusive Economic Zone and to investigate: 1) differences between hotspot locations with different measures of biodiversity; 2) whether the locations of hotspots overlap for different functional groups; 3) whether using different data sources affects where hotspots are located. Results show that hotspots overlap more than by chance for some but not all metrics. These results highlight the importance of incorporating numerous diversity metrics when locating hotspots. Hotspots of species diversity for different functional groups were shown not to overlap more or less than by chance for most groups, implying that functional groups may not have high diversity levels in the same areas. The datasets from the sources analysed in this study showed a positive correlation but not a strong one. However, the hotspots located by the datasets overlapped more than by chance. This indicates that different data sources may have discrepancies between diversity distributions but still locate hotspots in similar areas.

The effectiveness of Scotland's Marine Protected Area Network in conserving the functional diversity of marine fish and benthic ecosystems

Scotland's Marine Protected Area (MPA) network has been created for the protection of biodiversity and ecosystem functioning ensuring nature conservation and continued ecosystem service provision. Functional diversity is not considered during MPA establishment yet plays a vital role in ecosystem functioning. Very little attention has been paid to functional diversity in marine ecosystems and even less research has focused on the effectiveness of MPAs for the conservation of functional diversity. This is a newly emerging area of research but its application to conservation has been held back by a lack of data. A study (Beth Churn, 2018, MBiolSci thesis, Sheffield) aimed to assess the effectiveness of Scotland's MPA network in protecting functional diversity by bringing together new datasets on Scotland's functional diversity and MPA management. The spatial distribution of fish and benthic functional diversity was mapped, using the functional diversity metric, functional dispersion (FDis). The level of FDis in protected and unprotected areas is compared. FDis is also compared within areas of varying protection level and fishing intensity. The level of benthic functional diversity was no greater inside MPAs than in unprotected areas. However, areas of high fish functional diversity are contained within MPAs. The majority of Scotland's MPAs had little to no fishing restrictions, FDis in these MPAs was no different than in highly protected MPAs.

Climate induced range shifts in adult and juvenile fish on the European continental shelf

Ocean temperatures are warming, and fish have been observed at the species-level shifting their ranges in response. However, different life stages of fish have different thermal tolerances. Juvenile fish can tolerate both warmer average and a wider range of water temperatures than adults, meaning adults have been hypothesised to show greater sensitivity to increasing ocean temperatures. However, it is not known how the rates of latitudinal range shift of adults and juveniles of the same species in response to climate change are related. Using a spatially extensive and temporally replicated set of fisheries-independent surveys on European demersal fish, a study (Aaron Lines, 2018, MBiolSci thesis, Sheffield) confirmed that that the rates of range shifts of adults and juveniles of the same species are related. Juvenile rates of latitudinal range shift in response to both time and Sea Bottom Temperature were positively correlated with adult rates, with adults showing greater rates of response than juveniles, although adult rates only explain a small portion of the variation in juvenile rates. Furthermore, the relationship between adult and juvenile rates was unchanged across survey regions. Although latitudinal range shifts were observed for both adults and juveniles, the average distance between the distributions of adults and juveniles of the same species had shown no change through time, demonstrating that connectivity between juvenile nursery habitats and adult populations has not thus far been affected by climate induced range shifts. These results demonstrate that adult and juvenile fish are differing in their responses to climate change, and that further research is needed to better quantify what causes these differences in response.

A global review and meta-analysis of effects of invasive ecosystem engineers on marine biodiversity and ecosystem functions

Invasive ecosystem engineers (IEE) are potentially one of the most influential types of biological invaders. They are expected to have extensive ecological impacts by altering the physical-chemical structure of ecosystems, thereby changing the rules of existence for a broad range of resident biota. To test the generality of this expectation, we used a global systematic review and meta-analysis to examine IEE effects on the abundance of individual species and communities, biodiversity (using several indices) and ecosystem functions, focusing on marine and estuarine environments. We found that IEE had a significant effect (positive and negative) in most studies testing impacts on individual species, but the overall (cumulative) effect size was small and negative. Many individual studies showed strong IEE effects on community abundance and diversity, but the direction of effects was variable, leading to statistically non-significant overall effects in most categories. In contrast, there was a strong overall effect on most ecosystem functions we examined. IEE negatively affected metabolic functions and primary production, but positively affected nutrient flux, sedimentation and decomposition. We use the results to develop a conceptual model by highlighting pathways whereby IEE impact communities and ecosystem functions, and identify several sources of research bias in the IEE-related invasion literature. Only a few of the studies simultaneously quantified IEE effects on community/diversity and ecosystem functions. Therefore, understanding how IEE may alter biodiversity-ecosystem function relationships should be a primary focus of future studies of invasion biology. Moreover, the clear effects of IEE on ecosystem functions detected in our study suggest that scientists and environmental managers ought to examine how the effects of IEE might be manifested in the services that marine ecosystems provide to humans. This work was published (Guy-Haim et al, Global Change Biology, 2018, doi:10.1111/gcb.14007).

Benthic consumer functional responses and context-dependent scaling

Knowledge of feeding rates is essential for many forms of modelling of relevance to understanding marine ecosystems. It is recognised that useful generalisations of benthic consumer feeding rates must incorporate more than body size and temperature. A study led by QUB formed part of a larger data gathering exercise which sought to increase globally available data on benthic consumer feeding rates to develop a benthic consumer functional response dataset. Previous meta-analyses incorporated ~50 benthic consumer functional response data points. By revisiting the literature to extract more information on feeding rates, and augmenting the dataset with experimental data from QMUL, we have quadrupled this knowledge base. Once complete, we will make this entire dataset open access via publication. Based on data incorporated to date a paper has been published (Barrios-O'Neill, D., K. Ruth, J. Dick, A. Ricciardi, H. MacIsaac, and M. Emmerson. 2016. On the context-dependent scaling of consumer feeding rates. Ecology Letters 19:668–678. DOI: 10.1111/ele.12605) which is the first research to demonstrate that the structural complexity of a habitat can systematically alter the scaling of feeding rates—a pattern that we term Context-Dependent Scaling (CDS). By demonstrating how top-down feeding interactions are systematically weakened by habitat structure, this work informs objective 1 of MERP. In the longer term, this work will improve the parameterisation of models (objective 2 of MERP) by providing a large new dataset on benthic consumer feeding rates. Potential impacts are more relevant beyond MERP. This is because the size- and temperature-based generalisations, and assumptions of fixed capture rates (i.e. Type I or II functional responses), that are central to many whole-ecosystem models cannot incorporate the systematic patterns of CDS. The central impact of this work will be to stimulate future research efforts that focus specifically on unpacking the general effects of habitat structure on consumer feeding rates.

Given the paucity of good functional response data in the literature and the prevalence of poor model fitting methods, we have produced an R package to exemplify best practice (Pritchard, D. W., R. A. Paterson, H. C. Bovy, and D. Barrios-O'Neill. 2017. frair: An R package for fitting and comparing consumer functional responses. Methods in Ecology and Evolution doi: 10.1111/2041-210X.12784). Our intention is to improve data acquisition and model fitting across the field going forward. The work is particularly relevant to Objective 2.

Seabird diets

Seabirds are one of the groups of British vertebrates that are of highest conservation concern. Conservation organisations have identified diet as an important gap in their knowledge of our seabirds and from discussions with the RSPB it appears that this diet information will be a very important contribution to their conservation and management planning for seabirds. MERP has constructed, and continues to populate, a comprehensive time- and spatially-explicit database of diets for the 10 most important seabird species (with respect to biomass) of the British Isles. This brings together for the first time all the available information about the food resources of these British Seabirds. This is important information for many species-specific conservation and management plans to safeguard the food base of these important species. There are, of course, gaps in diet information in certain areas which we aim to interpolate from the existing databases on what seabirds consume and spatio-temporal information on the distribution and abundance of the relevant lower trophic levels (prey). The data were compiled from the relevant scientific literature and from unpublished reports from trusted sources. The current version is shared among users (collaborators within MERP) and the original spreadsheet version has been developed by Sheffield Research Software Engineers into a fully relational database. This recent data processing has involved full quality control of the seabird diet taxonomy and associated bibliography, and the creation of comprehensive meta data following the Ecological Meta Data (EML) standard, as well as the creation of simple R tools to interact with the data and provide useful spatial or taxonomic summaries. This version currently resides in a private GitHub repository (https://github.com/annakrystalli/seabirdPrey) with plans to make it public as soon as final QC is complete, to accompany a data paper that draws attention to the existence and content of this database. The information has fed into three parts of MERP: (i) Compiling long-term data sets and make them accessible via web services to interface with other databases (Webb); (ii) Linking the diet information with spatial variation in abundance of key seabird species (Evans) and (iii) Relationships of spatio-temporal heterogeneity in lower trophic levels on predator abundance, richness and population dynamics (Wanless, Daunt, Searle). It contributes to MERP's overarching goal of integrating existing data for use to improve our understanding of the whole marine ecosystem. The information in the database is the only information within MERP that contributes to the top end of the trophic levels (seabirds as top predators). Thus more specifically it contributes to understanding the regulation key ecosystem services by top down and bottom up processes and exploring the impact of environmental change and potential management solution on the structure, function and services associated with marine . Temporal and spatial changes at lower trophic levels will have impact on the distribution and abundance of seabirds. This will have important consequences for the planning of Marine Protected Areas (MPA) and how 'future-proof' these are. MERP scientists have started a new project to take this knowledge forward by modelling the distribution of an important forage fish of British seabirds (sandeels) under changing environmental conditions and assessing whether current MPAs will still be suitably located in 50 years' time.

Top predator distributions and predation pressure

Mapping the distribution and predation pressure exerted by top predators in UK waters underpins and informs interactions between wildlife and human activities (fishing activities, SPA designations and offshore renewable energy development). In the last six months we have continued to develop an energetics modelling framework for mapping predation pressure from breeding seabirds around UK colonies. The RSPB has developed a method to empirically estimate seabird utilisation from GPS tracking data (Wakefield et al. in press), and has applied this method to data for three important species (black-legged kittiwakes, common guillemots, and razorbills). A key part of this research lies in developing an energetics model for each species that allows the determination of the amount of energy required by breeding birds at specific colonies. In previous work we have developed individual simulation based bio-energetics models for these five species (Searle et al. 2014, 2017). We adapted the energetics component of this model, retaining the section that translates energy intake per hour of foraging, along with time-activity budgets, into subsequent adult and chick survival. This model can now be combined with estimates of adult and chick survival to estimate prey intake per hour of foraging. We are now obtaining species-specific estimates for these parameters around the UK in preparation for applying the energetics framework together with the utilisation maps to produce spatially explicit predation pressure maps for these three important species in UK waters.

Integrated research across various MERP partners (CEH, RSPB, University of Glasgow) developed predation-pressure maps (tonnes of energy removed per km2) for breeding populations of black-legged kittiwake, common guillemot, razorbill, European shag and northern gannets (together constituting over 2/3 of the total UK breeding seabird biomass). The maps fed in to a synthetic WP1 Module 1 analysis with the University of Sheffield and other Module 1 partners (University of Bangor) and were used for validation of spatially explicit ecosystem model predictions for densities of top predators. These maps are available for time periods around 2000 and the current day and are available to MERP consortium members now. They will be made publicly available upon publication of associated manuscript (Searle, K. R., A. Butler, M. Bogdanova, E. Wakefield, M. Bolton, S. Wanless and F. Daunt. Predation pressure of breeding seabirds in UK nearshore waters: changes over the last two decades. In prep. To be submitted to Journal of Applied Ecology). The maps will enable more informed assessments of key habitat areas used by breeding seabirds in the UK, and when overlaid with other marine pressures can identify regions and areas with likely strong trade-offs between competing wildlife and human activities. This analysis provides novel baseline understanding of the spatial patterns and temporal changes in top predator predation pressure in UK waters, which may then be combined with other data and models to better understand how ecosystem services such as wildlife tourism, commercial fishing and offshore renewable energy developments interact and trade-off against the background of environmental change. These maps were presented to Defra on 27/9/17 and we anticipate that they will be widely used by statutory bodies to inform marine spatial planning activities. The maps were also be used to validate ecosystem model predictions for top predators within MERP.

Habitat use by northern gannets

Population-level estimates of species' distributions can reveal fundamental ecological processes and facilitate more effective conservation and marine spatial planning. We are mapping the habitat use of breeding gannets around all major colonies occupying UK waters. These models provide spatially explicit estimates of habitat usage and derived predation pressure around the UK for this ecologically important and iconic species. This work is a direct outcome of collaboration between MERP partners (CEH, RSPB, University of Glasgow) and other external partners (Centre D'ecologie Fonctionnelle & Evolutive, University of Leeds, University of Liverpool, University of Exeter). The outputs from this research (gannet habitat utilisation maps and predation pressure maps) are used by MERP partners in WP3 Topic 2 to present to stakeholders to assess responses to likely changes in top predator habitat use and predation pressure under different future scenarios. The habitat utilisation and predation pressure maps will be made publicly available when the accompanying manuscript (Searle KR, A. Butler, M Bogdanova, E Wakefield, M Bolton, S. Bearhop, J Green, D Gremillet, K Hamer, S Votier, F Daunt and S Wanless. Regional distribution and predation pressure of breeding northern gannets in UK waters. In prep. To be submitted to Journal of Animal Ecology) is published. Maps were available to MERP project partners earlier. This research provides novel baseline understanding of the spatial habitat use and predation pressure of an ecologically important marine top predator. This knowledge may be combined with other data and models to better understand how ecosystem processes and the services they support, such as wildlife tourism, operate against the background of environmental change both now and into the future. We anticipate this work, once published, will have strong relevance to stakeholders (statutory nature conservation bodies) responsible for understanding and assessing the responses of top predator populations to human activities impinging upon predator populations and behaviour (e.g., offshore renewable energy developments, commercial fishing).

Density dependence of colonial seabirds

Unlike terrestrial systems where synthetic analyses across species have identified common responses of key population processes to environmental variation, marine systems have yet to be comprehensively investigated to see how variation drives fundamental aspects of population change. We tested whether unifying concepts derived from terrestrial systems also hold in marine systems, and demonstrated that density dependent processes in marine top predators appear to respond in similar ways to different components of environmental variation across a wide range of species. These findings can inform the development of ecosystem models to better capture processes of population dynamics and trophic interactions against a backdrop of environment change. This research has developed maps for 11 species of breeding seabirds in UK waters, identifying colonies showing evidence for particularly strong density dependent population processes. These maps can be used to highlight populations most likely to be particularly sensitive to changes in the marine environment such as the development of offshore renewable energy. This research provides empirical evidence for how density dependent processes in upper trophic levels are affected by environmental variation in both biotic and abiotic factors. Spatial maps of predicted density dependent population growth for each of the 11 species will be made publicly available upon publication of the accompanying manuscript (Searle, K. R., A. Butler, J. Waggitt, P. Evans, F. Daunt, N. T. Hobbs & S. Wanless. Into the great blue yonder: a search for unifying drivers of population processes in marine and terrestrial environments. In prep. To be submitted to Journal of Animal Ecology). This work results from a direct collaboration between MERP partners within Module 1 (CEH, Bangor University, Seawatch Foundation) and contributes to Objective 1 by providing novel baseline understanding of the population level response of top predators to two fundamental aspects of environmental change – temporal change in climate and spatial variation in lower trophic levels. This understanding may be combined with other data and models to better understand how ecosystem process and the services they support, such as wildlife tourism, operate against the background of environmental change both now and into the future. We anticipate this work, once published, will have strong relevance to stakeholders (statutory nature conservation bodies) responsible for understanding and assessing the responses of top predator populations to human activities impinging upon predator population growth rates (e.g., offshore renewable energy developments) and contributes to baseline understanding of population resilience in marine top predators in relation to environmental change.

We have finalised the analytical framework and derivation of environmental drivers to estimate and understand how direct and delayed density dependence operates in populations of 13 species of breeding seabirds in the UK. Working with colleagues at Colorado State University we have developed a Bayesian hierarchical model to estimate the strength of direct and delayed density dependence in 13 species of breeding seabirds in the UK (representing approximately 75% of the total seabird biomass in UK waters), and to relate the strength of density dependence to environmental drivers (in conjunction with University of Bangor). These models use data from the Seabird Monitoring Program, tracking changes in population size over five decades. Initial results suggest similar patterns to terrestrial systems in relation to temporal variation in the environment, but potentially opposing relationships to spatial variation in the environment.

Combined measurements of prey availability explain habitat selection in foraging seabirds

Understanding links between habitat characteristics and foraging efficiency helps predict how environmental changes influence populations of top predators. A paper combining various elements from MERP (Waggitt et al. 2018 Biology Letters doi: 10.1098/rsbl.2018.0348) examines whether measurements of prey (clupeids) availability varied over stratification gradients, and determined if any of those measurements coincided with aggregations of foraging seabirds (common guillemot *Uria aalge* and Manx shearwater *Puffinus puffinus*) in the Celtic Sea, UK. The probability of encountering foraging seabirds was highest around fronts between mixed and stratified water. Prey were denser and shallower in mixed water, whilst encounters with prey were most frequent in stratified water. Therefore, no single measurement of increased prey availability coincided with the location of fronts. However, when considered in combination, overall prey availability was highest in these areas. These results show that top predators may select foraging habitats by trading-off several measurements of prey availability. By showing that top predators select areas where prey switch between behaviours, these results also identify a mechanism that could explain the wider importance of edge habitats for these taxa. As offshore developments (e.g. marine renewable energy installations) change patterns of stratification, their construction may have consequences on the foraging efficiency of seabirds.

Seasonal distributions of top predators

We are producing distribution maps of the most common seabird and cetacean species (ten of each) across NW European waters, at a seasonal scale. These are currently being finalised and will form a paper for submission in the next 3-6 months. The processed and standardised collation of at-sea surveys covering ~3 million kilometres and 30 years is available to MERP colleagues at the present time. Our outputs predict distributions across a much wider range of species, a wider area and broader time periods than any previous attempt, and thus can be considered both nationally and globally novel. The data will allow a quantitative comparison with human pressures known to impact cetacean and seabird species, at fine spatial and temporal scales – enabling the production of risk maps and allowing seasonal and regional management strategies to be developed with greater confidence than before. They can also better parameterise ecosystem models which include top-down processes within their calculations and predictions. This work, led by Bangor, involved a close collaboration with CEH, sharing expertise and knowledge in developing appropriate techniques to predict seabird distributions. The spatial and temporal distributions of cetaceans derived from the MERP data were compared with those obtained from data more generally available via OBIS in a thesis chapter by NERC ACCE DTP student Alun Jones at the University of Sheffield. This work showed that while OBIS data provided reasonably robust estimates of the relative abundance and broad temporal trends of cetacean species in European seas, the MERP data provided very substantial added value in the assessment of fine scale spatial distributions and temporal trends. This work exists as a thesis chapter (Jones 2018, Cetacean abundance-occupancy relationships in European waters: how well does aggregated biodiversity data perform?) which is currently being prepared for publication (Jones, Waggitt, Evans, Webb, et al. In prep). Discussions with modellers at PML, SAMS, and University and Strathclyde helped both parties work towards outputs of mutual benefit. CEFAS, SAFHOS, and University of Glasgow provided and collated data on prey and some of the environmental variables used in our analyses. Information we have collated on top predator life history parameters has been utilised by QMUL and University of Sheffield, and on abundance and distribution by modellers from PML, SAMS, and the University of Strathclyde. The mapping of predation pressures at a seasonal and European scale is important for understanding marine ecosystem processes, and is therefore a key component of MERP. Explanatory models of spatiotemporal patterns in abundance of the top predators will contribute to our understanding of the effects of natural and anthropogenic change on the state of marine , and the environmental conditions required to maintain them. The risk maps and assessment of cumulative effects are fundamental to one of the overall goals of topic 2 in WP3. There is strong interest in our outputs from a variety of national (JNCC, NRW, NE, and SNH, Marine Science Scotland, RSPB, BirdLife) and European (UNEP/ASCOBANS, OSPAR/MSFD) stakeholders that wish to use our distribution maps to inform marine spatial planning and management decisions. An international workshop is being planned by UNEP that will draw upon the results of our work to establish whether it is possible to map the seasonal risk to different marine mammal species of bycatch within particular fisheries, and the same may be undertaken for seabirds. When combined with the ongoing mapping of anthropogenic activities being undertaken, we should be better informed to estimate individual and cumulative impacts of these activities on top predator communities. We are working closely with MERP colleagues at Sheffield University to combine our datasets with those on other taxa being collated within the programme, to ask broader questions on climate change and biodiversity gradients. Examination of spatiotemporal trends in abundance of marine mammals and birds, along with human pressures known to impact them (see module 8), will provide a better understanding of their effects at a population level. This can be applied to both individual and cumulative impacts. Several of these top predators are iconic species that attract public interest and help sustain coastal and marine tourism. The outputs from our analyses will inform us of the trade-offs between different ecosystem services (e.g. fisheries and recreation). Greater clarity on the role of top predators (marine mammals and birds) within food webs should derive from the suite of analyses being planned from the data we have collated on seabird and cetacean abundance and distribution in relation to fish and invertebrate prey. Similarly, our input of biological data for the different top predator species is contributing to size spectra analyses. The mapping of species distributions and how they vary in time will help clarify whether density hotspots are persistent and to what extent they coincide across marine taxa. This information should be a significant aid in the establishment and subsequent management of MPAs. The risk maps are fundamental to marine spatial planning, and the assessment of impacts from the development of various human activities such as offshore renewables, fishing, and marine recreation. Additional funding from Defra will support the production of a new Cetacean Atlas as an output from the programme.

Cetacean abundance-occupancy relationships in European waters: how well does aggregated biodiversity data perform?

The generally positive relationship between local abundance and regional occupancy, termed the abundance-occupancy relationship (AOR), is one of the most prevalent in macroecology. Identifying both inter- and intraspecific relationships is useful for numerous reasons, especially in a conservation context where they can be used to infer abundance from more easily collected occupancy data. A study (Alun Jones, 2018, Chapter 4 in PhD Thesis, Sheffield) derived AORs for 20 species of cetacean in European waters. It used data from effort-based surveys, and applied a multispecies occupancy modelling methodology to account for detection bias and surveyor effort. It used three additional sources of presence-only data to assess the ability of modelled estimates of occupancy both to replicate these AORs, and to estimate abundance. It found significant positive intraspecific AORs for 14 cetacean species, and significant positive interspecific AORs for all years assessed. Interspecific AORs were successfully replicated using occupancy modelled data. Estimates of abundance produced with modelled occupancy values and known AORs are positively correlated with known abundance values, indicating an ability to estimate the rank order of species abundance within a given year. These results indicate that occupancy modelling can be combined with available and easily collectable data to infer abundance in cetacean species, potentially leading to improved and more cost-effective conservation and management. However, intensive effort-based survey data allow for more accurate detection of temporal trends within species.

Effects of fishing on the diversity spectrum

There are many more small than large species. Previous studies have indicated that the distribution of adult body lengths or masses of species in aquatic communities (the “diversity spectrum”) follow Pareto (i.e. power) laws. Theoretical arguments show that the structures of the marine size spectrum (the distribution of community biomass over species sizes) and the marine diversity spectrum (the distribution of species richness over body sizes) are causally independent in a first approximation. While the Large Fish Indicator and the recently introduced Typical Length provide good indicators for the status of the size spectrum, there is currently no corresponding indicator for the status of the diversity spectrum. Accurate determinations of the Pareto exponent of the diversity spectrum from MERP research (Mindel, B. L., Bruggeman, J., Webb, T. J., Rossberg, A. G. (2017).

Fishing impacts richness of large species in marine communities: evidence from diversity spectra. Manuscript submitted) show how this gap in assessments of marine communities can be closed. This research shows that the characteristic exponents of these distributions are nearly identical across the Regional Seas defined for Charting Progress II. Residual differences in the exponents are largely explained by differences in fishing pressure. Indeed, the Pareto exponents of diversity spectra can be used as indicators for the status of marine biodiversity. Our method is sufficiently accurate to distinguish Regional Seas with impaired diversity spectra from those where impacts have remained low. This research combines data generated and/or mobilized by MERP Partners with theoretical and statistical analyses. Findings may be used to predict the impact of potential management solutions, such as reductions in fishing pressure or marine conservation zones, on biodiversity across body-size scales. It shows that regional loss of diversity of large species is likely to reflect cumulative impacts of fishing and potentially other pressures over many decades. We identified fishing pressure as the main pressure explaining regional differences in the Pareto exponents of diversity spectra and the work resolves variations in the impacts of fishing across the Charting Progress II Regional Seas.

This work confirms for the first time some key predictions of the theory of biodiversity in by Rossberg (2013, ISBN 9-780470973-55-4) and of the closely-related Population Dynamical Matching Model (part of the MERP Model Ensemble). It permits differentiation of this theory from other, competing theories of biodiversity. The contextual dependence of the effects of fishing were also explored in a European collaboration (Farriols MT, Ordines F, Somerfield PJ, Pasqual C, Hidalgo M, Guijarro B, Massuti E (2017) Bottom-trawl impacts on Mediterranean demersal fish diversity: not so obvious or are we too late? Cont. Shelf Res. 137: 84-102 doi: 10.1016/j.csr.2016.11.011), which showed that the ongoing effects of fishing may not be detectable against a baseline which already represents a long-term fishing effect.

Fieldwork to measure poorly known processes (Module 2)

This activity aims to fill knowledge gaps in marine ecosystem ecology through new field-based and experimental observations with recent theoretical advances from marine and terrestrial ecology.

We have identified key components and properties of marine ecosystems that are currently under-sampled and not adequately represented in existing ecosystem models. A programme of field surveys and experiments to generate new data and understanding of these features will be conducted and the results used in model development.

Coastal macroalgae fuel offshore benthic communities, and contribute to Blue Carbon pathways

Macroalgae drive the largest CO2 flux fixed globally by marine macrophytes. Most of the resulting biomass is exported through the coastal ocean as detritus and yet almost no field measurements have verified its potential net sequestration in marine sediments. This gap limits the scope for the inclusion of macroalgae within blue carbon schemes that support ocean carbon sequestration globally, and the understanding of the role their carbon plays within distal food webs. A major element of MERP field-work , experimental work and modelling pursued three lines of evidence (eDNA sequencing, Bayesian Stable Isotope Mixing Modelling and benthic-pelagic process measurements) to generate needed, novel data addressing this gap. A 13 month study was undertaken at a deep (50 m) coastal sedimentary site in the English Channel (L4 in the Western Channel Observatory), and the surrounding shoreline of Plymouth, UK. eDNA sequencing indicated that detritus from most macroalgae on surrounding shores occurs within deep, coastal sediments, with detritus supply reflecting the seasonal ecology of individual species. Bayesian stable isotope mixing modelling [C and N] highlighted its vital role in supporting the deep coastal benthic food web (22-36% of diets), especially when other resources are seasonally low. The magnitude of detritus uptake within the food web and sediments varies seasonally, with an average net sedimentary organic macroalgal carbon sequestration of 8.75 g C m-2yr-1. The average net sequestration of particulate organic carbon in sediments is 58.74 g C m-2.yr-1, the two rates corresponding to 4-5% and 26-37% of those associated with mangroves, saltmarshes and seagrass beds, habitats more readily identified as providing a blue carbon service. These novel data provide important first estimates that help to contextualise the importance of macroalgal-sedimentary connectivity for deep coastal food webs, and measured fluxes help constrain its role within global blue carbon that can support policy development. At a time when climate change mitigation is at the foreground of environmental policy development, embracing the full potential of the ocean in supporting climate regulation via CO2 sequestration is a necessity. This work has been successfully reviewed for pulication (Queirós et al. (in press) Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean. Ecological Monographs ECM18-0098), and will form the basis of further publications going forward. It also serves to place wider marine production and production-sequestration pathways into the Blue carbon agenda.

The extent of the macroalgal subsidy to the coastal ecosystem

Estimates of macroalgal subsidy drew on a combination of model estimation of biomass and rates of production scaled up to whole coastlines, and a field programme of seabed sampling at increasing distances from coastal kelp beds around the UK aiming to detect the declining signature of kelp-derived carbon in the biota, the sediment and water column.

Models of macroalgal biomass and carbon fixation contributed to two reports on coastal blue carbon budgets (Burrows, M. T, et al., “Assessment of Carbon Budgets and Potential Blue Carbon Stores in Scotland’s Coastal and Marine Environment.” Scottish Natural Heritage Commissioned Report No. 761. Scottish Association for Marine Science, 2014. www.snh.org.uk/pdfs/publications/commissioned_reports/761.pdf; Burrows, M.T., et al.. “Assessment of Blue Carbon Resources in Scotland’s Inshore MPA Network.” Scottish Natural Heritage Commissioned Report No. 957. Scottish Association for Marine Science, 2017. http://www.snh.org.uk/pdfs/publications/commissioned_reports/957.pdf). These reports give an assessment of the total budget for carbon fixed in the coastal ecosystem across Scotland, and how that capacity is spread among geographical areas and habitats. The work shows that around 50% of Scotland’s carbon dioxide emissions may be offset by addition of carbon to long-term stores, with kelp contributing up to 30% of the supply of carbon to the seabed. Estimates of biomass and organic carbon production at the level of individual MPAs are contributing to the development of informed management and conservation strategies. Blue Carbon is a continuing focus for Scotland with the Scottish-Government-funded Scottish Blue Carbon Forum and three associated PhD projects started in 2018 (on carbon storage in sediments, breakdown of kelp detritus and carbon storage by maerl). Coast-wide estimates of biomass and carbon fixation drew on significant efforts beyond MERP by research groups led by Dan Smale (MBA) and Pippa Moore (University of Aberystwyth) to measure production rates of kelp primary producers in UK coastal waters from southwest England to Orkney.

MERP-produced predictive models of kelp biomass and habitat extent around the whole UK have also been used in a stock assessment of kelp around Scotland, estimated at 20Mt wet mass. This assessment contributed to a report on wild kelp harvest as a potential new industry in Scotland (http://www.hie.co.uk/common/handlers/download-document.ashx?id=0336008d-db41-4b61-a9bd-6bfcbd31c876). The wild harvest report formed the basis of a Scottish Parliament briefing note prior to a recent vote on a Crown Estate Bill amendment to ban mechanical kelp harvest (https://digitalpublications.parliament.scot/ResearchBriefings/Report/2018/11/12/Kelp-harvesting). Aspects of the estimated biomass of kelp and the impact and recovery from harvesting were used on both sides of the debate.

The reported values for biomass and carbon production have contributed to Module 6, particularly as the quantity of organic detritus input to food webs, and complement those from dynamic simulations in Module 4 to give ecosystem capacity to offset GHG emissions. The estimate of coastal carbon contributed by macroalgae has contributed to a manuscript on a shelf-scale carbon budget (Legge et al, in submission, “Carbon on the Northwest European Shelf: Contemporary Budget and Future Influences”) produced by the NERC-Defra Shelf Seas Biogeochemistry programme.

Samples collected during the fieldwork component of this module have now been processed and analysed, primarily focussing on the stable isotope analysis of benthic samples for kelp-related, and additional information collected. Manuscripts based on patterns in these samples are in preparation, but emerging patterns suggest that the expected distinct patterns of decay in biomarkers with distance were not evident, and that tidal mixing at the main locations sampled (Plymouth, Anglesey, Northern Ireland) may have rapidly dispersed kelp-derived particulates.

There is a growing interest in “source to sink” carbon dynamics in coastal systems, linking losses from, for example, upland peatlands through riverine transport to the ultimate storage in coastal sediments. The NERC LOCATE programme is dealing with this to some extent, but presently lacks a specific coastal marine focus on the role of in-situ marine production. Stronger links with biogeochemists are developing, particularly through MASTS and SAGES (SAGES | Scottish Alliance for Geoscience, Environment & Society: http://www.sages.ac.uk/) forums and initiatives, with much potential for work developing biomarkers and tracking the fate of detrital organic carbon over short-term to geological timescales. The relative usefulness of MPAs as carbon stores has been assessed, and can now be compared with other functions to assess tradeoffs. By assessing the relative contribution of different habitat components at the scale of individual MPAs, the value of each MPA as a carbon producer or store can be included in management plans at local and national level.

Research in module 2 assessed large-scale differences in the biomass of intertidal macroalgae along the northeast Atlantic coastline and attributes these differences to various environmental and biological factors. As such, this work will assist in our understanding of how primary productivity within these coastal systems may be expected to change under future climate change scenarios. Primary productivity on rocky intertidal shores are 3-4 orders of magnitude higher along the west coast of Ireland than along the south and north coasts of Portugal, despite only minor differences in abiotic conditions. This suggests that primary productivity within cooler north Atlantic locations may be susceptible to even minor changes in temperature (Lathlean JA, Emmerson M, O’Connor N (in prep) Latitudinal variation in primary productivity of rocky intertidal habitats along the northeast Atlantic. Target journal – Marine Ecology Progress Series. Expected Submission date: October 2017). This output does not represent integrated work across MERP, being delivered by QUB alone. However, there is potential for the environmental and biological data to be used by other partners in the future, specifically modellers working on Module 1. This work contributes to the objective to 'explore the impact of environmental change on the structure, function and services associated with marine across scales' (Objective 2). It does this by undertaking correlating multiple environmental and biological parameters with primary productivity of intertidal macroalgae across multiple locations spread across a large latitudinal gradient. We anticipate that this work will make a significant contribution to understanding how the flow of nutrients and functional role of macroalgae within coastal waters of the United Kingdom may be expected to change under future climate change scenarios.

The structure and organisation of integral marine benthic communities in relation to sieve mesh size

Few studies consider meiofauna and macrofauna at the same time, even though both form parts of wider ecological networks, and fewer consider interactions between sample size, body size and spatial clustering. It has been suggested that the elements of the structure of the physical environment have fractal properties. If habitat complexity largely determines species diversity this leads to the prediction (for a single perfect fractal) that all organisms, regardless of size, will perceive the environment as equally complex and should have equivalent diversity and, as we move up the size spectrum, species composition should change in a regular and gradual fashion. A MERP study (Somerfield et al. 2018 Journal of Experimental Marine Biology and Ecology 502: 164 – 173) examined the degree to which infaunal assemblage structure varies with mesh size, sample size and sample dispersion within two different areas of homogeneous intertidal sediment, a muddy sand and a coarse sand, in the Isles of Scilly, UK. In each area samples were extracted using a standard range of 5 mesh sizes (63, 125, 250, 500, 1000 µm), with the sample areas and distances between samples scaled to the mesh size. All metazoans were identified to species level. Diversity and species composition did not show a gradual and even degree of change over the size range at either site. Instead, they showed a dramatic stepwise change between the 250 µm and 500 µm mesh size samples, being relatively constant in the< 500 µm and> 500 µm categories, with diversity higher in the former. Higher proportions of species in the< 500 µm categories showed evidence of spatial clustering than in the> 500 µm categories. This suggests a fractal structure within but not between the< 500 µm and> 500 µm body size categories, which apparently is not driven by differences in sediment structure. The biology of marine metazoan benthos does not scale continuously across the full range of taxa and body size as has been recently suggested, but may do so for individual taxa and restricted size ranges.

Interactive size-spectral effects of demersal fishing and productivity

Based on two MERP research cruises on the RV Prince Madog, Bangor University and MERP colleagues investigated the effects of fishing and primary production on the size spectra of benthic communities (from meiofauna to large demersal organisms) in the Celtic and Irish Sea. Comparisons were made between predators and detritivores, and between empirical observations and theoretical values predicted by a dynamic size spectrum model. Our results show that fishing bottom trawling pressure has greater impacts effects on the size spectra on benthic ecosystems in areas of high primary production. We compared models developed by Blanchard with the empirical data. There were similarities but also strong differences between how the modelled and observed communities responded to anthropogenic and environmental pressures. The research (Howarth LM, Blanchard JP, Somerfield PJ, Cendrier M, Maurin C, Allender S, Waggitt JJ, Hiddink JG (submitted) The effects of fishing and primary productivity on benthic size spectra. Ecosystems) contributes to understanding of how the regulation of key ecosystem services such as food production by marine are affected by 'top down' and 'bottom up' driven cascades and functional diversity at different trophic levels. This research indicates new and different measurements and assessments that could be implemented to provide more insightful and sensitive indicators of good environmental status and changes in the marine ecosystem. It can be used to project relative changes of descriptors of good environmental status (e.g. biodiversity, fish stocks, food webs, and seabed integrity) under different management scenarios to inform UK policy aligned with the EU MSFD and OSPAR, feeding into the development and understanding of food web indicators.

Effects of bottom trawling and primary production on the composition of biological traits in benthic assemblages

Although many studies have investigated the effects of disturbance and environmental drivers on marine ecosystems, comparatively few have studied their interactions. Using fuzzy coded biological traits, a recently published study based on data from the MERP cruises (Howarth et al. 2018 Marine Ecology Progress Series 602: 31 – 48) compared the functional composition, diversity and evenness of benthic communities in the English Channel and in the Celtic and Irish Seas across interacting gradients of bottom trawling and primary production. Fuzzy correspondence analysis indicated greater similarity in trait composition at sites of high trawling pressure than at those of low trawling. In contrast, the analysis revealed no relationship between trait composition and primary production. Trawling and primary production had no effect on the traits 'longevity', 'sediment position', or 'feeding mode'. However, trawling had negative effects on all modalities within the trait 'living habit', and these effects were strongest for attached and epifaunal organisms but weakest for burrow- and tube-dwelling species. Trawling also negatively affected most modalities within the trait 'maximum weight', with strongest effects for organisms weighing between <0.1 g and up to 1 kg. Conversely, trawling positively affected organisms weighing >10 kg. For the trait 'bioturbation', upward conveyors were positively related with primary production, whilst other modalities exhibited no clear pattern. Because trawling affected some traits more than others, community biomass was less evenly distributed across traits in highly trawled areas, which resulted in lower levels of functional diversity and evenness. Overall, the effects of bottom trawling were greater in areas of high primary production.

Remarkable resilience and stability of plankton size structure in a dynamic inshore system

Given the role of body size as a "master trait", size based models are being used increasingly to understand the functioning of diverse and complex aquatic assemblages. However, the paucity of high resolution time series with both size- and taxonomically based analyses has hindered our understanding of the pelagic response to variability at scales ranging from inter-annual to that of extreme weather events. We examined 275 timepoints collected at weekly resolution over 6 years at station L4 in the Western English Channel. Despite order of magnitude variability in the mean biomass of key functional groups across years, the total planktonic biomass (from picoeukaryotes to fish larvae) varied only twofold, with slopes of their normalised biomass size spectra (NBSS) being statistically indistinguishable. This reflected a strong "anchoring" effect by nanoplankton, with the much more variable larger taxa exhibiting replaceability according to size. The NBSS slopes were consistently steeper than -1, suggesting inefficient trophic transfer within the pelagic, likely due to export to the benthos. Conversely, a shallowing of the slope in spring related to imports of meroplankton from the benthos. In addition to the stability of the biomass and size spectra, they showed remarkable robustness to the largest storms experienced by the southwest UK for 60 years. These storms during winter 2013/2014 profoundly affected seabed integrity and water clarity. While this initially steepened the slope of the NBSS and reduced total plankton biomass, they rapidly recoiled to normal, emphasising remarkable resilience as well as stability in a strongly size-structured planktonic system.

Assessing plankton for WFD

Plankton are sensitive indicators of change and, at the base of marine , they underpin important ecosystem services such as carbon sequestration and fisheries production. Change in plankton functional groups, or 'lifeforms', is the formally accepted policy indicator used to assess Good Environmental Status (GES) for pelagic habitats in the UK and the Northeast Atlantic OSPAR area under the Marine Strategy Framework Directive (MSFD: 2008/56/EC). To identify changes in UK pelagic habitats, plankton lifeform groups were constructed based on biological traits, using diverse UK data sets collected by different methods, including plankton sampling by nets, water bottles, integrating tube samplers, and the Continuous Plankton Recorder. A Plankton Index approach was used to identify change in plankton lifeforms. This is the first time that the pelagic plankton community has been assessed on a UK-wide scale and forms the foundation of the UK's 2020 MSFD Assessment for pelagic habitat biodiversity. This approach revealed that some of the plankton lifeforms used in the assessment displayed spatially-variable changes during the past decade. Assessing plankton community change using a common indicator at the UK scale for the first time is a significant step towards evaluating GES for European seas. Determining GES for pelagic habitats, however, is a challenging process, with additional work required to interpret the assessment results and to identify causation of the changes observed. This work is accepted for publication (McQuatters-Gollop et al., Ecological Indicators).

Pelagic fish populations

Cefas continue to analyse data from the Poseidon/Peltic cruises in the SW approaches to examine the environmental drivers of dominant pelagic fish of the Celtic Sea and western Channel, with input from PML. Further work is required but results were presented at the ICES WG on Fisheries Acoustics Science and Technology in April 2017 and suggest that temperature plays an important role in driving both anchovy and sardine distribution with phytoplankton and frontal features also playing an important role. Cefas's John Pinnegar and Jeroen van der Kooij (and others) wrote the fisheries supporting document for the 2017 Marine Climate Change Impact Partnership (MCCIP) report card. This card has been widely disseminated across marine stakeholder organisations and has enjoyed some good media coverage, both in the UK and overseas. A copy of the report has also been sent to members of parliament in the UK and devolved administrations. Further discussions occurred between Axel Rossberg (Queen Mary University, London) and Cefas staff, regarding the construction of empirical size spectra to disentangle bottom-up and to-down effects. This work is ongoing. Following the conclusion of project Poseidon, the survey has been accepted as part of the Data Collection Framework to support the assessment of several pelagic species in ICES. The 2017

Peltic survey in the SW of the UK was completed. This survey (in October and November) covered a greater geographical area and included waters of the French part of the Channel for the first time. Some outputs from the MERP/Poseidon field programme were presented at a meeting of the 'Seafish Common Language Group' in London. This event was attended by more than 40 representatives from the UK fishing industry. PML (Elaine Fileman) has finished FlowCAM analysis of the Cefas Peltic cruise survey samples for Cefas, to be used in the construction of biomass spectra for the SW UK, to complement the time series biomass spectrum for L4. Data are now with Cefas.

The importance of gelatinous plankton in food webs

Samples of fish stomachs collected during previous MERP/Poseidon research cruises (between 04/10/2015 – 20/10/15) have now been analysed using sophisticated genetic identification techniques (by Philip Lamb at the University of East Anglia) to determine whether jellyfish represent a hither-to unknown prey resource for pelagic fish in the SW of England. Over 20% of all mackerel were shown to have recently consumed jellyfish (mostly *Pelagia noctiluca*), along with lower frequency of occurrence in sardine and sprat.

Molecular analysis of fish larvae and jellyfish gut contents from Station L4 have been used to elucidate trophic interactions. This data is currently being validated and analysed, and will be used to inform MERP models about previously unknown food web interactions. The complete dataset will be submitted to both NCBI GenBank (https://www.ncbi.nlm.nih.gov/) and BODC. Results show that fish larvae consume small jellyfish species at L4, which was previously unknown, and simultaneously some jellyfish species contain DNA from juvenile fish species. Therefore, there are complex interactions between these two taxonomic groups which we now understand in more detail. This is a collaboration between molecular biologists at PML and ecologist Martin Lilley (ex-QMUL) developing novel techniques at PML to look out interactions between fish and jellies, and competitive predation. The results described here were passed to the modellers in Modules 3 and 4, and ERSEM, so this work contributes to the use of targeted new data to directly increase our understanding of a previously understudied section of the food web. Fish-jellyfish interactions have been speculated upon, but we can now quantify several taxonomic interactions and describe which species of fish larvae and jellyfish predate on one another. Therefore, ecosystem cascades and functional diversity in these ecosystem groups are better understood. This research is likely to increase the profile of small jellyfish species in their impact on, and food resource for, young fish stocks. As a consequence, improved monitoring of small jellyfish species may be required to further enhance fisheries stock assessments. This work is likely to further the understanding of how many trophic levels jellyfish contribute to and their role within the wider ecosystem. We envisage interest in our publications from a wide range of researchers from ecologists to molecular scientists to fisheries and ecosystem modellers within and beyond MERP. This research takes targeted new data and improves our understanding of , trophic linkages and predator-prey interactions between fish and jellyfish. Such interactions may work in both directions between these broad taxonomic groups. Both jellyfish and fish larvae are GES indicators, so this research also has direct policy-relevance.

Another MERP approach to integrate gelatinous zooplankton into the whole food web was based on a combination of meta-analysis and analysis of the L4 time series (McConville et al. 2017 J Plankton Res). This found that the trait of water content (expressed as carbon mass as a percentage of wet mass) was continuous across the zooplankton and could indeed be modelled as a single continuous trait rather than a categorical variable. This study then used this property to develop unified zooplankton growth equations as a function of both carbon mass and carbon percentage of wet mass, which were used in developing ERSEM.

Sequencing fish

To support the investigation of trophic relationships using next-generation sequencing we have developed a reference sequence database of common local fish species at Station L4, facilitating the correct taxonomic annotation of unknown amplicon barcodes to local species. This capacity has previously been lacking, and the most closely matched species in the existing database were Indo-Pacific species. PML has been assisted in this work by Martin Lilley (QMUL) and data will be available for use publicly both within and beyond MERP. The dataset – DNA barcoding sequences from local adult fish caught frequently at WCO station L4 (50° 15.00' N, 4° 13.02' W) is available publically on NCBI GenBank (https://www.ncbi.nlm.nih.gov/), accession numbers MF796392-MF796439 and has also been lodged with BODC, making it available for all researchers and fisheries bodies who wish to use DNA sequences to identify fish species, particularly relating to English Channel waters. Molecular sequencing is a rapidly advancing field and all sequence data is of use in narrowing down identification of unknown sequences. This dataset is being used to identify the fish species which benefit from jellyfish prey and those which are impacted by jellyfish.

Experimental work on Context-Dependent-Scaling (CDS)

Using skate as a model predator, MERP research at QUB (Barrios-O'Neill, D., C. Bertolini, and P. C. Collins. 2017. Trophic cascades and the transient keystone concept. Biological Conservation 212:191–195.) explored the effects of habitat structure (biogenic reef) on top-down apex predator effects. We discovered that top-down effects are contingent on the absence of habitat structure. Where such structure is present, top-down effects are dampened. This finding is congruent with our central work on Context-Dependent Scaling (CDS, see module 1).

Enhanced long-term time-series data on plankton and the pelagic size-spectrum

MERP has developed an integrated 28-year time series of zooplankton biomass and traits from the Plymouth L4 station, 1988-2015 which was deposited on the MERP sharepoint in March 2016 and we plan for the data and metadata to be lodged at BODC before the end of MERP. Previously the time series of zooplankton from the L4 station was hard to use because: a) it had different levels of lumping and splitting of taxa throughout the 28 years; b) it was numerical abundance without any key traits such as body size or functional trait allocations. Within MERP we have rectified both of these limitations and the value-added time series has proved a much more valuable resource. It is being used increasingly for publications, ongoing modelling/biomass spectra analyses within MERP, MSFD/OSPAR policy-related reports to OSPAR, and the OSPAR 2017 interim assessment. This work involved melding an existing version of the time series abundance data stored at BODC with data arising partly from a series of 7 MERP mini-cruises completed in conjunction with Martin Lilley (M1) and Pennie Lindeque. Within MERP the data have so far been incorporated into a pelagic biomass spectrum manuscript (M2), into three modelling initiatives (M4 and M6) and the trait information has been requested by and sent to M1. Outside MERP the value-added time series data have been used to inform on UK MSFD and OSPAR-level policy directives via 3 reports to OSPAR, for the interim 2017 OSPAR assessment as well as contributing to a series of publications (e.g. Fanjul et al., 2017, 2018). This work fits Objective 2: to integrate improved knowledge and understanding into existing ecosystem models, and to explore the impact of environmental change on the structure, function and services associated with marine across scales. It also contributes to the programme goal of having a decisive influence on the next generation of marine monitoring programmes deployed in the UK and across Europe, and to provide a holistic framework to support decision making in the marine environment. This is exemplified by Atkinsons's authorship of two 2017 reports to OSPAR https://www.ospar.org/work-areas/bdc/ecaprha/reports that aim to overcome challenges in the development and reporting of planktonic indicators for Biodiversity in the OSPAR sub-regions.

The value-added L4 zooplankton time series was used by the UK Pelagics Expert Group in the OSPAR 2017 intermediate assessment for one of its three pelagic indicators, namely PH 1: Planktonic Lifeforms (This assessment is currently under the review stage). This L4 time series was the only UK fixed point zooplankton time series available for use in this particular assessment. External academic uses of this value-added time series are increasing, and there are currently five papers in review and two published/in press. This revised data set is also a contributing to an integrated network of ecological time series (IGMETS) http://www.st.nmfs.noaa.gov/nauplius/media/igmets/reports/IOC-UNESCO__TS129__ch04__North-Atlantic-only.pdf. We aim to combine the zooplankton biomass spectrum derived from L4 with spectra for smaller and larger size fractions within MERP to produce a paper examining the full biomass spectrum (up to marine mammals). We anticipate an increasing number of users of these data within and outside of MERP, including its use for size-based modelling. Three separate requests for these data have been made within MERP for advancement of size-based models.

A scale-based understanding of feeding, mortality and population control mechanisms

Feeding and mortality are key processes whose parameterisations are sensitive factors to many model outputs. A substantial effort within Module 2 went to improved understanding of feeding selectivity in zooplankton, including predator/prey size ratios. Djeghri et al. (2018 Progr Oceanog) found that the five dominant copepod species at the Western Channel Observatory could tackle surprisingly large food items and displayed generally unselective feeding behaviour. The large food items included copepod early larval stages, supporting the role of intraguild predation (including cannibalism) as a mechanism controlling copepod densities (Djeghri et al. 2018 Progr Oceanog). This intraguild predation was found to work in tandem with strong predation by gelatinous predators acting on the later life stages of the key copepod *Calanus helgolandicus* (Maud et al. 2015 Progr Oceanogr; Maud et al. 2018 Limnol Oceanogr). Parallel work on another dominant zooplankton species, the wasp waist-type species *Euphausia superba*) found the reverse situation to that of copepods, with very high predator prey mass ratios and ability to feed on very small food (Schmidt and Atkinson 2016). However, like in the copepods, feeding was basically unselective and included small lithogenic particles as well as living cells of similar size. Incidental ingestion of non-food particles by zooplankton is important to our understanding, both of the fate of nano and microplastic pollutants and of biogeochemical cycles. For the latter, ingestion and subsequent digestion of iron-rich suspended sediment was found to increase the bioavailability of this limiting nutrient (Schmidt et al. Current Biology 2016). Given the range of feeding selectivity functions being assigned to zooplankton in some models, our findings of relatively unselective feeding, albeit with varying predator-prey size ratios, supports some welcome simplification in size-based modelling approaches.

These feeding/mortality processes dictate the relative balance of top-down and bottom-up processes regulating the food web. The Marine Ecosystems Announcement of Opportunity stressed the importance of understanding the scale dependency of top-down and bottom-up controls, and

MERP work had one of its foci on seasonal and inter-annual scales provided by the weekly resolution sampling at the Plymouth L4 site. In a joint work with the modelling module 6, Atkinson et al. 2018 (Limnol Oceanogr) revisited a diverse suite of numerical and conceptual models that have been proposed to understand the seasonal succession of phytoplankton and zooplankton. These include both MERP-funded work (e.g. Sailley et al. 2015 J Plankt Res, Polimene et al. 2015 Progr Oceanogr, Atkinson et al. 2015 Progr Oceanogr, Cornwell et al. 2018 J Plankton Res) and other studies taking both top-down and bottom-up perspectives. Atkinson et al. 2018 (Limnol Oceanogr) proposed approaches to combine complementary models and to evaluate the output of others more critically. The dual role of predation and physical controls at this site is clear, and supported by ongoing work on the growth/mortality balance of protists based on a series of 17 dilution experiments at the nearby E1 site (Fileman et al. in prep). Our MERP work has also spanned larger scales of space and time to examine control on zooplankton populations. Top down controls are more prominent at small scales (Maud et al. 2018, Cornwell et al. 2018) with bottom up controls, manifested in temperature effects, being increasingly evident at ocean province (Fanjul et al. 2017 J Plankton Res, Fanjul et al. 2018, Cont Shelf Res) and especially at global scales (Beaugrand et al. Nature Climate Change, in review).

Within MERP, a comparative species approach to understand population controls has been instructive. For the biomass dominant copepod species at L4, *Calanus hegolandicus*, the interannual fluctuations in mean abundance are relatively small, and the abovementioned mortality studies suggest tight predation control as a density stabilising mechanism (Maud et al. 2018 Limnol Oceanogr). By contrast the wasp-waist type species (*Euphausia superba*) fluctuates in density by over an order of magnitude between years, and its recruitment is under strong climatic control (Atkinson et al. 2018 Nature Climate Change, in press). Despite the governing role of bottom-up process driving the population dynamic of this species, a superimposed change in mortality had a secondary and counterbalancing effect to help to stabilise a declining and poleward moving distribution. This again pointing to a density dependent process, albeit acting over much longer timescales than seen for *C. helgolandicus*. While density-dependent mortality is intuitive and assigned in many models, our attempts to look for how it works in nature helps to provides the better understanding needed for improved food web models.

Ecological processes and their representation in models (Module 3)

This area of work focuses on integrating improved understanding from modules 1 and 2 into marine ecosystem models, using concepts and expertise derived from non-marine models.

In contrast to macroecology, simulation models seek to assemble 'from the ground up' representations of relationships between groups of organisms, so as to reproduce the observed properties of the ecosystem as a whole under known driving conditions. We shall identify the implications of differences in model structure on macroecological patterns to reduce model uncertainty.

Module 3 and Module 4 have tended to run in an integrated fashion. Elements of work that could be presented here are therefore detailed in the following section.

Age uncertainty and growth parameters

Mike Spence, a MERP PDRA at the University of Sheffield, developed a new method of combining surveys to estimate life history parameters. The paper (Spence MA and Turtle AJ, Making the most of survey data: Incorporating age uncertainty when fitting growth parameters, Ecology and Evolution 7(17) 7058–7068) demonstrated a method that reduced the uncertainty in estimates of the von Bertalanffy growth parameters by considering the spawning time of the species. The research demonstrated that the current method of combining surveys leads to inconsistent models which had effects on management decisions from yield-per-recruit models compared to the new method. The method gave a way of getting life history parameters, with measurable uncertainty, which are used as inputs to many of the ecosystem models. Although the paper does not use MERP data or models directly, the data was extracted from ICES DATRAS using the rMERP package. The work demonstrated a way of quantifying the uncertainty for inputs to models used to advise policy makers. This work gives a means of using them to explore effects of environmental change (objective 2) and of management strategies (objective 3) and the dynamics of indicators (objective 3). Code from the study has been sent to people from Unite Ecologie et Modeles pour l'Halieutique as well as Cefas. The method will be presented at ICES working groups WGSAM and WGBIOP where it will get more exposure and will hopefully be used in stock assessment models. There is a current R package that is being developed to make these methods easy to use. This will increase the use of the method.

Simulating and predicting ecosystem changes using a model ensemble (Module 4)

This will focus on quantifying the uncertainty in future predictions as well as improving predictions about the fate of marine ecosystems and their services under different past and future scenarios, at local and regional spatial scales.

The predictive engine of the project will be a model ensemble comprising well-documented, whole or partial simulation models of marine ecosystems together with statistical models emerging from macroecological analyses. Optimisation methods will then be applied, following modelling principles defined by the International Panel for Climate Change (IPCC) for forecasting the consequences of greenhouse gas emissions, to forecast ecosystem states under scenarios of future conditions.

A Critical Review of a suite of modelling approaches used for projecting changes in the distribution and productivity of living marine resources

Working with partners at a European scale (Peck et al. 2018 Estuarine, Coastal and Shelf Science doi: 10.1016/j.ecss.2016.05.019), we reviewed and compared four broad categories of spatially-explicit modelling approaches currently used to understand and project changes in the distribution and productivity of living marine resources including: 1) statistical species distribution models, 2) physiology-based, biophysical models of single life stages or the whole life cycle of species, 3) food web models, and 4) end-to-end models. Single pressures are rare and, in the future, models must be able to examine multiple factors affecting living marine resources such as interactions between: i) climate-driven changes in temperature regimes and acidification, ii) reductions in water quality due to eutrophication, iii) the introduction of alien invasive species, and/or iv) (over-)exploitation by fisheries. Statistical (correlative) approaches can be used to detect historical patterns which may not be relevant in the future. Advancing predictive capacity of changes in distribution and productivity of living marine resources requires explicit modelling of biological and physical mechanisms. New formulations are needed which (depending on the question) will need to strive for more realism in ecophysiology and behaviour of individuals, life history strategies of species, as well as trophodynamic interactions occurring at different spatial scales. Coupling existing models (e.g. physical, biological, economic) is one avenue that has proven successful. However, fundamental advancements are needed to address key issues such as the adaptive capacity of species/groups and ecosystems. The continued development of end-to-end models (e.g., physics to fish to human sectors) will be critical if we hope to assess how multiple pressures may interact to cause changes in living marine resources including the ecological and economic costs and trade-offs of different spatial management strategies. Given the strengths and weaknesses of the various types of models reviewed here, confidence in projections of changes in the distribution and productivity of living marine resources will be increased by assessing model structural uncertainty through biological ensemble modelling.

Improved model-fitting methodology

Fitting complex and computationally demanding ecosystem models to data, to get accurate parameter estimates and to track uncertainty, is a challenge that needed to be addressed before developing the ensemble framework. MERP researchers developed new methods (Spence et al, 2016, Canadian Journal of Fisheries and Aquatic Sciences, doi.org/10.1139/cjfas-2015-0022) that allow dynamic ecosystem models to be fitted to time series data, rather than time-averaged data, and permits efficient exploration of high-dimensional parameter spaces. The method allows principled assessment of the uncertainty associated with parameters, projections, and derived quantities such as size spectral slopes or community-level indicators. Other work built on this, developing novel Bayesian statistical techniques to allow the development and parameterisation of more complex multi-species models, without the common reliance on pre-existing single-species models (Avoiding the curse of circularity: building a multi-species model from the ground up. Michael A. Spence, Robert B. Thorpe, Paul G. Blackwell, Simon Jennings, Finlay Scott, Richard Southwell and Julia L. Blanchard; in prep, to be submitted to Methods in Ecology and Evolution). This paper builds a multi-species model for the Celtic Sea, including 17 major fish species, and critically examines its performance. Follow-up work funded by Cefas, led by Spence (now at Cefas) and involving Blackwell and others, focused on strategies for applying this model-fitting under tight constraints on (computing or actual) time. Thus, ideas developed within MERP will continue to inform and improve best practice for modelling as applied to management questions.

A general framework for combining ecosystem models

When making predictions about ecosystems, we often have available a number of different ecosystem models that attempt to represent their dynamics in a detailed mechanistic way. Each of these can be used as a simulator of large-scale experiments and make projections about the fate of ecosystems under different scenarios to support the development of appropriate management strategies. However, structural differences, systematic discrepancies and uncertainties lead to different models giving different predictions. This is further complicated by the fact that the models may not be run with the same functional groups, spatial structure or time scale. Rather than simply trying to select a best model, or taking some weighted average, it is important to exploit the strengths of each of the models, while learning from the differences between them. To achieve this, Spence et al. (2018 Fish and Fisheries doi: 10.1111/faf.12310) construct a flexible statistical model of the relationships between a collection of mechanistic models and their biases, allowing for structural and parameter uncertainty and for different ways of representing reality. Using this statistical meta-model, we can combine prior beliefs, model estimates and direct observations using Bayesian methods and make coherent predictions of future outcomes under different scenarios with robust measures of uncertainty. In this study, we take a diverse ensemble of existing North Sea ecosystem models and demonstrate the utility of our framework by applying it to answer the question what would have happened to demersal fish if fishing was to stop.

This work shows how novel statistical methods can be used to synthesize predictions from varied ecological models, making the most of their different strengths. It incorporates two case studies using models within MERP, illustrating the relative recovery speeds and uncertainties for indicators, and the long-term values, dependencies and uncertainties in biomasses under particular management regimes. The methodology was specifically developed as part of MERP, in collaboration with the University of Tasmania (UTas). It uses model runs designed and carried out within MERP along with information on model uncertainties and expert opinions from MERP modellers and scientists, plus UTas, and indirectly (through the model fitting) data from across MERP. By synthesizing a range of models within MERP, this work gives a means of using them to explore effects of environmental change (objective 2) and of management strategies (objective 3) and the dynamics of indicators (objective 3).

The methodology and preliminary results have been of interest to ICES, resulting in Mike Spence being invited to join the ICES working group for multi-species assessment methods. The example on indicator dynamics was developed specifically to address questions raised by Defra, and results were presented to them in a separate briefing document (Nov 2016) and further developed for the 2017 briefing. Within MERP, this work was extended to look at a wider range of scenarios, defined either by considering management of each species separately – fishing at the maximum sustainable yield for each one – or in a more sophisticated way using the idea of "multi-species sustainable yield" based on the Nash equilibrium. Comparisons between scenarios were made at single-species and community levels (Spence et al, Modelling the Effect of Fishing Mortality on Commercial Fisheries Revenue using Bayesian Belief Networks; in prep, for submission to Fish and Fisheries).

Beyond MERP, the interest within ICES is likely to alter the way in which stock assessment are carried out. In addition, Cefas is now making substantial use of the ensemble approach, directly as a result of work in MERP. In particular, they are working on using ensemble modelling to combine single- and multi-species models, to obtain accurate, coherent projections over a range of time-scales. The MERP multi-model ensemble approach was selected as a case study in the European Marine Board Future Science Brief #4 (2018) "Enhancing Europe's capability in marine ecosystem modelling".

Interactive effects of top-down and bottom-up drivers

Further research using the MERP Model Ensemble confirmed observations that in most marine ecosystems top-down trophic cascades are damped, implying that fishing has a weak overall effect on lower trophic levels. Further, we constructed and analyzed a new data set of 25 empirical size spectra, showing a transition from damped to amplifying trophic cascades and a drastic re-organisation of the size spectrum ("dome" formation) at nutrient levels corresponding to around one microgram Chlorophyll-a per litre in average surface waters. In essence, the effects of top-down control vary with changes in bottom-up control. A paper describing this work is close to submission (Rossberg, A. G., Gaedke, U., and Kratina, P. Giant trophic cascades in pelagic ecosystems. Manuscript for submission) and will include a data-base of 25 high-quality pelagic size spectra covering a wide range of nutrient levels.

The critical level of chlorophyll a is already exceeded in some UK marine systems and global warming is expected to enhance them further. A new size-spectrum model developed by MERP explains and demonstrates the causal chain: nutrient enrichment - bottom-up trophic amplification - gradual consumer satiation - top-down effects - dome formation. MERP Partners measured marine size spectra in various parts of the Celtic Sea. With improved data, the present research allows us to mobilize this data to address management questions, such as to determine to what extent the Celtic Sea ecosystem exhibits signs of trophic amplification, top-down cascades, and dome formation. This research directly quantifies and explains top-down effects and trophic cascades in size spectra, showing that amplification of trophic cascades results indirectly from nutrient enrichment and bottom-up effects. As part of this a new model (the nonlinear Species Size Spectrum Model, SSSM) has been designed and implemented. This output confirms the weak overall top-down effect currently predicted by the MERP Model Ensemble for the UK, and shows under which conditions top-down effect will become amplified.

Linking macroecology and models to ecosystem services (Module 5)

This work is directed towards translating improved understanding of the dynamics of marine ecological communities into the currency of ecosystem services.

Outputs from the model ensemble will be mapped onto an inventory of ecosystem services developed by the National Ecosystem Assessment and the EU VECTORS programme. Outputs from modules 1, 2, 3 and 4 will also be translated into quantitative measures of goods and services and relevant indicators of ecosystem status, in particular indicators that are defined in the Marine Strategy Framework Directive (MSFD). This will create an integrated system capable of making forecasts of ecosystem status, goods and services for various scenarios of future environmental conditions.

Assessing sensitivity of services to pressures

The ecosystem services approach is widely recognised as a concept, but more attention must be given to the development of tools to facilitate practical implementation if the approach is to become more widely used to support decision-making. A key component of natural resource management is understanding the implications of changing levels of pressures on ecosystem components, which is achieved through sensitivity assessment. MERP research (Hooper T, Beaumont N, Griffiths C, Langmead O, Somerfield PJ (2017) Assessing the sensitivity of ecosystem services to changing pressures. Ecosystem Services 24: 160-169 doi: 10.1016/j.ecoser.2017.02.016) examined how sensitivity assessment could be applied to ecosystem services, as opposed to the underlying habitats and species, by considering the relationship between the sensitivity of a service to the sensitivity of the habitat responsible for its supply. The method is illustrated using a UK case study of supporting and regulating services provided by subtidal sedimentary habitats within the UNESCO Biosphere Reserve in North Devon, which is a key regional case-study area for much of the work in WP3.

Linking MSFD GES and ecosystem service indicators

An ecosystem service approach is increasingly being advocated at national and international levels to ensure sustainable use of the environment, and sets of indicators have been defined for ecosystem service assessments. We considered whether a selection of GES indicators related to biological descriptors, D1 Biodiversity, D2 Non-indigenous species, D4 and D6 Seafloor integrity, may provide information relevant to ecosystem services, potentially allowing use of collected environmental data for more than one purpose. Published lists of indicators for seven selected marine ecosystem services were compared to 296 biodiversity-related indicators included within the EU project Devotes DEVOTOOL catalogue, established for screening marine biodiversity indicators for the MSFD. We concluded that 64 of these biodiversity indicators are directly comparable to the ecosystem service indicators under consideration. All 296 biodiversity indicators were then reassessed objectively to decide which of them could be useful as ecosystem service indicators. To carry out this step in a consistent and transparent manner, guidelines were developed that helped the decision making process for each individual indicator. 247 biodiversity indicators were identified as potentially useful ecosystem service indicators. By highlighting the comparability between ecosystem service and biodiversity indicators it is hoped that future monitoring effort can be used not only to ensure that GES is attained, but also that ecosystem service provision is maximised. The research has been published (Broszeit S, Beaumont NJ, Uyarra MC, Heiskanen A-S, Frost M, Somerfield PJ, Rossberg AG, Teixeira H, Austen MC (2017) What can indicators of good environmental status tell us about ecosystem services?: reducing efforts and increasing cost-effectiveness by reapplying biodiversity indicator data. Ecological Indicators 81: 409-442 doi: 10.1016/j.ecolind.2017.05.057).

Developing conceptual models linking pressures and services via ecosystem effects

Working with participants from across the MERP consortia, we developed a conceptual model to link MERP's four focal marine ecosystem services (food provision, bioremediation of waste, leisure and recreation, biological checks and balances) to ecosystem processes and components of the ecosystem to identify key linkages and to help visualise trade-offs between services. Working with Module 7, we then extended the model to include potential pressures and suitable management options to the model to highlight how these may link to ecosystem services. This work has been submitted for publication (Broszeit S, Beaumont NJ, Hooper TL, Somerfield PJ, Austen MC (submitted) Developing conceptual models that link multiple ecosystem services to ecological research to aid management and policy, the UK marine example. Mar. Pollut. Bull.). The paper discusses ecosystem services and trade-offs among them. Potential impacts on the ecosystem as well as suitable management options for such impacts are also discussed. Though the paper does not present quantitative outputs it is an important step towards quantitative assessment of services which can help communicating with policy makers, and has been used for stakeholder workshops. This work contributes directly to Objective 3 (apply models to test the impact of potential management solutions) by visualising how management solutions can influence ecosystem services and will help to incorporate the ecosystem models into a more quantitative approach to ecosystem service modelling than is currently undertaken. The models provide a useful framework to discuss the effects of management options with stakeholders and managers. They are now being developed into statistical models to develop a quantitative approach to ecosystem service management, using a variety of MERP data.

Climate change alters fish community size-structure, requiring adaptive policy targets

Size-based indicators are used worldwide in research that supports the management of commercially exploited wild fish populations, because of their responsiveness to fishing pressure. Observational and experimental data, however, have highlighted the deeply rooted links between fish size and environmental conditions that can drive additional, interannual changes in these indicators. Queiros et al. (Fish and fisheries 2018, doi:10.1111/faf.12278) used biogeochemical and mechanistic niche modelling of commercially exploited demersal fish species to project time series to the end of the 21st century for one such indicator, the large fish indicator (LFI), under global CO_2 emissions scenarios. Modelling results, validated against survey data, suggest that the LFI's previously proposed policy target may be unachievable under future climate change. In turn, results help to identify what may be achievable policy targets for demersal fish communities experiencing climate change. While fisheries modelling has grown as a science, climate change modelling is seldom used specifically to address policy aims. Studies such as this one can, however, enable a more sustainable exploitation of marine food resources under changes unmanageable by fisheries control. Indeed, such studies can be used to aid resilient policy target setting by taking into account climate-driven effects on fish community size-structure.

Developing ERSEM scenarios

These statistical models will be used to assess changes in ecosystem services in response to management actions, using outputs from the MERP model ensemble driven by bottom-up and top-down ERSEM scenarios from the SSB programme being delivered by Cefas in conjunction with PML. Cefas input to the development of scenarios is closely linked to the blue Carbon element of the NERC-Defra-funded Shelf Seas Biogeochemistry (SSB) programme which is tasked with providing NEMO-ERSEM model runs for different marine management scenarios. Cefas has completed a set of trawling scenarios and riverine discharge scenarios, including reduction of nitrogen, reduction of phosphorus and combined reduction of both nutrients. The first one of these scenarios is available, the second one is running and will be available in mid-September and the third one will be available by the end of September. Delayed delivery of the scenarios is partly a result of delays in running and selecting the best model configuration in SSB. The ensemble is operational and the elements will be driven by the different ERSEM scenarios. Initial results of scenario evaluation in an ecosystem services context were presented at the Defra briefing (September 2017) based on the coupled MIZER-ERSEM system.

Developing a model-based understanding of ecosystem service regulation (Module 6)

This will increase capacity to assess the structure of marine ecosystems by improving the way that biodiversity and ecosystem function are represented in the European Regional Seas Ecosystem Model (ERSEM).

The cornerstone of this development is the transition of ERSEM from a one-size-fits-all model of fixed complexity to a hierarchy of models that selectively inserts detail (e.g. species diversity) when demanded by other applications. The enhanced model will be used to explore the impacts of human-induced stresses and natural variability on the structure of marine ecosystems (e.g. their species composition and size structure), and develop links to forecast ecosystem services in order to meet the *knowledge needs of future science strategies, environmental management initiatives and policy development.*

A vastly improved modular ERSEM

ERSEM is one of the most comprehensive biogeochemical models for shelf seas, but prior to MERP it remained a model of fixed complexity with a hard-coded number of functional types. Therefore it could not describe species that were not in the model and it could not systematically vary biodiversity. Within MERP, ERSEM has been rewritten from the ground up as a modular model. This lets ERSEM scale to potentially hundreds of types of zooplankton or benthic fauna, allowing it to be systematically diversified to assess the impact of diversity on ecosystem function. The modular version of ERSEM (http://www.pml.ac.uk/Modelling_at_PML/Access_Code) has been publicly released. Owing to its newly acquired ability to scale to many types of zooplankton and benthic fauna, ERSEM can now directly incorporate information on the functional diversity of these groups. This includes new datasets on size and gelatinousness in zooplankton (Atkinson and McConville; M3). ERSEM has 243 registered users with access to ERSEM's code and the Windows-based software application used in the MERP/SSB workshops. The new model has been used in workshops for SSB, MERP and AMEMR, with a total of approximately 50 participants, many from institutes not in MERP. The modular version of ERSEM is now the only version in development and use, and therefore already supports a great variety of projects, several explicitly exploiting ERSEM's newly gained modularity to investigate the impact of new processes or species. It also supports efforts by partner institutes to develop bespoke versions of ERSEM suitable for specific seas or oceans – for instance, the Norwegian Institute for Water Research is working on an "Artic ERSEM" with a different selection of functional types. Workshops given to non-modeller partners in MERP (1x) and Shelf Seas Biogeochemistry (2x), and to modellers at the Advances in Marine Ecosystem Modelling Research (AMEMR) 2017 allowed participants to explore the effect of removal and additional of species themselves. The new version of ERSEM allows us to model functional diversity and its effect on ecosystem functioning - and thus contributes to understanding the link between functional diversity and ecosystem services. It also supports the integration of existing and new knowledge on trait variability across species into ERSEM. Spatial patterns in functional and size diversity in the UK shelf sea predicted by the diversified version of ERSEM will be compared with functional diversity maps compiled within other MERP modules (M1, M2). Diversified versions of ERSEM are used to deliver information (e.g., maps) about taxa that are highly relevant for ecosystem services, but until now rarely included in models (e.g., jellyfish). With enhanced diversity in plankton size classes, ERSEM can better link to (size-based) fish models. Using results of the diversified ERSEM model, we will investigate the relationship between functional diversity and productivity, nutrient use, and trophic interactions. The diversified ERSEM model can produce maps of functional diversity that can inform MPA planning.

Improved modelling of bottom-up effects

A new model code describing a generic prokaryote metabolism has been developed and integrated into ERSEM. The new formulation accounts for both aerobic and anaerobic heterotrophic metabolism as well as chemolithotrophy (through nitrification). When properly parameterized, the new formulation can simulate a diverse prokaryote community. The new code has been archived in the (version controlled) ERSEM repository held at PML. This work has not been published yet but it is likely to be part of forthcoming PML model publications. This modification to the model provides a better representation of the nitrogen cycle in ERSEM (addressing bottom-up processes). More specifically, the denitrification process has been implemented for the first time and the nitrification process is now described with an increased level of physiological detail. The new model, describing different metabolic pathways, represents a first step toward the representation of microbial diversity in marine ecosystem models. After publication it will be usable by a wider community (within and beyond MERP) and represents an improvement of an existing modelling tool (ERSEM) in its capacity to represent the lower trophic level of the marine ecosystem (N-cycle processes in particular) and microbial biodiversity. In particular, the new formulation will enhance the capability of ERSEM to simulate the marine nitrogen cycle and the variability of the microbial community in reaction to environmental factors such as the availability of organic carbon, oxygen and nutrients.

Improving the benthic component

Diversifying benthic fauna in ERSEM has led to improved model skill and increased our understanding of benthic ecosystem functioning. This work involved updating the ERSEM model using available observational data from L4 and integrating it with benthic survey data to inform model parameterisation. Part of this was done through an 8 week NERC/EnvEast research experience placement, "Impacts of benthic faunal diversity on ecosystem functioning of shelf seas", filled by Owen Mayhem, supervised by Gennadi Lessin (lead), Jorn Bruggeman, Caroline Louise McNeill. A paper on model- and data based time scales of benthic faunal response is in preparation, with submission planned for Sept-Oct 2017. Another paper on modelling the functional roles of macrofaunal diversity is expected to be submitted in first half of 2018. The main message from this research is that ERSEM, applying the new parameterisation, is able to reproduce temporal dynamics of major macrofaunal groups in shelf seas, and hence their response to pelagic food supply. The modified model revealed dynamic response of macrofauna to pelagic productivity, with specific time scales characteristic for different functional groups. Moreover, it was demonstrated that the revised model can be used to further diversify benthic macrofaunal groups, which was done using WoRMS classification. This way the model reveals ecosystem connections and functional pathways that are not evident from scarce measurement data. On the other hand, modelling work allowed us to identify further critical data needs. The work is likely to have impact as part of ERSEM model development and application process. From a policy perspective, understanding how the benthic environment functions is vital for maintaining healthy and productive. The benthic environment is one of the key components of marine ecosystems, closely linked to marine productivity and hence fisheries and food provision, and benthic fauna is an important component of marine systems, influencing rates of solute and particulate exchange and thus has a significant effect on dynamics of marine system productivity. The benthic environment thus provides important ecosystem services.

Cefas has agreed a solution to the problem of representing benthic niche segregation between closely similar functional groups in terms of space competition. PML will implement this using the FABM formulation. In the remaining 6 months, new niche overlapping ERSEM will be constructed and run along the lines of the completion model run under the previous phase of MERP.

Diversifying plankton

A framework for ERSEM to include multiple zooplankton groups while taking into account the large array of size and groups that compose the zooplankton has been implemented. This framework can reproduce dynamics of copepods and jellyfish and will be made publicly available through publication (proposed submission date of January 2018). The code for creating the various size classes, and the associated parameter changes (e.g. grazing, food matrix) will be made available through an online repository (proposed availability date of January 2018). Prior to MERP ecosystem models like ERSEM were using generic groups to represent zooplankton with some distinction of size where necessary. Now it is possible to increase the number of groups to better represent the diversity of zooplankton and the resulting alternate . To our knowledge no models with jellyfish being explicitly represented exist, despite their increased occurrence and impact on the ecosystem that differs from other non-gelatinous organisms. This MERP derived information is now integrated into ERSEM. This work used MERP data from other organisms regarding size spectra, plus some information about jellyfish. It will be further used in module 6. It contributes to MERP objective 2 (“integrate improved knowledge and understanding into existing ecosystem models, and to explore the impact of environmental change on the structure, function and services associated with marine across scales.”) by integrating new knowledge and understanding of size spectra into ERSEM creating new functionality to explore impact of environmental change on ecosystem functioning.

A model for phytoplankton diversity in temperature-tolerance traits has been developed and tested in a model of the world ocean. This model uses an “adaptive dynamics” approach to describe trait diversity through a small number of variables (mean and variance of optimum temperature). Results suggest that community level adaptation (species sorting as well as genetic evolution) has the potential to dampen the response of marine biogeochemical processes to climate change. This model was presented at the ASLO Aquatic Sciences meeting (Hawaii) and the 3rd workshop on trait-based approaches to ocean life (Bergen, Norway) and a paper is in preparation.

Initial simulations of ERSEM with diversified zooplankton (traits: size and gelatinousness) across the UK shelf seas at 7 km resolution (NEMO AMM7) have been completed and a manuscript is in preparation. The next step is to integrate the new formulation into ERSEM simulations at the shelf scale. Outputs from these simulations are likely to have an impact on policies regarding ecosystem services and management.

Adding higher trophic levels

A new implementation of the size-structured fish model MIZER that can be two-way coupled to ERSEM, and run within high resolution spatial models, has been implemented. Most higher trophic level (HTL) models employed in MERP depend on ERSEM variables (nutrients, chlorophyll, primary production), but as they run separately they cannot feedback to ERSEM (e.g., by reducing plankton). Thus the model system cannot explore top-down and bottom-up effects simultaneously. The HTL models by design underestimate the role of top-down control on lower tropic levels. In turn, ERSEM itself is forced to use a simplistic HTL parametrization. To address these issues, we have developed a MIZER implementation that directly couples to ERSEM. This brings two key advances: feedbacks between lower and higher trophic levels are fully represented, and spatial fish distributions are captured in detail on the NEMO-ERSEM grid. The new MIZER implementation was developed with support from Julia Blanchard (originally M4), and has benefited from comparison with results of the MIZER examples developed by Mike Spence (M4) for the MERP model-data integration workshop. Furthermore, implementation details (e.g., vertical movement) have been decided based on discussions with other fish modellers in MERP, e.g., Sheila Heymans, Natalia Serpetti and Mike Heath. Given time, the new coupled model enables us to completely resolve the roles of top-down and bottom-up control in a consistent manner. In the meantime, spatially detailed results of the new MIZER implementation for the UK shelf seas, under number of scenarios, have been included in the Defra briefing planned for 27 September 2017 (although it should be noted that these simulations are still forced offline by ERSEM scenario results). The new MIZER implementation is also being used by PML to quantify the global impact of climate change on fish communities for the FAO, specifically for their upcoming 2018 update of technical report 530 (http://www.fao.org/docrep/012/i0994e/i0994e00.htm). Results of the new model can feed into the model ensemble constructed in M4. Here, it has the unique ability to produce highly detailed spatial distributions of fish biomass for a large number of fish size classes (1 mg – 100 kg), covering the UK seas and more. The model also allows us to assess the spatial variation in impact of model scenarios, e.g., riverine nitrogen reduction does affect fish, but much more along the East coast than the West coast. The two-way coupling allows us to fully assess the impact of top-down control, from fisheries and fish all the way to plankton and nutrients. The model can provide the spatial detail that is needed for analysis of the impact of planned and existing MPAs.

Refining spatial resolution (NOC)

The impact of increasing model resolution on the physics and ecosystem of the Celtic Sea and English Channel region was investigated using the 3D coupled hydrodynamics-ecosystem model NEMO-FABM-ERSEM. Three models were implemented using successively increasing horizontal grid resolution: standard (7km), intermediate (3km) and high (1.5km). To isolate the impact of resolution, the models were constructed to be as similar to each other as possible; they have the same vertical resolution (51 terrain-following levels) and use the same ocean, atmosphere and riverine forcing. The models were run for 2014 to 2015 and validated against Shelf Sea Biogeochemistry (SSB) mooring and cruise data, Western Channel Observatory (WCO) moorings (http://www.westernchannelobservatory.org.uk/index.php) and satellite-derived surface chlorophyll-a data. As horizontal resolution increases, the simulated hydrodynamics show finer spatial variations with increased intensity and variability of currents and differences between models in the onset and duration of thermal stratification. The differences in the physical processes influence the nutrient supply to surface waters and change the model ecosystem. There is some evidence that the 1.5km and 3km models are in better agreement with observations (eg at WCO moorings E1 and L4 and the SSB Central Celtic Sea station, CCS) than the 7km model. However, on daily timescales and longer, the differences between the models and observations are generally greater than the changes produced by increasing model resolution. When the water column is vertically stratified, changing horizontal resolution does have an impact in the region where water density increases rapidly with depth (the pycnocline). As resolution increases and allows additional physical processes to be resolved, the pycnocline depth becomes more variable in time. This leads to an increase in the temporal variability of temperature, salinity and the subsurface chlorophyll maximum and agrees better with observed variability at the CCS station. The 1.5km resolution Celtic Sea and English Channel model developed for MERP is being used to help improve understanding of the connections between rivers, coastal regions and the open ocean in the NERC LTS-M project Land Ocean CArbon TransfEr (LOCATE).

Developing ecosystem models other than ERSEM

While the focus of MERP has been on developing ERSEM, it must be stressed that major developments to other model systems have been delivered, which demonstrate how incorporating new processes or formulations increase their applicability and how, in turn, these applications may be highly relevant to policy.

Completing the process of converting the original non-spatial Strathe2E ecology model into a spatial version, testing and fitting

The spatial StrathE2E model is now completed and a manuscript for 'Methods in Ecology and Evolution' is almost ready to submit. The spatial resolution is very coarse compared to ERSEM, but this is intentional and consistent with the coarse taxonomic aggregation of the living components of the food web. There were several obstacles to overcome in arriving at a robust spatial model, the main ones being the dynamic representation of vertical and horizontal spatial distributions of actively migrating taxa, and the processes governing concentrations of slowly-degrading organic matter in sediments.

Representation of movement by actively migrating taxa is a fundamental requirement in a spatially resolved model. If we simply regard these taxa as being anchored then we cannot hope to properly represent their encounter rate with prey. Their whole existence in reality depends on their ability to forage at spatial scales which are large in relation to the usual spatial graininess of models. The problem is to develop a scheme which is based on solid ecological theory for why animals move, rather than ad-hoc rules to 'make then do what we think they should' in the model. The latter is a relatively easy 'engineering approach' but not necessarily transferable from one model region to another. The former is very hard because the trade-offs that animals make between feeding, environmental tolerance, predator avoidance and breeding are complex and we know very little about them. After many 'blind alleys' we ended up with a scheme based on the principle of 'ratio-dependence' which has strong precedence in theoretical ecology. In this scheme, animals of the same type move in such a way as to try to maintain a spatially uniform ratio of the preference-weighted density of their prey to their own population density. At an individual level, this implies that animals are able to monitor gradients in the encounter rate of their prey and in competing conspecifics. Obviously, this is only a partial explanation of the motivations for active migrations, but as far as it goes it is at least based on solid ecology. In terms of the model details, the fundamental time-scale for biological processes within the model was daily, so we could regard diel vertical movements as being a sub-grid scale process and force a vertically uniform ratio of prey to predator density at all times. However, this was not the case for horizontal movements, so gradients in prey to predator density in the model were parameterised to generate a proportional exchange rate between adjacent cells (proportion of downstream biomass migrating per day). The parameters were incorporated into the overall model fitting process which included observed data on concentration gradients of migratory predator groups.

The issue with representation of slowly degrading organic matter in sediments was that we know very little about the chemistry involved. In simple terms, organic matter in sediments has a wide range of chemical forms. Some fractions of newly settled material are rapidly mineralised by bacteria to release ammonia. But, over time only the more refractory fractions remain. The proportion of refractory material increases with depth in the sediment due to burial, but even so, around 60-90% in the upper 10-20cm may be regarded as resistant to bacteria and only slowly degrading. Most ecosystem models tend to ignore this component of the sediment ecosystem since the nutrient fluxes arising from it are presumably very small. But the refractory material does contribute some nutrient release and perhaps more importantly acts as ballast in the diet of detritivorous benthos. There may also be some dynamic conversion between labile and refractory material depending on oxygenation of the sediment and priming of bacterial activity by deposition oi fresh labile matter. The extent to which detritivorous benthos can digest the material is largely unknown. In terms of our model, it was desirable to try our best to include the refractory matter because it is included in all observed data on sediment organic content and we wish to use this for model fitting. However, the problems were that mineralisation rates are extremely slow compared to all other process rates in the ecosystem, so refractory matter processes completely dominated the progress of model runs towards a stationary state when driven by repeating annual cycles of environmental drivers. Also, we know absolutely nothing about processes which may regulate the degradation rate, so stationary states of a model with dynamic refractory detritus were fragile. In the end, we opted to include refractory detritus concentration in sediments as a fixed concentration, but with a temperature dependent emission rate of ammonia proportional to its mass, an exchange rate with labile detritus, and availability to act as ballast in the diet of detritivores. The net effect is that the model has an open boundary for ammonia within the sediment, and sediments may act as a net sink for nitrogen (representing burial) or a net source depending on environmental or ecological conditions. Having implemented this representation the model did a very good job of simulating seasonal cycles of sediment organic nitrogen contents and the patterns of organic nitrogen across different grain size classes and seabed depths.

The previous section outlined work carried out to extend the StrathE2E model to include horizontal spatial resolution and active migrations by fish and top predators. Further work was undertaken to incorporate:

- implementation of dynamic macrophyte (seaweed) biomass
- disaggregating the combined bird&mammal group into discriminate functional groups.

A dynamic representation of macrophyte forest biomass in inshore waters has been implemented in StrathE2E, and the original combined bird&mammal group was disaggregated into birds, pinnipeds (seals) and cetaceans. All three of these top-predator groups undertake active horizontal migrations within the model driven by gradients in food concentration. The extended model was been extensively tested and parametrised against data for the North Sea and West of Scotland. A publication is planned for ‘Methods in Ecology and Evolution’ to include the new extensions to the model.

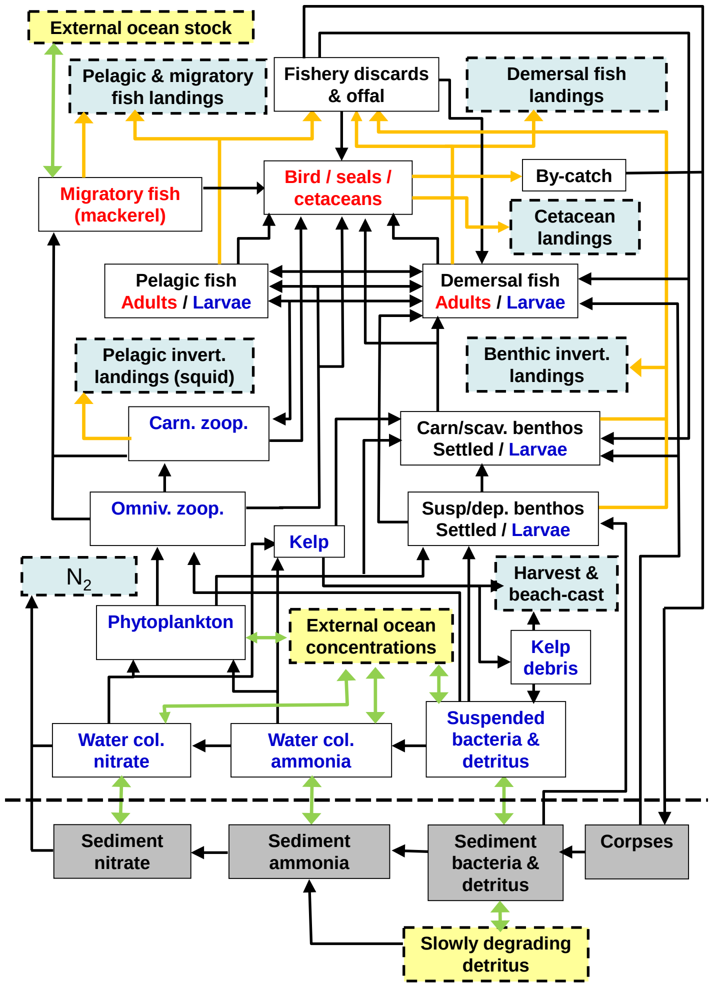


Figure 9: Schematic of the food web compartments of the StrathE2E model. Green arrows represent advection, mixing and migration; orange arrows represent fishery-related fluxes; black arrows represent biological fluxes. Red labelled components are active migrators, blue are subject to passive advection and mixing and black are anchored. Pale blue boxes represent quantities exported from the model whilst yellow are imported. For clarity fluxes from living components to ammonia, detritus and corpses due to excretion, defecation and death are not shown. Also for clarity, birds, pinnipeds (seals) and cetaceans are combined as group but in the model are separate entities. The term 'kelp' is used for all macrophytes.

CEH worked closely with the University of Strathclyde to adapt and provide parameters and validation data for the StrathE2E ecosystem model (figure 9). As a result of this collaboration StrathE2E has been adapted to include three guilds of seabirds, for which we are providing empirical parameter estimates and validation data for model fitting in three regions (whole of North Sea, Celtic Sea, west of Scotland sea). We extracted long-term monitoring data for seabird colonies in these three model regions and are currently compiling this data into guild level metrics to be used in model validation. CEH also worked with SAMS to help adapt, and provide input and validation data for, the EcoPath/EcoSim models.

Developing Bayesian methodologies for fitting StrathE2E to observed data

The StrathE2E marine ecosystem model was originally fitted using simulated annealing which relies on the Metropolis-Hastings algorithm to converge on an estimate of the maximum likelihood of a set of observed data given a set of parameters. This produced point-estimates of the optimal parameters, but gave no indication of associated uncertainties. Fitting with Bayesian methods produces optimal distributions for each parameter, which are used to calculate credible intervals around parameter values and model output. We initially tried applying the Robust Adaptive Metropolis algorithm (Statistics and Computing (2012) 22(5):997-1008) to StrathE2E. This was unsuccessful as exploration of parameter space ceased after several hundred iterations. This failure seems to be due to a combination of a large number of fitting parameters and a complex solution surface in which parameter covariance varies substantially across the surface. Most adaptive Metropolis-Hastings methods tune the algorithm to adhere to the global covariance of parameters, and therefore often become stuck in regions of the solution surface that conflict with the global covariance. Hamiltonian Monte Carlo (HMC) is the foremost method for optimising problems where covariance strongly varies with parameter position. We coded StrathE2E into Stan (dedicated software for HMC) but found that the combined number of fitting parameters and state variables was too large to fit the model in reasonable time. Planned future updates to Stan will decrease integration times, so the StrathE2E Stan code may yet prove valuable. A recently developed algorithm, Kernel Adaptive Metropolis-Hastings (KAMH) (arXiv:1307.5302v3 [stat.ML]), applies Gaussian similarity kernels to the history of parameter values to adapt to the local parameter covariance. This prevents the algorithm becoming stuck in highly curved regions of the solution surface. The KAMH method appears suitable for StrathE2E. We have generated converged parameter distributions (total sample size 600,000 split over 3 chains), and produced credible intervals for model outputs. The main issue that remains is how to specify parameter prior distributions. We have used Dirichlet distributions for the simplex-constrained preference parameters, and log-normal distributions for the remaining (positive) parameters. The parametrisation of these priors were determined from a separate optimisation procedure. It would be preferable to estimate prior parametrisation within the KAMH algorithm, but this has proved problematic. As a minimum, further investigation of the effects of less informative priors is still required. We have begun a write-up of this work, which we intend to submit for publication.

Implementing StrathE2E for West of Scotland, Celtic Sea and English Channel

The main tasks involved in implementing StrathE2E for new model regions are (a) assembly of physical configuration rata (volumetric and sediments) for each model region, (b) assembly of driving data as inputs to the ecology and fishing fleet models within StrathE2E, (c) assembly of by-catch data for birds, seals and cetaceans in fishing gears. The input data and parameters of the models are shown in Tables 3 and 4.

We completed these tasks for the West of Scotland, Celtic Sea and English Channel. However, extensive testing and model runs were undertaken only for the West of Scotland, since these were a priority for use in the Module 7 MCA workshop. Only preliminary runs have been carried out for the Celtic Sea and English Channel.

Table 3. Ecology model parameters, input and outputs

Static configuration data
Model domain sea surface area; area-proportions of bathymetric zones and water column layer thicknesses; area-proportions of seabed habitats and median grain sizes of sediments
Parameters for deriving sediment porosity, permeability and organic nitrogen content in each seabed habitat from median grain size, and light attenuation coefficients from suspended particulate matter (SPM) concentration

Ocean biomass of migratory fish stock and the annual proportion entering the model domain
Monthly resolution internal driving data
Proportion of each seabed habitat sediment layer volume disturbed by natural bed shear stress per unit time.
Vertical mixing and horizontal advection rates between compartments within the model
Temperature and suspended particulate matter concentrations in water column layers, sea surface irradiance in each depth zone, significant wave height adjacent to the coast
Monthly resolution external boundary influxes of nutrient
Volume inflows across the external ocean boundaries of the model and from rivers, and concentrations of nutrient, phytoplankton and suspended detritus in the inflows
Atmospheric deposition of nutrient to the sea surface
Other nutrient discharges into the model domain (assumed to enter the inshore zone)
Inputs from the fishing fleet model
Inshore and offshore zone harvest ratios, proportions of catch rejected (discarded) and proportions of retained catch processed at sea for each resource group
Area-proportion of each seabed habitat abraded by trawling per unit time
Proportion of discards and offal deposited over each seabed habitat
Biological parameters (* indicates fitted parameters)
*Prey preference parameters for each predator-prey pairing
*Maximum uptake rate and prey half saturation concentration for each consumer group
*First-order rate coefficients for microbial processes
*Density dependent mortality coefficients
*Coefficients for active horizontal migration rates of fish and top-predators
*Sinking rates for detritus
*Parameters for the exploitable fraction of biomass for each group subjected to fishing.
Saturating irradiances for nutrient uptake by phytoplankton, and carbon uptake by macrophytes
Assimilation efficiency for each consumer group
Maximum and minimum nitrogen:carbon ratios for macrophytes
Food-independent metabolic rates for each consumer group, and density-dependent carbohydrate excretion rate for macrophytes
Q_{10} temperature dependency coefficients for autotropic and heterotrophic maximum uptake rates, metabolic rates and microbial processes
Annual weight-specific fecundities for fish and benthos groups; start and end dates for egg production, and for recruitment of larval stages to the settled stocks
Start and end dates for immigration and emigration of migratory fish
Parameters for relationship between demersal fish biomass and a) proportion of non-quota demersal fish and b) proportion of undersize quota-limited and non-quota fish in the catches
Model outputs (all at daily intervals)
Mass of each state variable
Model import and export fluxes (transport, atmospheric deposition, river inflows, denitrification, fishery landings)
Derived internal fluxes: consumption flux for each prey-predator pair, consumption and production fluxes of nitrate and ammonia in each depth zone and layer, fishery discards and offal

Table 4. Fishing fleet model inputs and outputs

Input data for each gear type (maximum 12 types)
Annual model domain averaged fleet activity density (number of boats x time spent fishing per boat, per day, per unit area)
Proportion of annual activity over each model seabed habitat
Selectivity (catching power) for each ecology model resource group
Rejection (discard) rate for each ecology model resource group
Proportion of each catch group processed (gutted) at sea
Seabed area abraded per unit activity
Gear-independent parameters
Parameters for scaling effort (activity x power) to harvest ratio for each ecology model resource group
Seabed sediment penetration depth (common value across all gears)
Damage-related mortality rate of benthos per bottom-contact gear pass (common value across all gears)
Proportion by weight of viscera for catch groups processed at sea
Model outputs
Bathymetric zone harvest ratios and processing-at-sea and discard rates for each ecology model resource group due to all gears combined (required for input to the ecology model)
Area-proportion of each seabed habitat abraded per unit time by all gears combined (required for input to the ecology model)
Proportion of discards (rejects and offal) from all gears combined, which are deposited over each seabed habitat (required for input to the ecology model)
For each horizontal zone separately, proportion of total effort directed at each ecology model resource group which is attributable to each gear (required for disaggregating simulated landings and discards to individual gears from ecology model output)

(a) Assembly of physical configuration rata (volumetric and sediments) for each model region,

Seabed sedimentology data for each model region were assembled from the datasets generated in MERP. The model regions and their sediment types are shown in Figure 9.

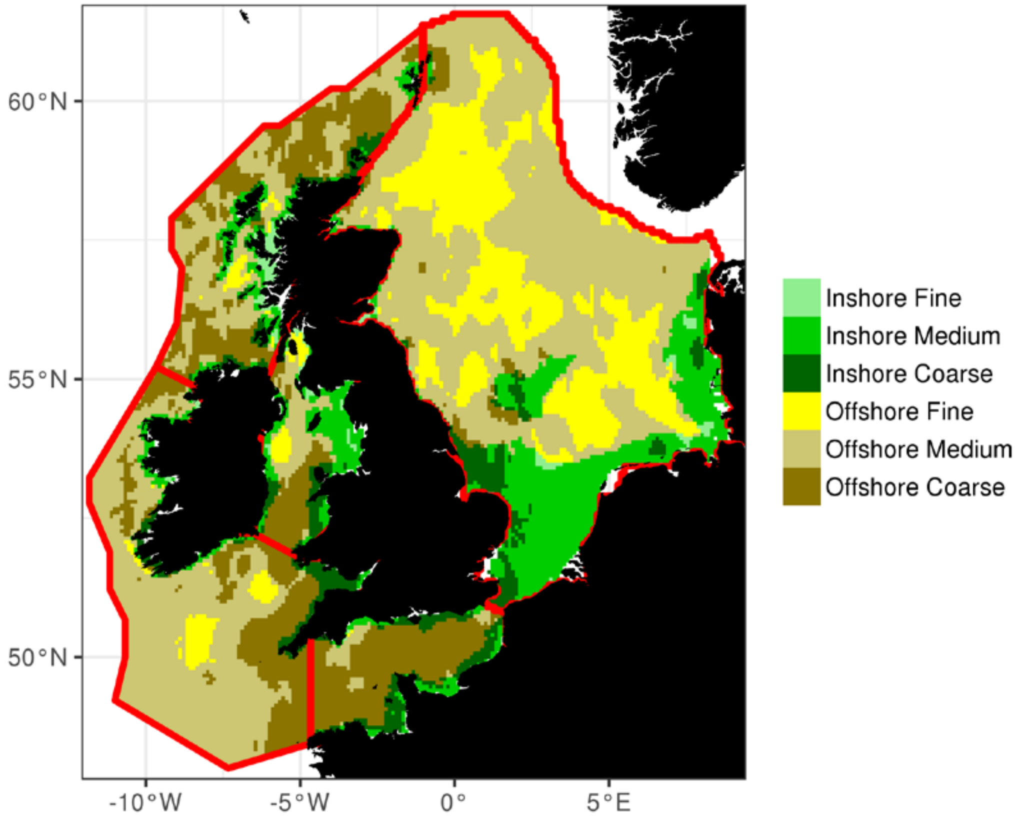


Figure 10. Map of the StrathE2E model regions. The models resolve sub-area of seabed sediment habitat divided into inshore (shallower than 30m) and offshore. Within each zone, three sediment classes are represented – fine (muddy), medium (sandy) and coarse (gravel). Within each of the six sediment habitats a proportion of the seabed area may present as exposed bedrock (not shown) which has different geochemical properties and in the inshore zone supports the kelp forests which are included in the model food web.

(b) Assembly of driving data as inputs to the ecology and fishing fleet models within StrathE2E

The plan was to assemble the input data for Strathe2E ecology models of West of Scotland, Celtic Sea and English Channel from outputs of ERSEM, and the inputs to the fishing fleet model from the EU-STEFC fisheries database. The information required from the STECF database was the activity rates of each of a set of fishing gear categories, and their annual landings and discards of each of the functional groups in the StrathE2E ecology model. This was all extracted successfully from the data base for each region.

Assembly of the hydrodynamic and chemical boundary inputs to StrarthE2E from ERSEM outputs was more problematic. Monthly resolution inputs of the variables shown in Table 3 were compiled from the years 1980-2015 from ERSEM outputs. However, comparison of the values for nutrients and chlorophyll with independent observational data showed some large biases which were both time and space dependent. In particular patterns of nitrate and ammonia concentrations deviated significantly from the World Ocean Atlas (WOA) and ICES databases, suggesting that ERSEM over-estimates nitrate and under-estimates ammonia. In the end, we developed input data for each StrathE2E on boundary nutrients, chlorophyll and detritus which were a climatological version of the ERSEM outputs, bias-corrected to the WOA and ICES.

(c) Assembly of by-catch and targeted-catch data for birds, seals and cetaceans in fishing gears.

Data on international regional by-catches of top predators in fishing gears are not readily available in databases. Working with Bangor University, we developed parameters linking the international activity density of each category of fishing gear in the STECF database, and the proportion of population biomass of each of the major vulnerable species. Using these, we could then estimate the total by-catch quantity given data on population biomass. Data on catches of Minke whales in the Norwegian sector of the North Sea were provided by the Norwegian Directorate of Fisheries.

Table 5. Fishing gears for which there are quantitative data on by-catch weights of particular species of top-predators

Gear	**Vulnerable seabird species**	**Vulnerable seal species**	**Vulnerable cetacean species**
Demersal gillnets	Guillemot, razorbill, fulmar, gannet	Grey seal	Common dolphin, striped dolphin, harbour porpoise
Pelagic trawl	Gannet		Common dolphin, bottlenose dolphin, striped dolphin, pilot whale
Pelagic seine	Gannet		Common dolphin
Pelagic longlines	Fulmar		
Creels & pots			Fin whale, Minke whale
Norwegian whaler			Minke whale

Developing a scheme for integrating StrathE2E ecology, fishing fleet, and valuation models to create an interactive system

Previously the linked ecology and fishing fleet StrathE2E involved only one-way coupling – that is, the fishing fleet model provided input to the ecology model, but the ecology model could not return any information to the fishing fleet model. We developed the system to include the two-way feedback between the two parts of the system. A two-way link was enabled by allowing the spatial distribution of fishing activity to be a dynamic property of the system, rather than an externally-provided driving dataset. Individual fishing gears were modelled as changing their distribution of activity across the spatial zones of the model on an annual basis, depending on the profit margins in the previous year (revenue from each spatial zone depends on landings, while costs depend on activity distribution and an interference terms with other gears).

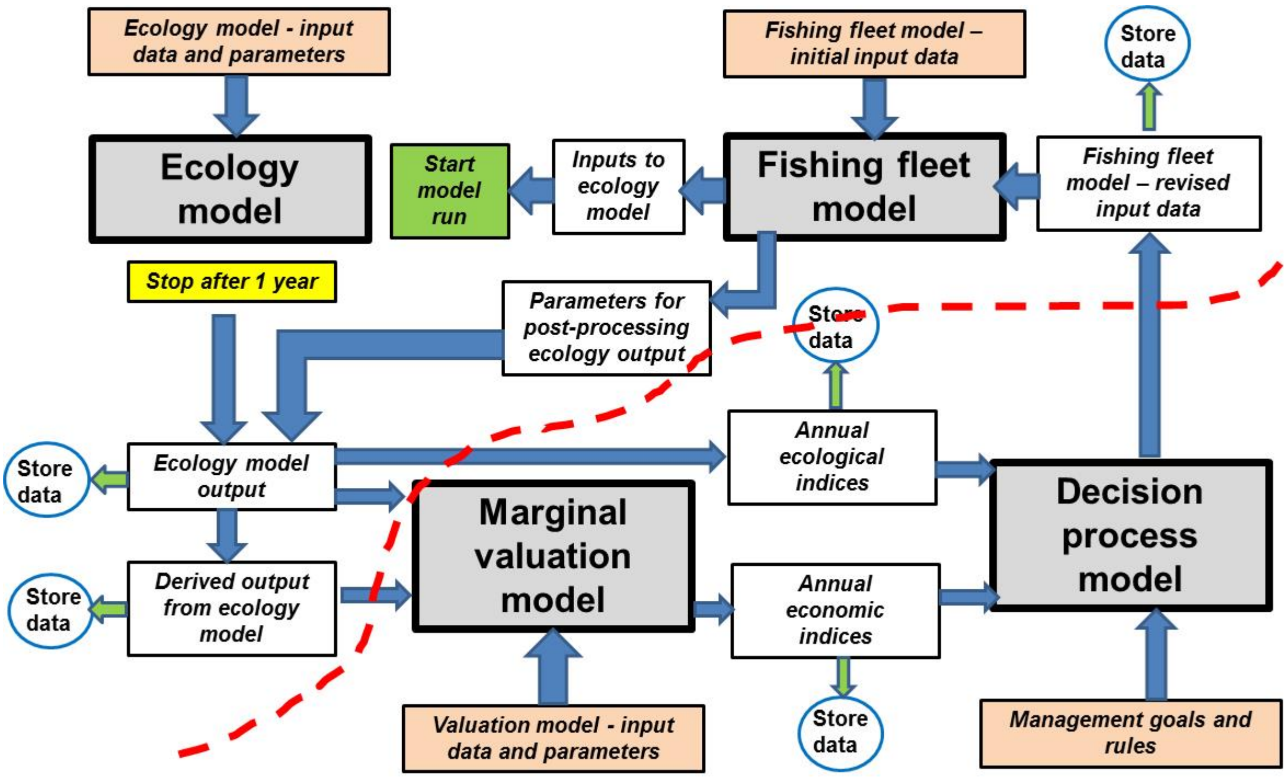


Figure 9. Schematic of the structure of the integrated ecosystem management strategy evaluation scheme. Parts below the red line are recently completed and the system used in Module 7.

The final stage of this part of the project was to develop a 'management simulation' component of the system, whereby simple harvest control rules could be programmed into the model so that the overall activity of each gear (as well as its spatial distribution) could become a dynamic property rather than a prescribed value, dependent on the extent to which landings or effort meet management targets. The coding also included a means to simply represent the displacement of effort die to the establishment of spatial protection zones applied to some or all of the gears.

All of these aspects of the project were completed and were an essential pre-requisite for the Module 7 MCA workshop task.

Discarding and policy: StrathE2E

The issue of trade-offs between fishery yields and management measures, and MSFD status is at the heart of both MERP and the issues around discarding. Discarding is just a part of the story about how fisheries affect ecosystems. Combined with other issues, such as the seabed impacts of trawling, it contributes building an understanding of the whole-ecosystem impacts. Fisheries, especially trawl fisheries catch quantities of fish that are below the minimum landings sizes, are not marketable species, or are in excess of landing quotas. Up to 2016 these fish were thrown back into the sea (discarded) without restriction. The EU landing obligation progressively placed limits on discarding, aiming to reduce it to an absolute minimum. The publicity campaign which resulted in the EU adopting a discard ban suggested that discarding was caused by restrictive quota limits that caused fishermen to throw away over-quota catch, and that discarding was a waste of resources. In fact, the majority of discarded fish are undersize or not marketable, and over-quota catch is relatively minor. Also, from a holistic ecosystem perspective discards do not go to waste, they are recycled back into the food web via scavenging birds, mammals, fish and benthos. A study using the new spatial StrathE2E developed in MERP assessed the ecosystem consequences of eradicating the practice of discarding. There are two potential ways of achieving reductions in discarding: 1) carry on catching as usual but bring everything ashore; 2) improve the selectivity of fishing gears so that unwanted fish are no longer caught. The research using the StrathE2E model showed that 'bring everything ashore' had only very small effects on the food web implying that, overall, discards were a trivial contribution to food supply for the food web. Such impacts as there were were mostly negative, affecting the abundance of scavengers. In contrast the 'improved selectivity' strategy had very large impacts on the ecosystem due to the effective reduction in harvesting rates. This created a strong trophic cascade with generally positive effects for fish and top predators. This is strong evidence for implementing a policy of concentrating fishing effort in the most highly impacted areas, which contrasts strongly with advice from conservation organisations that, as the potential for recovery is strongest in the most highly impacted areas, conservation effort should focus on those areas.

Managing trawling effects: StrathE2E

A set of ICES Workshops convened to provide advice to the EU based on the new spatial StrathE2E which was developed as part of MERP. The European Commission's Directorate-General for Environment (DG ENV) asked ICES to "Evaluate indicators for assessing pressure and impact on the seafloor from bottom-contacting fishing. Using this assessment, demonstrate trade-offs in catch/value of landings relative to impacts and recovery potential of the seafloor." Work to produce the ICES advice began in 2016 with the use of international vessel monitoring system (VMS) and logbook data to generate maps of fishing intensity (effort per unit of area). These formed the basis for three interconnected workshops in 2017 – WKBENTH, WKSTAKE, and WKTRADE – which culminated in the ICES advice. The WKBENTH task was to evaluate ways of modelling the sensitivity of different seabed habitats to pressure, and produce maps and indicators for measuring what effect fishing has on the seabed. WKSTAKE took these maps and indicators and, along with information on catches and values of landings, brought together stakeholders to explore how trade-offs could occur. Finally, WKTRADE considered how to inform managers of these trade-offs. The University of Strathclyde contributed to the WKTRADE workshop, with a series of North Sea case study simulations using the MERP StrathE2E end-to-end ecosystem model. Simulations show that the seabed impacts of trawling are cumulative. The more often an area is hit by trawling the lower the biodiversity and biomass. As a result, damage per trawl-hit is low in intensively fished areas. Conversely, damage per trawl-hit is very high in infrequently trawled areas. The ICES advice to the EU was, therefore, that the most efficient way to achieve an improvement in regional seabed integrity indicators is to eliminate trawling in lightly fished areas, and concentrate effort in areas which are already heavily fished. To assess what the direct and indirect effects that this would have on catch, landings and other ecosystem indicators StrathE2E was used. As a result of the StrathE2E modelling carried out during WKTRADE, the ICES advice was issued with the caveat that "interconnectivity of all marine life through food webs means that every management decision will have an effect, sometimes in opposing directions, on every part of the system. It is important that these further ecological consequences are taken into account to reduce the risk that management produces unwanted results". Although the ICES advice was produced as a result of huge collaborative effort involving many strands of evidence, data and modelling, StrathE2E was a key part of this. The work, acknowledging MERP, was presented at AMEMR 2017 (Heath, M., Wilson, R. & Speirs, D. 2017. Modelling the whole-ecosystem impacts of trawling).

Implementing a West of Scotland version of FishSUMS

Modelling the west of Scotland fish community with FishSUMS will provide insight into the nature of trophic interactions and species-level, size structured community responses to fishing pressure. The species we included in the model were those which cumulatively account for 85% of the landed biomass, 85% of total fish biomass estimated from IBTS data, and species present in both data sets up to a cumulative 95% biomass. This totalled 15 species: cod, haddock, whiting, saithe, ling, hake, Norway pout, anglerfish, spotted dogfish, spurdog, herring, mackerel, horse mackerel, blue whiting and Norway lobster. We specified predator-prey links following west of Scotland and Irish Sea diet data and information from FishBase. Lots of data are required to parametrise FishSUMS. Fixed parameters include von Bertalanffy growth parameters, maturation sizes, spawning seasons, fecundity, egg size and development time, and prey-size preferences for each species. These were set at values observed in the west of Scotland or neighbouring seas. FishSUMS is fitted to data on total landings and discards, length measurements, and biomass estimates. We used IBTS data for length measurements, and ICES landings data. Single-species stock assessments providing time series of discards and biomass estimates were available for six of the modelled populations. In line with the Scottish western shelf sea Ecopath model, discards and biomass estimates for other species were extrapolated from data published in geographically wide-ranging stock assessments combined with west of Scotland landings. As many of the discard and biomass estimates are crude they will be treated as guidelines and down-weighted in the model. Fitting parameters include background and density-dependent mortalities and prey preferences for each modelled species. As few species are assessed we also need to estimate time series of fishing mortality rates at age, which massively increases the number of fitting parameters. By specifying fishery selectivity-at-age curves we reduced this to time series of annual fishing mortality rate for each species, but there remain hundreds of fitting parameters. A numerical optimisation scheme is required to fit the model. We are using simulated data from the original North Sea FishSUMS model to test optimisation methods. This work is ongoing, and taking some considerable time as FishSUMS runs in 5 seconds and many thousands of iterations are required. A particle swarm heuristic search method (J. Heuristics (2014) 20:417-452) is showing some promise. Once the North Sea simulated data are fitted successfully we will apply the optimisation algorithm to the west coast model. Further reducing the number of, or constraining, the fitting parameters may prove necessary for successful optimisation or completion in reasonable time. Asides from optimisation, further work on the west coast FishSUMS model should include accounting for migration schedules of mackerel, horse mackerel and blue whiting as these represent large periodic fluxes of biomass in and out of the system which will greatly influence community feeding patterns.

Temporal-spatial effects of bottom-up controls: EwE and Ecopath

EwE and Ecopath have also developed in MERP. The updated EwE model for the West coast of Scotland has been coupled with ERSEM spatial primary productivity outputs. This has been used to assess the. This model is also being linked with top-predator distribution maps supplied by Peter Evans and Kate Searle and with fishing effort (in collaboration with Mike Heath) to elucidate top-down controls on this ecosystem. The new EwE ecosystem model was fitted using fishing and temperature as ecosystem drivers. Future predictions were carried out using fishing mortalities at MSY and rising temperatures (under IPCC scenarios). Cumulative effects of future climate change and sustainable levels of fishing pressure on selected target species were assessed. Results highlighted the importance of including temperature as an ecosystem driver to better advise sustainable fisheries management. Moving forward, the updated EwE model for the West coast of Scotland coupled with ERSEM and top-predator distributions will be used to assess the final goals of MERP: (a) Understanding trade-offs to maximise the benefits from living marine natural capital (Module 7); (b) Cumulative impacts and the management of marine ecosystems (Module 8).

There is an ongoing interest by colleagues (co-authors) at Aberdeen University to use the model in the ClimeFish H2020 project (http://climefish.eu/c5f-west-scotland/). As there is a growing interest in assessing cumulative effects of temperature (and/or climate change) and human impacts the updated version of this Ecopath model will allow us to test temporal and spatial scenarios to advise the management of this marine ecosystem. A paper has been prepared (Serpetti, N., Baudron, A.R., Burrows, M.T., Payne, B.L., Helaouët, P., Fernandes, P.G., Heymans, J.J., submitted. Impact of ocean warming on sustainable fisheries management informs the Ecosystem Approach to Fisheries.) but importantly this study also includes an analysis of the model uncertainties and model validation for Ecopath. Model validations have been rarely assessed in this modelling approach and the results will be used to write an additional publication regarding statistical validations methodology for Ecopath modelling.

Programme deliverables

No.	Deliverable	Date completion	Lead partner	Contributing partners	Deliverable status and accessibility
D1.1	Inventory of large-scale, long-term datasets for major functional groups in the Western Seas, including known sampling issues and biases	(M12)	Sheffield (Webb)	Cefas, BODC, SWF, all MERP	Complete
D1.2	Submit R package for accessing marine taxonomy to CRAN	(M12)	Sheffield (Webb)		R package available https://github.com/MarineEcosystemResearchProgramme/
D1.3	Joint meeting with British Ecological Society Macroecology Special Interest Group & National Biodiversity Network on frontiers in marine macroecology and data	(M18)	Sheffield (Webb)	All M1 and MERP	British Ecological Society Aquatic Macroecology Meeting in collaboration with MERP took place in September 2016
D1.4	Paper on macroecology of major functional groups in the Western Seas: scale dependence and the role of environmental covariates	(M24)	Sheffield (Webb)	Glasgow, SWF	Data collated and analyses in progress in collaboration with Cefas and with SWF. Manuscripts delayed due to SWF PDRA Waggitt taking temporary lectureship, work now complete and manuscripts due end 2018.
D1.5	Submit additional R packages for accessing marine macroecological data to CRAN	(M24)	Sheffield (Webb)	Cefas	R package available https://github.com/MarineEcosystemResearchProgramme/
D1.6	Report on methods for interpolating sampled distribution and abundance data across taxa, and advice on best practice	(M36)	Sheffield (Webb)	Cefas, SWF	Analyses in progress including machine learning and SDMs, in collaboration with Cefas and SWF. Manuscript writing delayed due to PDRA turnover.
D1.7	Report empirical relationships between size spectra and species-level macroecological patterns, and scale-dependence of species abundance distributions across functional groups	(M36)	Sheffield (Webb)	SWF, CEH	Data collated and initial analyses run by PDRA Vergnon prior to his departure but final writing up has stalled since. However collation of species-level body size data for >2000 species and library of code to link this to occurrence data is complete and has been used in ms led by QMUL. ms describing the data in draft form.
D1.8	Report on environmental and biological correlates of regional differences and temporal variation in top-predator communities	(M48)	CEH (Searle)	SWF, Glasgow	Extensive spatial and temporal datasets compiled for major cetacean and seabird species, models linking these to environmental variation at local and regional scales have been run and draft manuscripts are in production.
D1.9	Deliver synthetic data products and tools to BODC in accordance with Research Data Management Plan	(M48-60)	Webb	All	Research Software team at Sheffield engaged, currently cleaning and serving data. Additional large libraries of code for working with marine biodiversity data in final stages of cleaning prior to release in suitable GitHub and FigShare.
D2.1	Report on the quantification of trophic and non-trophic benthic-pelagic coupling pathways for macroalgae-derived carbon sources	(M36)	Burrows (SAMS)	O'Connor (QUB) Quierós (PML) Pinnegar (Cefas)	A range of publications complete this deliverable, including: Latlean et al. *Latitudinal variation in primary productivity of rocky intertidal habitats along the northeast Atlantic*: ms for submission to MEPS Field data still being collected with help of PhD student Abby Gilson. She is also finishing a mesocosm experiment to examine kelp subsidy. Data and metadata to be entered by the end of the year

					SAMS: Several Reports and papers already published, for example Burrows et al (2017) http://www.snh.gov.uk/publications-data-and-research/publications/search-the-catalogue/publication-detail/?id=2453 Based on the MERP UK-wide spring and autumn transects, about 15% of isotopic samples have still to be processed.
D2.2	Report on the dynamics of interactions between gelatinous zooplankton and fish larvae	(M36)	Lindeque (PML)	Atkinson (PML) Hirst (QMUL)	Some work has already been published 10.1093/plankt/fbw023 Main work was molecular work from 7 minicruises from Plymouth. Reference fish were sequenced to plug a gap in reference database. These sequence data have now been submitted to GenBank and are awaiting its publication. Once these sequence data have been added to reference database, OUT will be re-annottated and a manuscript working title "*The dynamics of interactioins between gelatinuous zooplankton and fish larvae: using Next Generation Sequencing to provide insights*" will be written
D2.3	Report on "end to end" pelagic and benthic biomass spectra across regional gradients and seasons	(M42)	Hiddink (Bangor)	Hirst (QMUL) Pinnegar/van der Kooij (Cefas) Quieros/Atkinson (PML)	**PELAGIC data from L4:** Carbon and other trait data have been added to the L4 planktonic database. This has been used in a series of policy reports to OSPAR and is being processed into a L4 plankton biomass spectrum manuscript currently in draft form. It will also provide an input to a synthetic "end-to-end biomass spectrum manuscript. This is in draft form being formatted for Ecology Letters **PELAGIC data from PELTIC**: Sample processing is well underway: data planned for "end to end" biomass spectrum synthesis paper **BENTHIC Biomass spectra** Howarth et al. *Effects of bottom trawling and primary production on the composition of biological traits in benthic assemblages* (Marine Ecology Progress Series, Vol:602, 31-48) doi.org/10.3354/meps12690 Another manuscript in preparation synthesis paper on benthic and pelagic size spectra planned
D2.4	Report on the parameterisation of functional responses of feeding and mortality related to traits	(M42)	Emmerson (QUB – benthic) Atkinson (PML - pelagic)	Emmerson (QUB)	**PLANKTON COMPONENT**: Several trait papers already published: Zooplankton Gut Passage Mobilizes Lithogenic Iron for Ocean Productivity. Current Biology, Volume 26, Issue 19. DOI: http://dx.doi.org/10.1016/j.cub.2016.07

					.058 How does *Calanus helgolandicus* maintain its population in a variable environment? Analysis of a 25-year time series from the English Channel. Progress in Oceanographhttp://dx.doi.org/10.1016/j.pocean.2015.04.028 Questioning the role of phenology shifts and trophic mismatching in a planktonic food web. Progress in Oceanography, Volue 137, Part B, 498-512. http://dx.doi.org/10.1016/j.pocean.2015.04.023 Re-purposed L4 time series (with added trait data) to be sent to BODC before end of project These data contributed to unpublished policy reports to OSPAR **BENTHIC COMPONENT**: Barrios-O'Neil et all. 2018. Trophic cascades and the transient keystone concept. Biological Conservation, Volume 212, 191-195. https://doi.org/10.1016/j.biocon.2017.06.011
D2.5	Parameterization of trophic and non-trophic pathways of carbon assimilation in coastal benthic-pelagic systems in ecosystem models	(M42)	Quierós (PML)	Burrows (SAMS) O'Connor (QUB)	A series of manuscripts are in preparation including one by Quierós with title "Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean" currently in review in Ecological Monographs (accepted for publication). Data will be submitted to BODC on publication of this paper
D3.1	Report empirical values of relevant elasticity indices confronted with analytic results	(M18)	Cefas/UoS	SU	This Deliverable was delayed due to its dependence on input data. It is now included in Deliverable 3.3
D3.2	Joint module 3/4 workshop	(M24)	Cefas/SU	UoS, SAMS, QUB, PML, CEH	Completed March 2016, report available at http://www.marine-ecosystems.org.uk/getattachment/6ac1ab86-570d-4993-b160-229d9153c5da/Module_3_4_mini_workshop_report
D3.3	Manuscript on in-depth comparison between models and macroecological data	(M36)	Cefas, SU	UoS, SAMS, QUB, PML, CEH	Dome patterns in pelagic size spectra reveal strong trophic cascades: Axel Rossberg, Ursula Gaedke, Pavel Kratina (submitted to Nature Communications).
D4.1	Report on model fitting methodology and results	(M18)	Sheffield	Strathclyde, Cefas, SAMS, (PML), (CEH)	Spence MA, Blackwell PG, Blanchard JL. 2015. Parameter uncertainty of a dynamic multi-species size spectrum model Canadian Journal of Fisheries and Aquatic Sciences 73(4), 589-597. 10.1139/cjfas-2015-0022
D4.2	Paper on model skill specifying the selected model ensemble	(M24)	Sheffield	Strathclyde, Cefas, SAMS, (PML), (CEH)	Spence, M, Julia L. Blanchard, Axel G. Rossberg, Michael R. Heath, Johanna J Heymans, Steven Mackinson, Natalia Serpetti, Douglas Speirs, Robert B. Thorpe, Paul G. Blackwell. 2018. A general framework for combining ecosystem models. 10.1111/faf.12310
D4.3	Report on ensemble predictions of ecosystem responses and services across scenarios.	(M36)	Sheffield/PML	Cefas, SAMS, PML, Strathclyde,	Manuscript in preparation. Modelling the effect of fishing levels on commercial fisheries revenue using Bayesian Belief

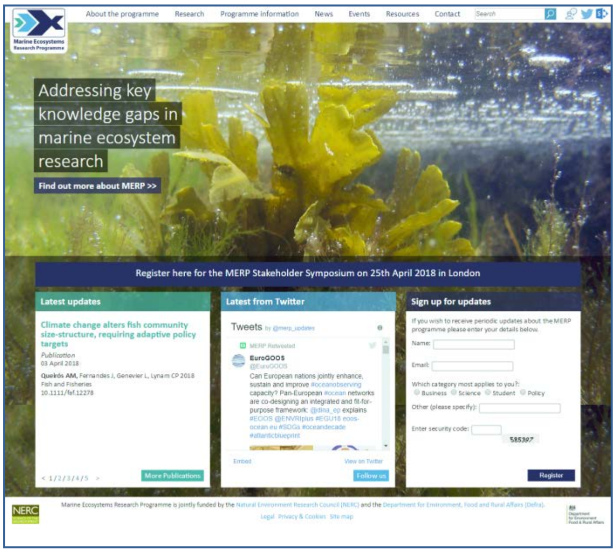
				(CEH)	Networks.
D4.4	Policy report on ecosystem service predictions and uncertainty.	(M42)	PML/Sheffield	Cefas, SAMS, PML, Strathclyde, (CEH)	Some preliminary results.
D5.1	Paper on conceptual models relating ecosystem structure and processes to ecosystem services	(M30)			Broszeit S; Beaumont NF; Hooper TL; Somerfield PJ; Austen MC: Developing conceptual models that link multiple ecosystem services to ecological research to aid management and policy, the UK marine example, Marine Pollution Bulletin. Under revision
D5.2	Paper on analysis of changes in ecosystem services at different spatial and temporal scales	(M42)			Progressed the indicator work to a greater extent in order to help address needs of policy customers regarding MSFD, the Biodiversity Strategy and the Environment White Paper. This, aligned with unforeseen complexities in scenario and ensemble modelling causing delays in generating model outputs that we could use, led to adjustment in the focus of output papers.
D6.1	Published version of the model code – submitted manuscript	(M24)			Available through http://www.pml.ac.uk/Modelling_at_PML/Access_Code, currently has 255 registered users.
D6.1	Community modelling tools available on the web	(M30)			Available through http://www.pml.ac.uk/Modelling_at_PML/Access_Code, currently has 243 registered users. A paper is in prep, proposed submission Jan 2018.
D6.3	Paper(s) on new trait based models - submitted manuscripts	(M30)			**Zooplankton diversity**: paper in prep, proposed submission 2019. Initial results have been presented at the 2016 and 2017 MERP ASMs, AMEMR 2017, and will further be the topic of abn oral presentation at the 2018 Ocean Sciences meeting. **Benthic diversity**: (1) Lessin, Bruggeman, McNeill, Widdicombe "Time scales of benthic macrofaunal response to pelagic production differ between major feeding groups" accepted by Limnology & Oceanography. (2) Paper in prep, proposed submission June 2018. Initial results have been presented at the MERP ASM 2017.
D6.4	Paper on advanced advective methods - submitted manuscripts	(M30)			This work has been replaced by high resolution modelling (1.5 km) of the Celtic Sea. Paper in prep, proposed submission Dec 2018. Initial results have been presented at the MERP ASM 2017.
D6.5	Hindcast simulations and re-analysis simulations, sub sets of the data deposited with appropriate BODC data centre	(M36)			**Analysis of diversity in hindcast simulation with reference ERSEM configuration**: Ford, D. A., van der Molen, J., Hyder, K., Bacon, J., Barciela, R., Creach, V., … Forster, R. (2017). Observing and modelling phytoplankton community structure in the North Sea. Biogeosciences, 14(6), 1419–1444. https://doi.org/10.5194/bg-14-1419-2017 **Simulation with enhanced-diversity configurations**: planned for WP2 phase II, M48-M54
D6.6	Scientific paper(s) on the sensitivity and resilience of shelf	(M42)			As for D6.5, the schedule for enhanced diversity simulations has been reviewed for

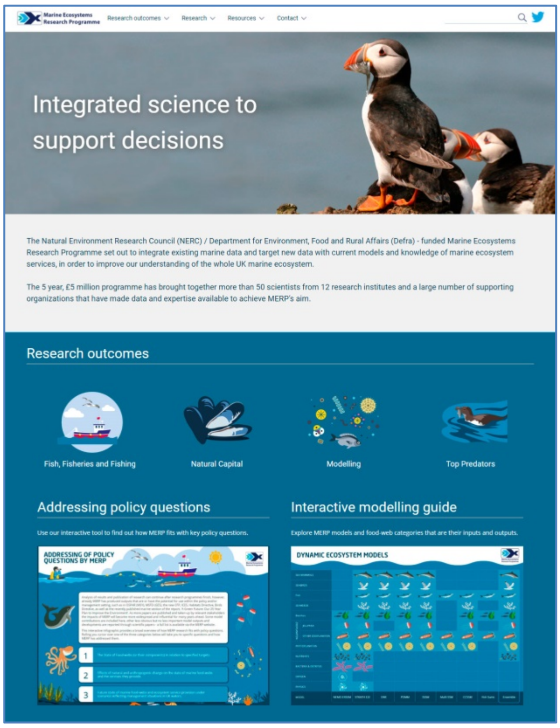
	seas marine ecosystems, to climate change and other anthropogenic drivers – submitted manuscripts				WP2 phase II. Simulation, analysis and publication is now scheduled for M48-M60

MERP Knowledge Exchange and Communications Overview

MERP Website | www.marine-ecosystems.org.uk

The MERP website and redeveloped legacy website have received 22,211 visitors since the launch in June 2014. This breaks down to 79,351 sessions with an average of 2.56 pages per session and an average of 2:14 mins per session. The active project website was regularly updated with news and events relating to MERP while the legacy website has been developed as a user-friendly information platform for stakeholders to easily and quickly find information on MERP research and the associated contacts for areas of work.





It includes infographics on the MERP models and policy questions addressed by MERP scientists. The ultimate aim of this website is to be a starting point for specific discussions relating to policy questions, environmental management queries and other areas of interest to marine stakeholders.

Twitter

The MERP Twitter feed (@merp_updates) has 583 followers and over 86k impressions. The feed has been a great way of disseminating MERP programme information but also sharing the work of the individual MERP scientists as they undertake their research. Top followers include: Copernicus Marine, BBC Wildlife, EU Environment, JNCC, Euro Parliament, Hugh Possingham (Chief Scientist of The Nature Conservancy), Fish farming Expert, Paul Rose (NatGeo), Natalie Bennett (Green Party), UN Environment (Caribbean), Frontiers in Marine Science, Marine Climate Change Impacts Partnership (MCCIP), European Marine Science Educators Association, UK Environment Agency, Macroalgae UK, British Phycological Society, CommOcean, Centre for Environmental Change & Human Resilience, International Marine Conservation Congress, IUCN Red List of Ecosystems, The Wildlife Trusts, Nick Baker (BBC wildlife correspondent), EnviroNews, Severn Estuary Partnership, European Centre for Nature Conservation, Ocean Leadership, ICES, MBARI, MASTS , European Marine Board and WHOI.

Newsletters

5 newsletters were sent during the course of MERP to participants and stakeholders with all the latest news from the programme, to help maintain momentum between stakeholder engagement activities and ensure the participants were aware of the work being undertaken across the programme and partner institutes. The newsletters had an average open rate of 53% by stakeholders (industry average 20%) and an average 21% click-through rate (industry average 2.3%). All MERP Newsletters are available on the website.

Video

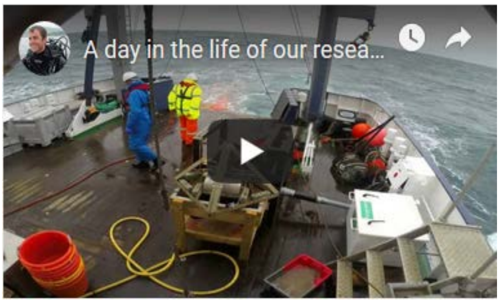
A brief introductory video (https://www.youtube.com/watch?v=8ZHp9ZNORIs) was produced in the early years of MERP to explain the structure of the programme and what it hoped to achieve. To date, it has received 497 views with a watch time of 927 minutes and was received well by the Stakeholder Advisory Group.

Introducing the Marine Ecosystems Research Programme
A video introducing the Marine Ecosystems Research Programme

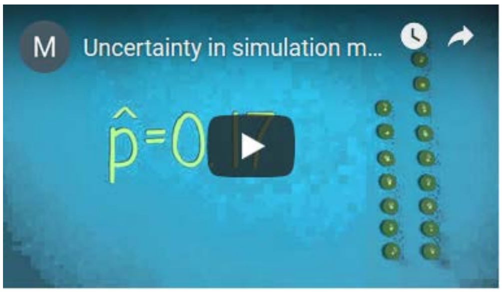
A number of other videos highlight MERP activities were also developed over the lifetime of the project including:

1 minute in the life of a marine biologist
Dr Leigh Howarth attempts to rapidly summarize his research in the Irish and Celtic Sea within just one minute (and fails by 8 seconds)

A day in the life of our research vessel
Time Lapse video of a day on board the RV Prince Madog while carrying out research for the MERP programme.



Uncertainty in simulation models
Michael Spence from the University of Sheffield describes different types of uncertainty found in simulation models.



Infographics
Infographics were created to visually explain the capabilities of the models being used within MERP and the policy question that have been address by MERP science. These are available from the MERP website:

- The MERP Modelling interactive allows users to explore MERP models and the food web categories that are their inputs and outputs.
- The MERP Policy Interactive provides a broad overview of how MERP research fits with policy questions. By clicking one of the three categories users are directed to specific questions and can learn how MERP can help address them.

    1. The State of Food webs (or their components) in relation to specified targets

    2. Effects of natural and anthropogenic change on the state of marine food webs and the services they provide

    3. Future state of marine food webs and ecosystem service provision under scenarios reflecting management situations in UK waters

Summary cards
Five summary cards were created to distill MERP research and outputs into policy-relevant topics, aimed at non-expert stakeholders. The topics were:

- Addressing policy questions
- Top predators
- Modelling
- Natural capital
- Fish, fisheries and fishing

These were launched at the MERP Stakeholder Symposium in April 2018 and are available through the MERP website at http://www.marine-ecosystems.org.uk/Resources.

MERP glossary

A glossary of MERP terms was produced and distributed in the Stakeholder Symposium delegate pack, it is also available on the main website. The aim of the glossary was to define complex or interchangeable term to facilitate understanding by a wide range of stakeholders at the Symposium.

Editorials

As part of the final stages of MERP, a summary of the programme's research and achievements has been published in Ocean Challenge (https://www.challenger-society.org.uk/oceanchallenge/2018_23_1.pdf), the publication of the Challenger Society. 3 more editorials are in progress, aimed at Planet Earth, Marine Biologist and Fishing News.

Integration and Engagement meetings

MERP scientists regularly participate in meetings and workshops with colleagues both internal and external to MERP to discuss and share programme science.

Internal meetings

Monthly MERP Steering Committee meetings were held to monitor and manage progress. There were also several additional meetings for the WP3 projects. These meetings help everyone to keep up to date with each other's activities, plan collaborative work and make sure work plans are on track. In addition the Consortium met in full at our Annual Science Meetings and integration workshops throughout the course of the programme. Reports from project meetings and workshops can be found on the Resources page of the website.

Stakeholder Advisory Group

The Stakeholder Advisory Group (SAG) was established at the start of the Programme to provide advice and guidance on how to maximise the impact of the programme to societal stakeholders (industry, policy-makers etc.). The MERP Management team met with the Chair of the SAG every two months throughout the project and the entire group met at least once annually. SAG meetings were generally held close in time to the Annual Science Meeting allowing SAG members to participate and learn more about ongoing activities. The SAG were given access to all project documentation and outputs, and provided valuable advice on key areas to focus on and ways of targeting sharing information.

The SAG was instrumental in developing the list of key policy questions that MERP research aligned to. These policy questions and the roles MERP science and scientists could play in addressing them were turned into a web based interactive that was launched at the MERP Stakeholder Symposium in April 2018 and is currently available on the MERP website. It is regularly updated as new information becomes available.

Finally the SAG played a key part in developing the MERP Stakeholder Symposium, co-designing the format of the day along as well as sitting on each of the discussion panels and providing input and guidance throughout the day.

Policy engagement

Policy Briefings

Defra: MERP work has been showcased and discussed with Defra through 2 dedicated briefings (2016 and 2017). The briefings showed how MERP outputs can be used to address policy questions concerning the sustainable use of the marine environment. The briefings were chaired by the Defra Head of Evidence and attended by 15 policy customers and 10 MERP scientists. Policy customers confirmed that the policy questions prioritised by the MERP are appropriate and largely cover their evidence needs. In particular, the briefings identified opportunities for the MERP consortium to provide scientific advice proactively to policy-makers. Briefs and related reports available on Resources page of the website.

Natural Resources Wales (NRW): Held in November 2016, MERP hosted a webinar with NRW to target discussions around key issues of interest to Welsh stakeholders. Feedback about this webinar was extremely positive and this approach to stakeholder engagement was supported by all involved. The purpose of this briefing was to discuss MERP research activities with policy customers at NRW and Welsh Government and highlight some examples of existing and planned policy-relevant MERP outputs. The meeting provided opportunities for policy-makers to influence the focus of MERP science, examine the utility of MERP science outputs to policy-makers, to help the MERP consortium maximise the policy-relevance of research products (i.e. to ensure that appropriate and accessible outputs are delivered) and to identify opportunities for the MERP consortium to provide scientific advice proactively to policy-makers. A meeting report is available on the website.

Marine Scotland: MERP scientists (from PML, SeaWatch, Sheffield, Strathclyde) met with Scottish Government and their advisors about ongoing and planned MERP work, including: linking and enriching biodiversity data to assess the state of marine ecosystems and developing virtual marine ecosystems for conducting management scenario experiments. Participants included people from Marine Planning and Policy, Marine Scotland Science, Marine Analytical Unit, Fisheries, Aquaculture and Scottish Natural Heritage. Discussions were focused on understanding the maps of bird and cetacean distributions which are is statistical interpolations of survey data using independent variables to guide the interpolation. Key lessons taken away from the briefing were in how the programme team project and explain their scientific work to stakeholders. It is important to highlight not only the potential relevance to the day to day work of stakeholders but also show how the work could have important future strategic impact. Download meeting report.

Policy Workshops/Events

MERP Stakeholder Symposium – In April 2018 MERP hosted a symposium for a broad range of stakeholders. Throughout the 4-year programme MERP has engaged actively with stakeholders including relevant marine policy formers, managers, regulators, NGOs, and industry. The Symposium was design to allow us to share with stakeholders across the UK how the advances made across MERP could support the broad management and sustainable use of the UK's marine environment.

This meeting focused on 4 key themes, with a session on each which included short presentations followed by panel discussions:

- More understanding – The MERP approach to generating scientific evidence from knowledge, data and tools
- Fishing and marine ecosystems – Addressing the different facets of fishing in the marine ecosystem using the MERP approach for evidence generation
- Marine top predators, people and policy – Generating evidence for assessing the status of, and risks to, marine ecosystems
- MERP, marine space and management – Using information of what is where, when and why to support evidence-based decision-making

The Symposium was attended by over 70 stakeholders from a broad range of agencies and organisations including: ABPmer, Centre for Environmental Data and Recording, Defra, Fishmongers' Company, ICES, JNCC, Marine Biological Association, Marine Management Organisation, Marine Scotland, Scottish Government, Marine Stewardship Council, National Federation of Fishermen's, Organisations, Natural England, NERC, Natural Resources Wales, Peter Barham Environment Ltd, Pew Trust, SACA, Scottish Government, Scottish Natural Heritage, Scottish White Fish Producer's Association, Sea Watch, WWF.

European Marine Board modelling workshop – In July 2017, the European Marine Board (EMB), in association with Plymouth Marine Laboratory (PML), organized an expert workshop 'Towards end-to-end (E2E) marine ecosystem models: R&D needs for ecosystem-based management'. The main purpose of the workshop was to bring together experts in marine ecosystem modelling to assess how such models are currently used as support tools in environmental decision-making and policy-setting. The workshop was co-chaired by MERP scientist Sheila Heymans (SAMS) and over 10 MERP scientists joined the discussions providing their expert advice to help identified research and development needs for developing next generation end-to-end (E2E) marine ecosystem models to meet existing and emerging policy drivers. Community-driven recommendations and key messages from the workshop were taken forward by the EMB Working Group on Marine Ecosystem Modelling into an EMB Policy Brief in which MERP is featured as a case study.

MERP @ COP22 - Dr Ana Queiros from PML attended COP22 (Marrakech, November 2016) to disseminate information about MERP and the role of the marine ecosystem in mitigating climate impacts through locking away carbon dioxide from the atmosphere. She gave presentations, spoke with national and international media outlets and had a strong twitter presence throughout COP22 promoting the work she has been doing through the Marine Ecosystem Research Programme.

Committee on Fisheries, European Parliament, April 2015

The European Parliament's Committee on Fisheries invited MERP's Prof. Mike Heath (UoSt) to present his research on "An ecological approach to implementing the discard ban" to a hearing of experts entitled "How to improve selectivity in the context of the discard ban". Representatives of the Commission were highly interested and engaged in the proceedings.

ICES Working Groups – throughout the programme MERP scientists have provided expert input to a number of **ICES working groups** including; Biodiversity Science, Marine Mammal Ecology, International Pelagic Surveys, WKIRISH3 – Stock assessment workshop, Fisheries Acoustics, Science and Technology.

A new report from the International Council for the Exploration of the Sea (ICES) has been published with contributions from MERP's Prof. Mike Heath. Following an EU request for guidance on how fishing pressure maps could contribute to habitat assessments and a series of ICES expert group workshops, this report was produced to advise on best-practice use of such maps and recommendations on improved environmental management practices. During the 'Trade-Offs' workshop, Mike Heath configured and ran the spatial Strathe2E model of the North Sea to illustrate the whole ecosystem consequences of proposed changes in fishing activity, to alleviate the impact of trawling on the seabed.

Broader Stakeholder engagement

MERP scientists have actively engaged with both academic and non-academic communities throughout the life of the programme, discussing the advances made in our understanding of marine ecosystems and how this knowledge is relevant and useful to stakeholder communities. Through attending national and international workshops, conferences and small working groups MERP scientists have been able to share their expertise and influence global understanding of marine ecosystem function and services and contribute to the development of marine policy and management. The examples below just give a flavour of some of the events MERP scientists have participated in, for a full list of the extensive external engagements activities undertaken by MERP scientists please see Appendix 3.

- Axel Rossberg met with **Defra customers**, where he advised among others on the findings of a recent MERP paper (https://doi.org/10.1093/icesjms/fsw113) on high-level policy options for fisheries management. The meeting took place at Nobel House in London on 11 January 2017 and was organized by Sarah Andrews (Defra). About 24 Defra staff attended. Also presenting where Adrian Farcas (Cefas) and Robert Thorpe (Cefas).
- CEH facilitated liaison between the organisers of the **2018 Round Britain and Ireland Yacht Race** and the MERP community to explore if the MERP community can contribute ideas and capacity for citizen science and promotion of marine science during the event.
- May 2017, SAMS facilitated a **scenario development workshop** held in Glasgow with 23 policy, business and community stakeholders for the West of Scotland.

- MERP's Dr Ana Queirós visited the Plymouth School of Creative Arts to talk to children about careers in marine science, highlighting MERP research and the many ways in which art and science can be linked.

- CEH (Dr Francis Daunt, Dr Kate Searle, Prof. Sarah Wanless) attended a Fisheries Innovation Scotland (FIS) workshop designed to understand how interactions between top predators and their prey may affect the implementation of an ecosystem approach to fisheries management in Scotland. This workshop and its subsequent report (see outputs below) will help to shape future funding by Scottish Government and FIS, having specific relevance to policy questions including:

  - How can we define and describe biodiversity hotspots?
  - How are populations of vulnerable species (cetaceans, seabirds, elasmobranchs etc.) distributed in space and time?
  - Where do key foraging areas for sea birds occur in space and time?
  - How to evaluate cumulative impacts, especially for mobile species (to ultimately create the ability to carry out strategic assessments through marine planning or SEA that consider the capacity of marine mammal and bird populations to cope with cumulative impacts across their biogeographic range)?

Added value

Through securing additional funding from a variety of sources MERP has been able to enhance and add value to areas of the work programme. The list below is not exhaustive but provides examples of some of the key areas where additional funding has contributed to extending MERP activities.

Fisheries
Strathclyde University led a bid including several MERP partners (CEH, CEFAS, SAMS, Bangor/Seawatch) to Fisheries Innovation Scotland and secured funding to conduct a project "Scoping the background information for an Ecosystem Approach to Fisheries in Scottish waters – review of predator-prey interactions with fisheries, and balanced harvesting". The main purpose of the project was to scope the background information on predator-prey interactions with fisheries which will be required to implement an Ecosystem Approach in Scottish waters and identify key areas for further research. The second purpose of the project was to review the social, economic and technical practicalities of implementing a balanced harvesting scheme in Scottish fisheries. The project hosted two intensive workshops to be attended by scientific experts (including several MERP scientists) and representative FIS Board members. Key outcomes of the project were an increased understanding of the issues in the FIS Board and a prioritised catalogue of knowledge gaps and researchable constraints that can be used by FIS and other funding bodies as the basis for directing future research-spend. A full report of the project is available at
https://www.researchgate.net/publication/314446885_Scoping_the_background_information_for_

an_ecosystem_approach_to_fisheries_in_Scottish_waters_Review_of_predator-prey_interactions_with_fisheries_and_balanced_harvesting_Project_report_Fisheries_Innova.

WWF project

As a result of input to the SAG meeting in January, Strathclyde was commissioned to carry out a modelling study for WWF using the MERP-developed StrathE2E, to simulate the ecosystem consequences post-Brexit break-down of fisheries negotiations. The scenario to be used simulates that the UK stakes claim to what it believes to be its entitlement to TAC for fish species in the North Sea, but Norway and the remaining EU states do not yield up any of their quota. As a result, EU vessels are expelled from UK waters and vice-versa, and some stocks are over exploited. Report title: "Risks to fish stocks and wildlife in the North Sea posed by failure of post-Brexit fishery negotiations to reach agreement on quotas and access to UK waters".

Occurrence data

MERP work on enriching occurrence data with biological traits and environmental data has been developed through additional funding secured by University of Sheffield (through Tom Webb) from EMODnet biology to develop data products for a European Atlas of Marine Life (where MERP support will be acknowledged). A gridded data product on thermal tolerance of European marine species is in the final stages of production, and will be accompanied by a manuscript describing the workflow and comparing experimentally-derived and occurrence-derived thermal tolerance (target journal: Ecology Letters). The library of code associated with this work is a MERP legacy that will be publicly available on GitHub as soon as possible.

Top Predators Atlas

Through work achieved during MERP, Peter Evans (SeaWatch) has updated the "Atlas of Cetacean Distribution in Northwest European Seas". The original report was produced in collaboration with JNCC and this has been the main source of reference used by government, NGOs and a wide range of marine stakeholders ever since. The updated version for 2019 will serve as the main reference across NW Europe amongst policy makers, regulators, their advisors, environmental NGOs, and marine-related industries. Defra has provided additional funding for the production of this Atlas.

Publications

MERP currently has produced around 100 peer reviewed publications directly associated with the programme, with many more in the pipeline. Examples of recent publications are listed below, for the full list please refer to the publications section of the website which will updated as new publications are released.

Upcoming publications

Searle KR, Butler A, Bogdanova M, Wakefield E, Bolton M, Bearhop S, Green J, Gremillet D, Hamer K, Votier S, **Daunt F and Wanless S**. Regional distribution and predation pressure of breeding northern gannets in UK waters. *In prep. To be submitted to Journal of Animal Ecology, Spring 2019.*

Searle KR, Butler A, Bogdanova M, Wakefield E, Bolton M, **Wanless S and Daunt F**. Predation pressure of breeding seabirds in UK nearshore waters: changes over the last two decades. *In prep. To be submitted to Journal of Applied Ecology Spring 2019.*

Searle KR, Butler A, **Waggitt J, Evans P**, Bogdanova M, **Daunt F**, Hobbs NT and **Wanless S**. Worse things happen at sea : identifying fundamental environmental drivers of intrinsic population processes in breeding seabirds. *In prep. To be submitted to Ecology in Spring 2019.*

Ainsworth G, Kenter J, O'Connor S, **Daunt F, Young J** (Submitted Nov 2018). A fulfilled human life: sense of place and cultural identity in the marine environment. *Special Issue on "Multiple Values for the Management and Sustainable Use of Coastal and Marine Ecosystem Services", Ecosystem Services.*

Howarth LM, **Blanchard** JP, **Somerfield** PJ, Cendrier M, Maurin C, Allender S, **Waggitt** JJ, **Hiddink** JG (submitted) The effects of trawling and primary production on size-structured in marine benthic systems. *ICES J Mar Sci*

Broszeit S, **Beaumont** NJ, **Hooper** TL, **Somerfield** PJ, **Austen** MC (submitted). Developing conceptual models that link multiple ecosystem services to ecological research to aid management and policy, the UK marine example. *Mar. Pollut. Bull.*

2018

Burrows MT, Fox CJ, Moore P, Smale D, Sotheran I, Benson A, Greenhill L, Martino S, Parker A, Thompson E, Allen CJ. *2018*. **Wild seaweed harvesting as a diversification opportunity for fishermen.** A report by SRSL for HIE.

Cole E, Borger L, Hedenstrom A, Holton M, Piano M. **Waggitt JJ**. Shepard E. *2018*. **Fine-scale movements and habitat selection of diving birds in tidal waters as measured with an Ornithodolite.** Integrative Zoology 10.1111/1749-4877.12327

Cornwell L, Findlay H, **Fileman E**, Smyth T, **Hirst A**, Bruun J, **McEvoy A**, **Widdicombe C**, Castellani C, Lewis C, **Atkinson A**. *2018*. **Seasonality of *Oithona similis* and *Calanus helgolandicus* reproduction and abundance: contrasting responses to environmental variation at a shelf site.** Journal of Plankton Research 10.1093/plankt/fby007

Fanjul A, Iriarte A, Villante F, Uriarte I, **Atkinson A**, Cook K. *2018*. **Zooplankton seasonality across a latitudinal gradient in the Northeast Atlantic Shelves Province.** Continental Shelf Research 49-62. 10.1016/j.csr.2018.03.009

Fu CH , Travers-Trolet M, Velez L, Gruss A, Bundy A, Shannon LJ, Fulton EA, Akoglu E, Houle JE, Coll M, Verley P, **Heymans, JJ**, John E, Shin YJ. *2018*. **Risky business: The combined effects of fishing and changes in primary productivity on fish communities.** ECOLOGICAL MODELLING 265-276. 10.1016/j.ecolmodel.2017.12.003

Guy-Haim T, Lyons D, Kotta J, Ojaveer H, **Queirós A**, Chatzinikolaou E, Arvanitidis C, Como S, Magni P, Blight A, Orav-Kotta H, **Somerfield PJ**, **Crowe T,** Rilov, G . *2018*. **Diverse effects of invasive ecosystem engineers on marine biodiversity and ecosystem functions – a global review and meta-analysis.** Global Change Biology 10.1111/gcb.14007

Horne CR, **Hirst AG,** Atkinson D. *2018*. **Insect temperature-body size trends common to laboratory, latitudinal and seasonal gradients are not found across altitudes.** Functional Ecology 948-957. 10.1111/1365-2435.13031

Howarth LM, **Somerfield P, Blanchard J, Hiddink JG**. *2018*. **Celtic and Irish Sea benthic biomass size spectra data collected across gradients in fishing pressure and primary productivity.** British Oceanographic Data Centre - Natural Environment Research Council 10.5285/674d4224-7cc5-4080-e053-6c86abc0626e

Howarth LM, Bolam SG, **Waggitt JJ**, Bolam GG, Egglerton J, **Somerfield, PJ, Hiddink JG**. *2018*. **The effects of bottom trawling and primary production on the biological traits composition of benthic assemblages.** Marine Ecology Progress Series p31-48 . 10.3354/meps12690

Howells RJ, Burthe S, Green JA, Harris MP, Newell MA, Butler A, **Wanless S. and Daunt F**. 2018. Pronounced long-term trends in year-round diet composition of the European shag *Phalacrocorax aristotelis*. Marine Biology. DOI: 10.1007/s00227-018-3433-9

Ingels, J, dos Santos G, Hicks N, Vazquez YV, Neres PF, Pontes LP, Amorim MN, Román S, Yongfen D, Stahl H, **Somerfield PJ, Widdicombe S**. *2018*. **Short-term CO_2 exposure and temperature rise effects on metazoan meiofauna and free-living nematodes in sandy and muddy sediments: Results from a flume experiment.** Journal of Experimental Marine Biology and Ecology. 10.1016/j.jembe.2017.07.012

Kaiser ML, Hormbrey S, Booth JR, Hinz H and **Hiddink JG**. *2018*. **Recovery linked to life history of sessile epifauna following exclusion of towed mobile fishing gear.** Journal of Applied Ecology 1060-1070. 10.1111/1365-2664.13087

Keys M, Tilstone G, Findlay HS, **Widdicombe CE**, Lawson T. *2018*. **Effects of elevated CO2 and temperature on phytoplankton community biomass, species composition and photosynthesis during an experimentally induced autumn bloom in the western English Channel.** Biogeosciences 3203-3222. 10.5194/bg-15-3203-2018

Lessin G, Artioli Y, Almroth-Rosell E, **Blackford JC**, Dale AW, Glud RN, Middelburg JJ, Pastres R, **Queirós AM**, Rabouille C, Regnier P, Soetaert K, Solidoro C, Stephens N, Yakushev E.. *2018*. **Modelling Marine Sediment Biogeochemistry: Current Knowledge Gaps, Challenges, and Some Methodological Advice for Advancement.** Front. Mar. Sci. 10.3389/fmars.2018.00019

Lieber LL, Nimmo-Smith WAM, **Waggitt JJ**, Schmitt P, Kregting L. *2018*. **Fine-scale hydrodynamic metrics underlying predator occupancy patterns in tidal stream environments.** Ecological Indicators 397-408. 10.1016/j.ecolind.2018.06.071

Martino S, Tett P, **Kenter J**. *2018*. **The interplay between economics, legislative power and social influence examined through a social-ecological framework for marine ecosystems services.** Science of the Total Environment 1388-1404 . 10.1016/j.scitotenv.2018.09.181

Maud JL, **Hirst AG, Atkinson A, Lindeque P,** McEvoy AJ. *2018*. **Mortality of Calanus helgolandicus: Sources, differences between the sexes and consumptive and nonconsumptive processes.** LIMNOLOGY AND OCEANOGRAPHY 1741-1761. 10.1002/lno.10805

Peck MA, Arvanitidis C, **Butenschön** M, Melaku Canu D, Chatzinikolaou E, Cucco A, Domenici P, Fernandes JA, Gasche L, Huebert KB, Hufnagl M, Jones MC, Kempf A, Keyl F, Maar M, Mahévas S, Marchal P, Nicolas D, **Pinnegar** JK, Rivot E, Rochette S, Sell AF, Sinerchia M, Solidoro C, **Somerfield** PJ, Teal LR, Travers-Trolet M, van de Wolfshaar K. *2018*.
Projecting Changes in the Distribution and Productivity of Living Marine Resources: A Critical Review of the Suite of Modeling Approaches used in the Large European Project VECTORS. Est. Coast. Shelf Sci. 10.1016/j.ecss.2016.05.019

Queirós AM, Fernandes J, Genevier L, Lynam CP. *2018*. **Climate change alters fish community size-structure, requiring adaptive policy targets.** Fish and Fisheries 1-9. 10.1111/faf.12278

Schmidt K, Brown A, Belt S, Ireland L, Taylor W, Thorpe S, Ward P, **Atkinson A**. *2018*.
Do pelagic grazers benefit from sea ice? Insights from the Antarctic sea ice proxy $IPSO_{25}$
Biogeosciences 10.5194/bg-15-1987-2018

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Appendix 1. West of Scotland narratives and simulation results for each of the four NEA worldviews analysed by the project (Module 7)

National Security

Storyline
National Security is driven primarily by increasing global energy and resource prices that force most countries to seek greater self-sufficiency and efficiency in many of their core industries. This is not an easy transition for the UK and it relies on a heavy government hand in setting policy for ecosystem service provision and in creating a competition-free environment for industry within the UK. Trade barriers and tariffs have been increased to protect jobs and livelihoods. Technological development is state funded and many industries are subsidised. Food, fuel, timber and mineral resources are prioritised over conservation of biodiversity. Economic growth is low and every last resource in the UK is utilised for the provision of services. Resource consumption is curbed but more out of economic necessity than environmental concern.

Stakeholder perspectives & cultural values
Cultural values most commonly related to systems of governance and anthropogenic drivers. Some interviewees appreciated that in this scenario the UK aims becomes a more self-dependent nation, and some similarities were drawn to aspects of Local Stewardship in terms of relying on UK food and renewable energy production. Most appealing was the notion of UK fish stocks being protected from foreign vessels as some thought this could lead to more sustainable fisheries management either through implementation of fairer quotas or a grid system. This could provide greater livelihood security for fishermen if managed appropriately. However, others considered this worldview insular or unfeasible because the UK is a low producer and high consumer country which currently exports most fish produce overseas due to a lack of market value at home and increasing trade tariffs may make it more difficult to sell produce overseas. Some interpreted this worldview as short-sighted and creating difficulties for people for example due to a lack of freedom of choice, the impact of high energy costs on health and wellbeing, decreasing opportunities for leisure and tourism and over-exploitation of natural resources.

Model assumptions/inputs
Fisheries: The main targeted fish stocks are harvested at maximum sustainable yield. By-catch species are fully utilized with no discarding – undersize and unwanted species landed for fishmeal to support aquaculture. Even by-catches of marine mammals are fully utilised rather than being discarded.
Conservation: No implementation of no-take-zones/marine protected areas. No concerns about by-catch rates of marine mammals and birds. No by-catch mitigation measures enforced.
Aquaculture**:** increase from the baseline up to 250,000 t per year based on increase in the taste for salmon or higher export. Nutrient emissions to inshore waters commensurate with production.
Seaweeds**:** a production of 60,000 t per year, similar to French production. This amount is insufficient for the French industry but reasonable for the nascent UK seaweed industry. Price of seaweed at £42 in 2010 currency, cost of vessel £500 per day following French figures.
Fish prices and costs of fishing**:** import tariffs and hence reduced imports of fish products lead to increased first-sale prices of fish and shellfish by a factor of 1.66 compared to the baseline using the FAO Food Price Index. Fuel costs also increase by factor of 1.25 from the

baseline calculated from change in demand of petroleum as reported by NEA for the current scenario.

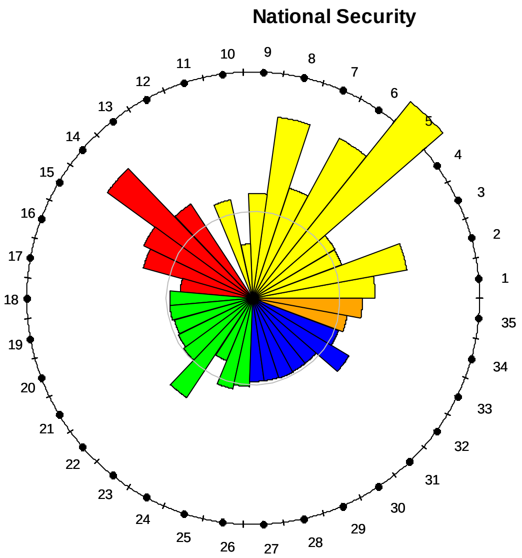
Model predictions

Fisheries and biodiversity

In terms of the response of the bulk biomass groups in the model, StrathE2E suggests that the zooplankton, planktivorous fish, bird and cetaceans groups all show increases in abundance relative to the baseline in this scenario, while benthos, demersal fish and seal groups show decreases. This reflects the relaxation of demersal fish predation pressure due to increased fishing, so that the pelagic system can increase in productivity. To this extend, the response is a more extreme version of Nature at Work and Local Stewardship. Both models show high by-catches of top predators – in this scenario bycatches of cetaceans and seals are landed rather than being discarded. Both StrathE2E and EwE show decreases in the biomass of the migratory pelagic group due to the MSY-level fishing effort. For the demersal fish group, both models show increased catches and reduced biomass relative to the baseline. EwE predicts that cod is lost from the community of species, and whiting reduced to an extremely low biomass. The demersal community become dominated by saithe, haddock and hake, so there is a loss in diversity. The benthos biomass is markedly reduced relative to the baseline in StrathE2E due to pelagic fish predation on their larvae and the slightly increased fishing pressure. EwE shows no noticeable change in the species composition of the benthos.

In this scenario fisheries as a whole runs at a loss, but the pelagic and shellfish gears run at profit. Thus, the results imply some structural issues that would need to be addressed in the fishery by way of subsidies or cost reductions in order to sustain an economically viable demersal fishing fleet; however subsidies are consistent with the storyline of this scenario.

In terms of environmental impact this worldview results in overall higher seabed abrasion rates than the baseline, but biased offshore. So the impact in inshore waters may be slightly less. This arises from the dynamic distribution of fishing gears between inshore and offshore waters in theStrathe2E model in response to patterns of catch rates and profits.



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14	Seal catch ratio	31	Welfare of divers
15	Bird catch ratio	32	Welfare of wildlife watchers
16	Seabed abraded area ratio	33	TLR consumer suplus change
17	Inshore/total area abraded	34	Consumption of aqua products
		35	Aquaculture profits

Segment lengths are proportional to the ratio of scenario : baseline values.
Inner grey circle represents the baseline (scenario:baseline ratio = 1)

Aquaculture
Salmon price increases by 3.14%, while salmon demand increases by 31.66% (+42,271 t/year) because of higher prices and less consumption of wild fish.

Tourism, leisure and recreation
Reduction in seals and increase in seabirds and whales lead to a net increase of 707 wildlife watchers and no change for divers and anglers. Negligible welfare change for anglers and divers, but positive for wildlife watchers (+£1.04per trip). Total use values are £m 205.5.

Non-use value (including option values) for wildlife watchers increases by £24k/y as a result of an increase in whales biomass compared to the baseline.

Economic values (annual, £million*)

Fisheries	Profit	-180.23
Aquaculture		385.09
Seaweed		0.468
Wildlife watching	Change in consumer surplus – use values	0.197
Angling		
Diving		
Wildlife watching	Change in consumer surplus – non-use & option values	0.024

* Adjusted to 2010 consumer price index.

World Markets

Storyline
World Markets is driven by the push for economic growth through the complete liberalisation of trade. International trade barriers have dissolved. Consumption in society is high, which results in greater resource use and more imports. This means that biodiversity is often the loser. Technological development in all industries is mainly privately funded and is burgeoning. Food production has benefited from technological development and intensification and food is cheap and plentiful, but mostly of low quality. Land and sea are mainly seen as resources for exploitation and there is little effort to manage them sustainably.

Stakeholder perspectives & cultural values
Cultural values most commonly related to systems of governance and anthropogenic drivers. Interviewees strongly disliked the emphasis on commercial pressure and political influence which they saw as potentially leading to decisions that are ‘unnecessarily unhelpful’ to environmental protection and management, such as increased, profit-driven extraction of natural resources, and a lack of consideration for the wellbeing of future generations. Several feared this worldview would destroy local economies and communities. For example, a decline in water quality was described as detrimentally impacting on the significant benefits that surfing and tourism can bring to an area, while competing in world markets would encourage cheaper exports and cheap labour which would diminish disposable income. It was suggested that mental health and cultural identity would suffer as a direct result of degraded marine environments. Some uncertainty was expressed about the future of fish exports post-Brexit and the impact on local fisheries. However, others identified positively with reduced restrictions on use of natural assets for example to be able to offer a stable, regular supply of produce, especially if such activities were monitored or certified for appropriate environmental management.

Model assumptions/inputs
Fisheries: Unregulated, open access, with no rules and no quotas. Effort by each gear governed by profit margins (StrathE2E), or set at 160% of that required to deliver maximum sustainable yield (EwE). Discarding as in the 1990’s, no application of technology to limit by-catches of top predators.
Conservation: No marine protected areas, and no constraints governed by environmental impacts, by-catches or discards.
Aquaculture**:** Expansion of production to cope with the increase in world production. Targeted 300,000 ton as expected to be achieved in at least 20 years, considering the slow pace of production recorded in the last 10 years owing to space limits and environmental issues. Nutrient emissions to inshore waters commensurate with production implemented in the Strathe2E model.
Seaweeds**:** 90,000 t per year production justified by demand by the global pharmaceutical industry. Price of seaweed are £42 in 2010 currency, cost of vessel £500 per day as per French figures.
Fish prices and costs of fishing**:** According to NEA, first-sale prices of fish and shellfish are set at 166% of baseline using the FAO Food Price Index. Fuel costs reduced at 81.2% of baseline calculated from change in demand of petroleum.

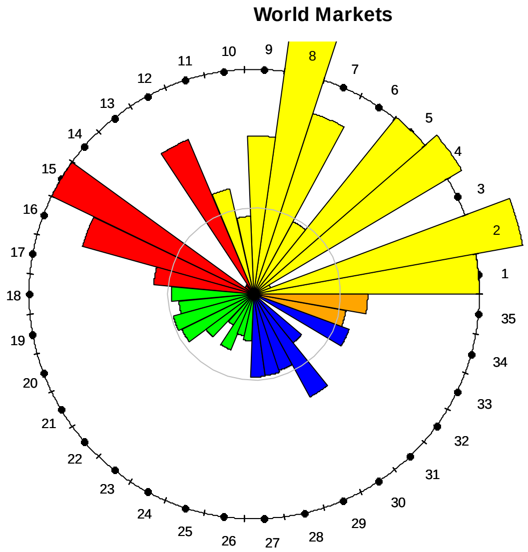
Model predictions
Fisheries and biodiversity
This scenario has by far the greatest negative impact on the food web. The method of representing fishing effort in this scenario is different for the two models. In StratheE2E a dynamic open access scheme is used to represent the changes in given economic rules. In EwE the effort is set at 160% of maximum sustainable yield. Hence, StrathE2E gives a more

extreme outcome – the entire top part of the food web, from fish upwards, is substantially decreased relative to the baseline and carnivorous zooplankton in effect become the main predator group. All the benthos groups also show declines. The majority of the fishery revenue flows from migratory fish and molluscs – here we have to suggest that the large increase in landings of filter and deposit feeding benthos are supported by harvesting currently unexploited species in the region such a mussels. As expected, profit margins for the fishery as a whole are reduced to zero as this is the stable solution to the dynamic fleet model in this case, following the 'invisible hand' of supply and demand operating here. EwE gives a less extreme version of these events. Catches remain high but because fishing effort is fixed (albeit at a high rate), it cannot increase to the point where the food web is severely depleted. So there remain significant populations of top-predators and by-catch of the same. Nevertheless, both cod and whiting have disappeared in the EwE model results and the demersal fish community is dominated by saithe and hake.

Economically the fishery as whole breaks even, but many of the gears have become extinct in the system so there is a significant loss of diversity in the fleet.

In terms of environmental impact this is by far the most damaging of the scenarios with extreme seabed abrasion and by-catch mortality rates especially on birds.

Although this scenario has the highest aquaculture production and hence nutrient emissions in inshore waters, the impact on nutrient concentration and primary production in the model is negligible. There is an impact of sediment pore-water nutrients, but this is related to the high seabed disturbance rather than the emissions.



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16	Seabed abraded area ratio	33	TLR consumer suplus change
17	Inshore/total area abraded	34	Consumption of aqua products
		35	Aquaculture profits

Segment lengths are proportional to the ratio of scenario : baseline values.
Inner grey circle represents the baseline (scenario:baseline ratio = 1)

Aquaculture
Salmon price is expected to be -6.46%, and salmon demand to increase by 38.83% (+35,248 t/year) because of substitutability effect for increased wild fish price.

Tourism, leisure and recreation
Reduction in seals, whales and seabirds causes negligible positive changes in the number of anglers (37/y), and negative changes in diver numbers (- 46/y) but a more substantial decreases with wildlife watchers (- 2,871/y) compared to baseline. There is a negative

welfare change for wildlife watchers (-£4.22 per trip) and divers (-£3.73 per trip), but positive for anglers (£2.35 per trip) because of the reduction in seals. Because there are far more sea anglers than divers and wildlife watchers, the net total use value increases by £ 0.491m/y.

Aggregate non-use value (including option values) for wildlife watchers decreases as a result of the loss of whales, by £70,000.

Economic values (annual, £million*)

Fisheries	Profit	0
Aquaculture		419.09
Seaweed		0.702
Wildlife watching	Change in consumer surplus – use values	0.491
Angling		
Diving		
Wildlife watching	Change in consumer surplus – non-use & option values	-0.070

* Adjusted to 2010 consumer price index.

Nature at Work

Storyline
Nature at Work is a scenario where population growth and the adoption of new technologies are dominant driving forces. Maintaining and enhancing the output of ecosystem services in response to climate change is a key priority and society accepts that trade-offs are necessary to achieve it. Conservation of habitats and species remains desirable, but not at the expense of wider benefits. Society takes a pragmatic view that values nature for what it provides or does and accepts the need to create multifunctional landscapes to maintain ecosystem services and quality of life. 'Balanced service provision' is key and many ecosystem services are the result of careful evaluation of the trade-offs through scientific and community review.

Stakeholder perspectives & cultural values
Cultural values most commonly related to systems of governance and human wellbeing. Many interviewees talked about Nature at Work in relation to physical, energy and livelihood security and comments were mostly positive in this respect. This worldview was viewed as favourable because it appears to balance environmental protection and appreciation with increased employment opportunities across a range of industries (fisheries, aquaculture, leisure & tourism and renewable energy), which subsequently benefits the broader community and promotes human wellbeing. In particular, marine renewables were considered a pragmatic means of harvesting marine energy and were associated with conservation via fisheries exclusion zones, allowing fish to reproduce and spill over. However, there was uncertainty about the trade-offs between biodiversity, food and energy provision indicating that impact assessments would be required. It was suggested that better managed fleets based on days at sea allowing fishermen to land what they catch rather than based on quotas could improve working conditions for fishermen and increase market opportunities by valuing more diverse species of fish. The emphasis on tourism and recreation and protected landscapes were highlighted as beneficial to nature and human wellbeing but doubts were expressed about how this would be managed effectively. Some described this worldview as potentially offering a practical solution to ensuring sustainable economic development while others described it as utopian due to not being financially sustainable or unfeasible because the natural environment was seen as too degraded to support a modern human economy.

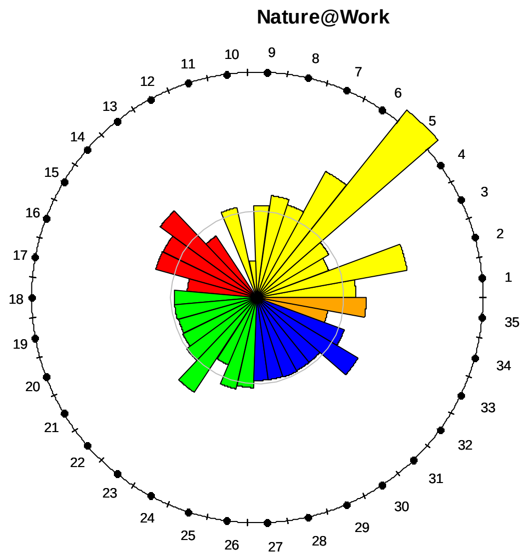
Model assumptions/inputs
Fisheries: Main targeted fish stocks harvested conservatively at 80% of maximum sustainable yield. Improved selectivity results in no catch of undersized demersal fish, and no over-quota discarding allowed.
Conservation: 15% of the area of inshore waters set aside as no-take-zones. By-catches rates of marine mammals by selected gears reduced by 50% through the use of mitigation measures (acoustic deterrents, pop-up creels).
***Aquaculture*:** we assume an increase from the baseline up to 250,000 t per year (similar to the National Security scenario). Nutrient emissions to inshore waters commensurate with production.
***Seaweeds*:** we can expect for a nascent industry a production of 30,000 t per year; this is justified considering that this harvest shows economic feasibility and can be considered a benchmark for the nascent industry. Price of seaweed are £42 in 2010 currency, cost of vessel £500 per day as per French figures.
***Fish prices and costs of fishing*:** According to NEA, first-sale prices of fish and shellfish are set at 53% of baseline using the FAO Food Price Index.
Fuel costs also reduced at 62.5% of baseline calculated from change in demand of petroleum as reported by NEA for the current scenario.

Model predictions

Fisheries and biodiversity

This scenario is in-between Local Stewardship and National Security in terms of fishing effort, and the ecosystem response is consistent with that. With high demersal fish landings, the predation pressure on the pelagic stocks is reduced so their productivity can increase. Despite the levels of effort, seabed abrasion in the StrathE2E results are similar to the baseline due to the emergent pattern of effort across gears. By-catch rates of cetaceans and seals are similar to the baseline despite the higher fishing effort, due to the combination of effort pattern and the presence of by-catch mitigation measures in this scenario. In the EwE model, cod is significantly reduced relative to the baseline, but not extinct, while whiting shows a strong recovery. Herring remains at similar levels to the baseline. Demersal catches are dominated by saithe, haddock, flatfish and hake.

In terms of economics, the fishery as whole operates at a loss, with only the pelagic trawls/seines and mollusc dredges able to make a profit. Hence Nature at Work implies subsidy or restructuring of fishing operations to reduce costs especially in the demersal sector.



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		35	Aquaculture profits

Segment lengths are proportional to the ratio of scenario : baseline values.
Inner grey circle represents the baseline (scenario:baseline ratio = 1)

Aquaculture

Salmon price is expected to increase by 3.14%, and salmon demand to reduce by 25.58% (-34,533 t/year) because of substitution effects with cheaper wild fish.

Tourism, leisure and recreation

Reduction in seals and increase in seabirds and whales causes an increase in the number of wildlife watchers (879/y), but no change in anglers and divers. Compared to baseline, negligible welfare change is expected for anglers and divers, but positive for wildlife watchers (+£1.31 per trip). Total increase in use value is £0.249 million – more than National Security but less than Local Stewardship and World Markets.

Non-use value (including option values) for wildlife watchers also follow this ranking compared to the other scenarios, improving by £28,000 due to the increase in biomass of cetaceans.

Economic values (annual, £million*)

Fisheries	Profit	-272.29
Aquaculture		385.08
Seaweed		0.234
Wildlife watching Angling Diving	Change in consumer surplus – use values	0.249
Wildlife watching	Change in consumer surplus – non-use & option values	0.028

* Adjusted to 2010 consumer price index.

Local Stewardship

Storyline

Similar to National Security, Local Stewardship is driven by growing pressures around energy and resources, but society has made a more conscious effort to reduce the intensity of economic activity. People understand the need to think and act differently and want to be responsible for managing resources for the future. Political power has been devolved and many major issues are decided at a regional or local level. Local resource production is encouraged and there is great pride in the varied local food products. Consumption has reduced to more sustainable (and healthy) levels and societal equity fits alongside environmental equity. Technology supports sustainability and its development and is driven by a mix of private innovation and government funding. Increased local specialisation means that the UK is now less homogenised. Economic growth is slow but the economy is stable. This storyline is the most rural and as localism is a dominant paradigm in society, people have a strong 'sense of place'.

Stakeholder perspectives & cultural values

Cultural values most commonly related to systems of governance and human wellbeing. Interviewees perceived a positive relationship between local empowerment, responsibility/accountability and livelihood security. Communities were said to be more motivated and to function well when they have a real connection to their environment through sense of place and pride in diverse local produce. Devolution was mostly viewed positively with those directly receiving ecosystem benefits best placed to manage them, because they value them more highly and would want to ensure their sustainability. However, placing this additional responsibility on local government may stretch already limited resources. Many favoured the idea of introducing local fishing quotas and of increasing the market value of locally caught fish species as a sustainable means of helping local communities beyond provisioning and tourism. However, increases in number of vessels in coastal waters need to be managed to avoid over-exploitation of resources and local management of fisheries could be seen as protectionism. Some thought the emphasis on local distinctiveness and locally grown produce could be perceived as inward-looking and may not work for communities with less access to suitable natural resources. A greater emphasis on integrated aquaculture-farming practices was viewed positively if properly managed and if diverse stakeholder views were considered.

Model assumptions/inputs

Fisheries: Overall Total Allowable Catch set to correspond with 50% of maximum sustainable yield. Technical measures and other selectivity improvements to reduce the fishing mortality on cod and increase on saithe. Improved selectivity results in no catch of undersized demersal fish, and no over-quota discarding allowed.
Conservation: 50% of the area of inshore waters set aside as no-take-zones. By-catch rates of marine mammals by selected gears reduced by 50% through the use of mitigation measures (acoustic deterrents, pop-up creels).
Aquaculture**:** production of 200,000 t per year, slightly higher than current production (180,000 t in 2018). Nutrient emissions to inshore waters commensurate with production.
Seaweeds**:** production of 15,000 t per year, the lowest viable to be extracted using the technical and economic model adopted in Brittany. Price of seaweed set at £42 in 2010 currency, cost of vessel £500 per day (based on French figures).
Fish prices and costs of fishing*:* following NEA assumptions, first-sale prices of fish and shellfish are set at 39% of baseline using the FAO Food Price Index. Fuel costs are set at 109% of baseline calculated from change in demand of petroleum as assumed by NEA for the current scenario.

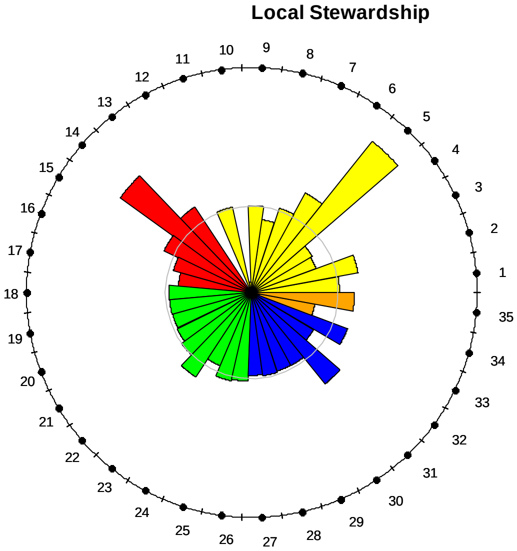
Model predictions

Fisheries and biodiversity

The StrathE2E model suggests that the zooplankton, planktivorous fish, bird and cetaceans groups all show increases in abundance relative to the baseline in this scenario, while benthos, demersal fish and seal groups show decreases. This reflects the relaxation of demersal fish predation pressure due to increased fishing, so that the pelagic system can increase in productivity. Both models show by-catches of cetaceans and seals, increasing relative to baseline. Their catch ratios (proportion of biomass taken) also increase despite the presence of mitigation measures, due to their increase in biomass and the higher fishing activity. The corresponding EWE model simulation shows that cod and whiting both increase as a percentage of demersal biomass in this scenario, while saithe and hake biomass (and predation pressure) are reduced relative to the baseline due to the selectivity changes induced in the fishing gears. Herring, on the other hand, make up as smaller proportion of the pelagic biomass than in the baseline, and sprat show a large increase.
In the benthos, the models disagree on the response. EwE shows an increase in biomass relative to the baseline, while StrathE2E shows a decrease, at least for the carnivore/scavenge feeding group. The two models represent the benthos rather differently – StrathE2E includes the larval stages of benthos, which are predated on by pelagic fish, and this top-down predation effect seems to be responsible for the difference in response here. EwE does not differentiate between larvae, juveniles and adults and can therefore not represent this interaction.

All gears run at a loss in this scenario, so fishing is not sustainable without subsidy or significant changes in fishing practices to reduce costs per unit of activity.

In terms of seabed impacts, this is the most environmentally friendly, with the area ratio of abrasion being the lowest of all cases, and lower than the baseline – especially inshore which is to be expected given the presence of the large no-take zone area in the model setup.



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Segment lengths are proportional to the ratio of scenario : baseline values.
Inner grey circle represents the baseline (scenario:baseline ratio = 1)

Aquaculture

Salmon price is expected to increase by 15% and salmon demand to decrease by 30% (-54,567 t/yr).

Tourism, leisure and recreation

Increase in seals and seabirds causes a very small but positive change in the number of divers (+81/y) compared to baseline and no change for anglers, but decrease in whales leads to a reduction in wildlife watchers (-225/y). No welfare change expected for anglers, with a minor negative change for wildlife watchers (-£0.32 per trip), but a substantial positive change of £ £8.63 for divers.

As a result, the aggregate consumer surplus in this scenario (around £0.5m/yr) is the highest of all scenarios.

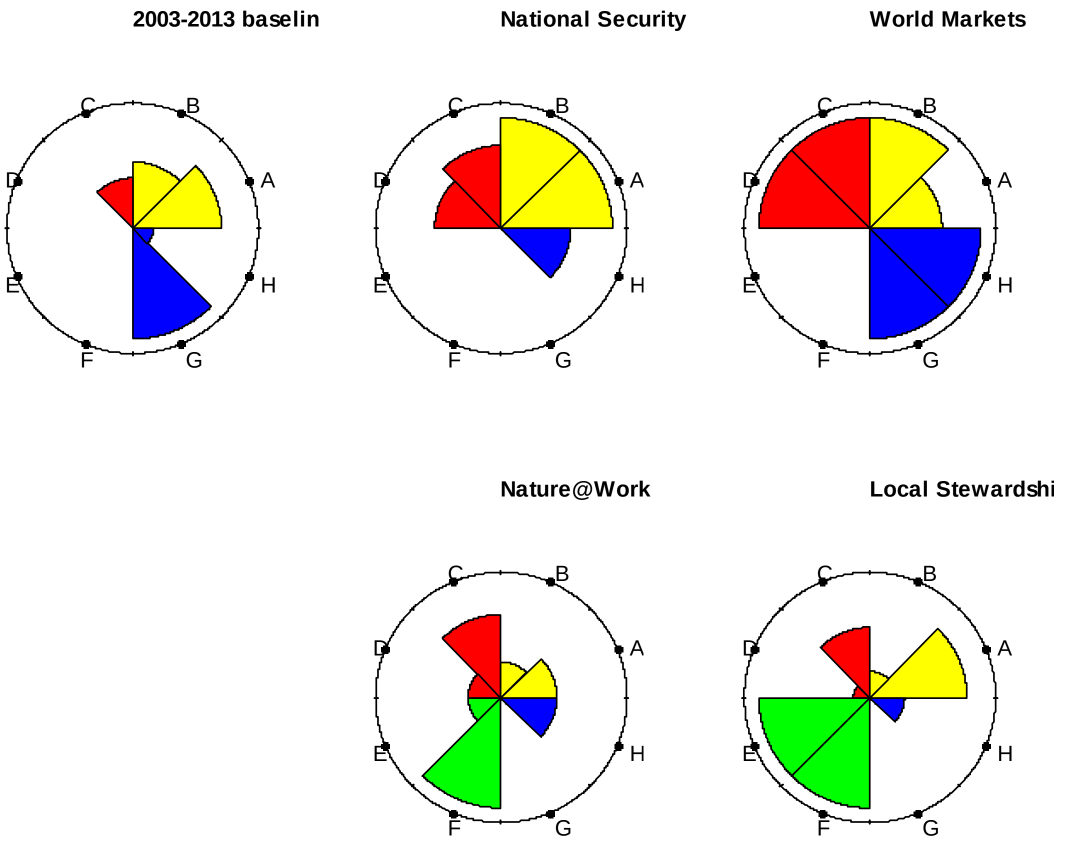
Economic values (annual, £million*)

Fisheries	Profit	-343.60
Aquaculture		343.46
Seaweed		0.117
Wildlife watching Angling Diving	Change in consumer surplus – use values	0.523
Wildlife watching	Change in consumer surplus – non-use & option values	-0.010

* Adjusted to 2010 consumer price index.

Scenario comparison

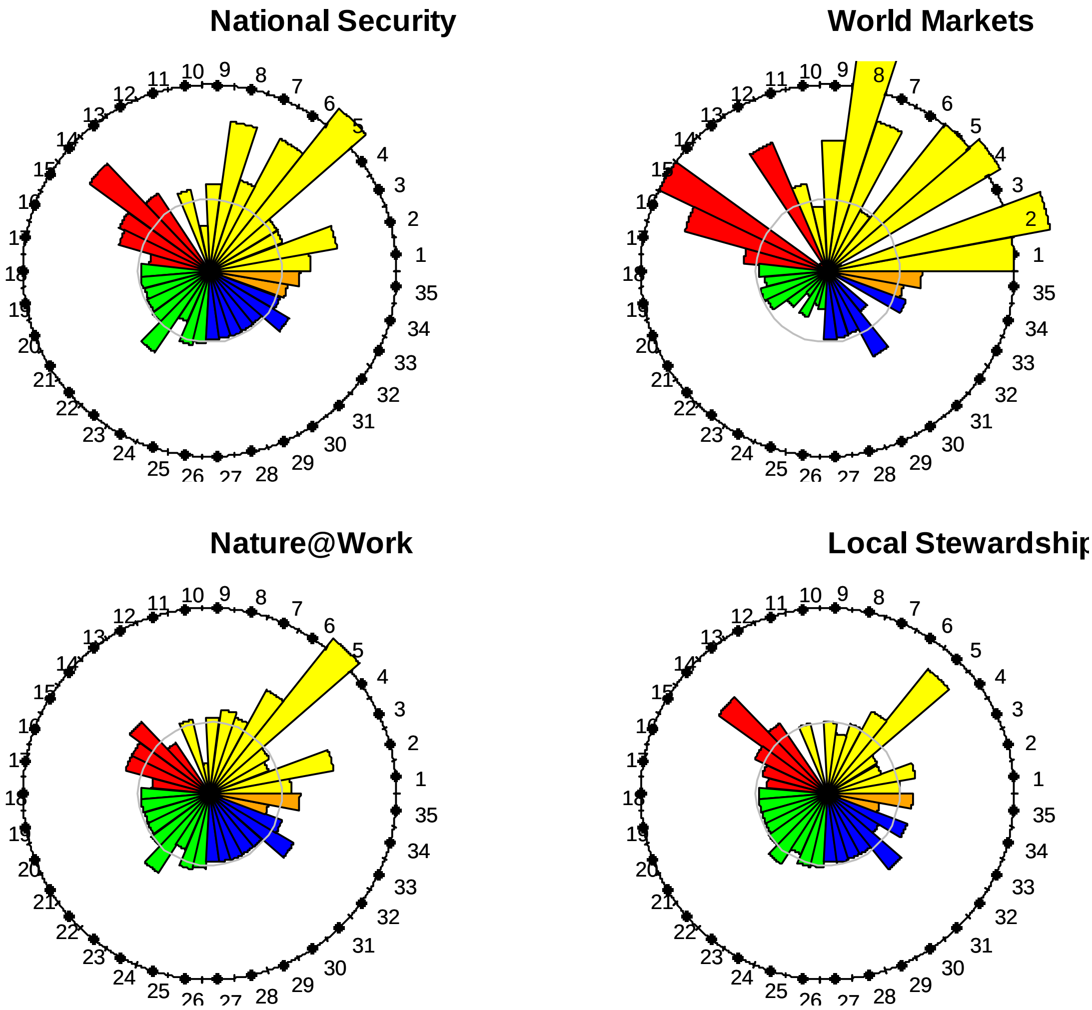
Model inputs for each worldview and the baseline model



Length of each segment is proportional to the magnitude of each variable

Label		Description
A		Fuel costs
B		Market prices of landings
C		Aquaculture production (and nutrient emissions)
D		Kelp harvest
E		No-take-zone extent
F		Wildlife by-catch mitigation measures
G		Discard rates
H		Fishing activity

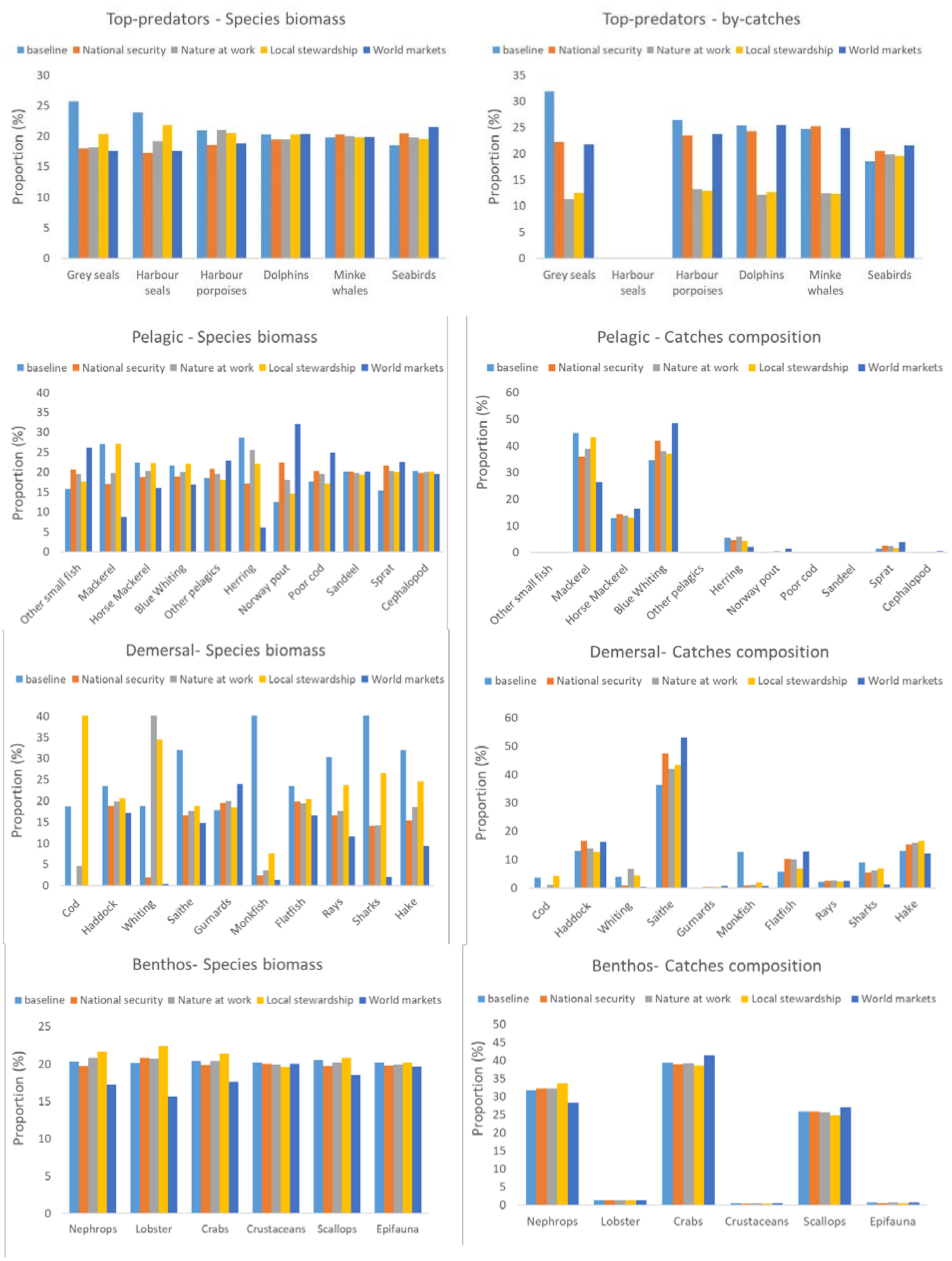
Model outputs for each worldview relative to the 2003-2013 baseline



Segment lengths are proportional to the ratio of scenario : baseline values.
Inner grey circle represents the baseline (scenario : baseline ratio = 1)

Label		Description	Label		Description
1		Mobile pelagic effort	18		Winter surface nitrate
2		Mobile demeral effort	19		Mud porewater ammonia
3		Static gear effort	20		Total PP inc kelp
4		Shellfish landings	21		Benthos biomass
5		Demersal fish landings	22		Finfish biomass
6		Planktivorous fish landings	23		Planktivorous/total fish biomass
7		Migratory fish landings	24		Seal biomass
8		Fishery revenue	25		Bird and cetacean biomass
9		Fishery profit margin	26		Top-predator prodn/Primary prodn
10		Fishery profits	27		Number of anglers
11		Seaweed profits	28		Number of divers
12		Total discards	29		Number of wildlife watchers
13		Cetacean catch ratio	30		Welfare of anglers
14		Seal catch ratio	31		Welfare of divers
15		Bird catch ratio	32		Welfare of wildlife watchers
16		Seabed abraded area ratio	33		TLR consumer suplus change
17		Inshore/total area abraded	34		Consumption of aqua products
			35		Aquaculture profits

Comparison of predicted catches and biomass composition



Species biomasses (left panels) showed species proportional changes across the scenarios. Catches composition (right panels) showed changes of species contribution (in proportion) to the overall catches domains (demeral-pelagic-benthos) across the scenarios.

Comparison of predicted economic values (annual, £million*)

		Baseline	*National Security*	*Local Stewardship*	*Nature @Work*	*World Markets*
Fisheries	*Profit*	49.27	-180.23	-343.60	-272.29	0.00
Aquaculture		224.02	385.09	343.46	385.09	419.09
Seaweed		0.00	0.47	0.12	0.23	0.70
Total profit		**273.29**	**205.33**	**-0.02**	**113.03**	**419.79**
Wildlife watching	*Change in consumer surplus – use values*	n/a	0.197	0.523	0.249	0.491
Angling						
Diving						
Wildlife watching	*Change in consumer surplus – non-use & option values*	n/a	0.024	-0.010	0.028	-0.070
Total change in consumer surplus		n/a	**0.221**	**0.513**	**0.277**	**0.421**

* Adjusted to 2010 consumer price index.

Appendix 2. Description of management and policy measures represented in the simulations of worldview scenarios (Module 7)

1. Overall fisheries regulation

a. Catch control (quota)
b. Effort control
c. Unregulated (open access)

The first set of measures relates to the degree to which fish catch is regulated overall: i.e. by controlling how much fleets can catch through a quota system, or alternatively through controlling fishing effort by means of a combination of limitations to the fleet capacity and the amount of time that can be spent at sea. Either way, in our models we have assumed catch or effort are managed to direct fisheries to harvest at levels which correspond to selected proportions of maximum sustainable yield (MSY). This mimics the current fisheries management regime. We do not distinguish between UK and other European fleets in this regard. We also consider a third option in which there is no management of catch or effort. Here we allow economics to determine the outcome of how much effort is expended and catch taken, without regard to the sustainability consequences.

The essential first step to implementing fisheries management scenarios in our models was to, in a sense, mimic the stock assessment process. To do this we pre-ran a set of simulations to map out the fishing mortality rates that generate MSY for groups of species in the food web. This allowed us to specify the levels of fishing that correspond to ecosystem MSY (as opposed to individual species MSY).

In *National Security*, *Nature at Work* and *Local Stewardship* we ran the models primarily under catch control rules with catch limits set to represent pre-determined proportions of MSY for each species group (100% for *National Security*, 80% for *Nature at Work*, and 50% for *Local Stewardship*). In *World Markets*, the only regulation was economic. In StrathgE2E, gears were programmed to increase their effort so long as profit proportions were positive, or decrease if profit proportions were negative. This mimics an open-access fishery. Since the gears overlap in their selectivity for species groups this results in a battle for dominance between the competing gears, in which the likely winners are those with the lowest costs per unit revenue (overall, the winners in our World Markets simulation were pelagic trawls targeting mackerel, demersal seine, and mollusc dredge). It was not possible to dynamically change the effort in EwE so, the mimic the open-access fishery we use a static fishing set at 160%MSY.

2. Marine protected areas

a. Current level of spatial restrictions (no take zones)
b. Increase spatial restrictions (no take zones)
c. Restrictions on bottom contact mobile gears.

Although around 11% of inshore waters off the west of Scotland are covered by marine protected areas (MPAs) of one sort or another, only a very small fraction of these comprise no-take-zones (NTZs). The narratives for *Nature at Work* and *Local Stewardship* are clear that NTZs would be envisaged, so we included provision for 15% of inshore waters to become no-take-zones in *Nature at Work*, and 50% in *Local Stewardship*. There is no elegant mechanism for implementing such measures in EwE without the use of Ecospace, but in StrathE2E we were able to represent an NTZ as an exclusion of all gears from a given fraction of the inshore zone. The initial effect of this in the model is increase the operating costs for gears in the inshore zone because the economic functions in the model take account of interactions between fishing gears (i.e. packing activity into a smaller space leads to more encounters and conflicts between vessels e.g. between mobile and static gears). In the model, this eventually affects the inshore-offshore distribution of gears, as vessels attempt to mitigate this increase in costs by relocating offshore, subject to a cost premium for operating further from land. Finally, changes in the inshore-offshore distribution of fishing mortality has an impact on the ecosystem. In *National Security* and *World Markets*, there are no areas set aside as no-take zones. We did not attempt to model restrictions on bottom contact mobile gears (dredging, demersal trawling) separately to no-take zones.

3. Technical measures

a. Discard ban for commercially regulated species, with exceptions (business as usual)
b. Discard ban / landing obligation for all species and without exceptions
c. Promote selective and ban unselective gears (e.g. static gear that may entangle marine mammals, longlines with bird bycatch)
d. By-catch mitigation devices (e.g. acoustic beacons on gill nets and trawls to warn seals and cetaceans; use of high acoustic reflectance materials in nets; pop-up creels and pots with no surface lines so as to reduce entanglement).

This third set of management considers addressing discarding and by-catch in fisheries. Discarding is the practice of returning unwanted catches to the sea, either dead or alive, because they are undersized, due to market demand, the fisherman has no quota, or because catch composition rules impose this. New EU regulations on discarding (Landing Obligation) come into full force in January 2019. These will require vessels to land all of their catch of regulated species (species managed under quotas), with some exceptions, for example when fish have a high survivability. Regardless, all the catch needs to be recorded. A stricter option is to not allow any discarding whatsoever.

Management of bird, seal and cetacean by-catch is not covered by the current Landing Obligation (which only applies to species governed by quota restrictions). Key gears with respect these top-predators are bottom-set gillnets, surface longlines, pelagic trawls, and creels and pots. Certain bird species are vulnerable to longlines and trawls with substantial by-catches being recorded (though generally not in the west of Scotland). The pick-up lines for creels and pots pose a well-documented entanglement risk to minke, fin and humpback whales. In the North Sea, English Channel and Celtic Sea there is already an EU Directive requiring the use of acoustic beacons on bottom set gill nets to reduce the by-catch of small cetaceans, but this does not apply to the west of Scotland. The effectiveness of such devices is debated, with some research indicating that animals become accustomed to beacons after a relatively short time, or even become attracted to them (so called 'dinner-bell' effect).

Our baseline model for the period 2003-2013 represents pre-Landing Obligation discarding rates (both undersize and over-quota), so the model includes both undersize and over quota discarding. The data from this period indicate that over 40% of demersal fish caught in the region were being discarded. Of the four worldview scenarios, only *World Markets* allows discarding. In *Nature at Work* and *Local Stewardship*, we invoke technical improvements in the selectivity of gears so that only human consumption sized fish are caught and 100% of the catch is landed. In *National Security*, there are no changes in selectivity, but also no discarding, so quantities of undersized fish and bycatch are landed and utilized for fish meal – which we represent as a proportionate reduction in the mean price obtained for fish assuming that catch sold to fishmeal commands the same price as sand eels, rather than the usual market price for human consumption fish.

Our baseline models did not include any representation of by-catch mitigation devices, since none were in operation on the west of Scotland. The storylines for *Nature at Work* and *Local Stewardship* indicate that such measures would be envisaged so we represented them by reducing the mortality rates on cetaceans and seals by 50% for gillnets and pelagic trawls, and on cetaceans for creels and pots. No such measures were implemented in the *National Security* or *World Markets* scenarios.

4. Aquaculture

a. Business as usual (2030 target of doubling aquaculture)
b. Slower expansion.
c. Further expansion beyond 2030 target

The Scottish aquaculture industry is led by Atlantic salmon farming, which we have focused on. The Scottish Government has endorsed an industry growth strategy that targets roughly doubling the size of the sector between 2016 and 2030.

Overall in the last 30 years, the salmon industry has shown economies of scales, with reducing costs and high production rate. Continuing historical trends, we assume a slow pace of expansion in *Local Stewardship*, up from 170,000 to 200,000 t per year. In *World Markets* we follow the growth strategy to meet the increase in global demand, producing 300,000 ton in 2030. We chose this maximum considering the slow pace of production recorded in the last 10 years owing to space limits and no main change in technology. Intermediate productions set at 250,000 t per year are considered for the *Nature at Work* and *National Security* scenarios.

In terms of our ecosystem models, we envisaged that aquaculture could affect the system is at least two ways. First, the supply of aquaculture products could affect the price obtained for wild-caught fish. While there is some evidence for this we considered the effect to be very small and disregarded it. Secondly, the emission of nutrients from fish farms into coastal waters is a well known issue of concern, influencing the licensing of fish farming sites. In StrathE2E we included an addition nutrient input for each worldview, corresponding to the amount of nutrient (ammonia) emitted as a result of the specified rates of annual salmon production.

Appendix 3. Engagement at external meetings and workshops

Author	Title	Activity	Name of event and location	Date	Relevant Module
Somerfield PJ	The Marine Ecosystem Research Programme – an update	Oral presentation	Coastal Futures 2019 – Review and future trends, London.	January 2019	All
Austen M	Natural Capital: can it be operationalised for the marine environment?	Oral presentation	Coastal Futures 2019 – Review and future trends, London.	January 2019	All
T Webb	EMODnet biological data products workshop	Workshop	Ostend	Oct 2018	M1
Waggitt J	Ecologically informed and dynamic distribution maps for seabird communities in the north-eastern Atlantic Ocean	Oral Presentation	Seabird Group Conference, Liverpool, UK.	Sep 18	M1
Wakelin S	The effects of increasing model resolution on physics-ecosystem interactions in the Celtic Sea	Oral	Challenger Society for Marine Science Biennial Conference, Newcastle upon Tyne	10-13 September 2018	M6
Webb T et al	Marine biodiversity: metrics, function and drivers	Poster presentation	University of East Anglia Biology Research Colloquium, Norwich	July 2018	M1
Thompson M, Cooper K, Couce E, Schratzberger M, Webb T, Grace M, Somerfield P	Assessing biodiversity stocks and flows and the emerging use of eDNA to support offshore science.	Presentation	Beyond the Coast 2018: JNCC's conference on the future of our offshore marine environment, University of Hull	June 2018	M1
Somerfield PJ	Predicting the consequences of marine ecosystem change in a complex world.	Invited talk	12th Panhellenic Symposium of Oceanography and Fisheries, Corfu	June 2018	All
Ainsworth, G., J.O. Kenter, S. O'Connor, F. Daunt, J.C. Young	Cultural values of marine ecosystem services	Invited presentation and workshop participation	Sea Scotland 2018, Kinghorn, Scotland	20^{th} -21^{st} June 2018	M7
Searle, K. R., S. Burthe, M. Newell, M. Harris & S. Wanless	North Sea seabirds: responses to fisheries and changing climate	Invited presentation	PICES 4^{th} International Symposium : the effects of climate change on the world's oceans	June 4^{th}-8^{th} 2018	M1
Sarah Wakelin	The impact of resolution on the modelled ecosystem of the Celtic Sea	Poster	National Partnership for Ocean Prediction (NPOP) Workshop, Liverpool	15-17 May 2018	M6
T Webb	Linking and enriching data to understand the dynamics of marine biodiversity	Oral Presentation	EMODnet Biology annual meeting, Trieste	May 2018	M1
Somerfield PJ	Data, models and ecosystem services: the Marine Ecosystems Research Programme	Presentation	4th World Conference on Marine Biodiversity (WCMB), Montréal	May 2018	All
Somerfield PJ et al	Solutions for ecosystem-level protection of ocean systems under climate change	Presentation	4th World Conference on Marine Biodiversity (WCMB), Montréal	May 2018	All
T Webb	Linking and enriching data to understand the dynamics of	Oral Presentation	World Conference on Marine Biodiversity, Montreal	May 2018	M1

	marine biodiversity				
Ainsworth, G., J.O. Kenter, S. O'Connor, F. Daunt, J.C. Young	Cultural values of marine ecosystem services	Presentation	Virtual meeting with Defra fisheries economists	16th May 2018	M7
T Webb	More understanding – The MERP approach to generating scientific evidence from knowledge, data and tools.	Oral Presentation	MERP Stakeholder Symposium, Royal Society London	25 April 2018	All
M. Heath	Fishing and marine ecosystems – Addressing the different facets of fishing in the marine ecosystem using the MERP approach for evidence generation	Oral Presentation	MERP Stakeholder Symposium, Royal Society London	25 April 2018	All
F Daunt	**Marine top predators, people and policy –** Generating evidence for assessing the status of, and risks to, marine ecosystems	Oral Presentation	MERP Stakeholder Symposium, Royal Society London	25 April 2018	All
M Schratzberger	MERP, marine space and management – Using information of what is where, when and why to support evidence-based decision-making.	Oral Presentation	MERP Stakeholder Symposium, Royal Society London	25 April 2018	All
James Waggitt	Ecologically informed and dynamic distribution maps for cetacean communities in the north-eastern Atlantic Ocean	Oral Presentation	Sea Watch Foundation AGM, Skegness, UK	Apr 18	M1
James Waggitt	Ecologically informed and dynamic distribution maps for cetacean communities in the north-eastern Atlantic Ocean	Oral Presentation	European Cetacean Society Conference, La Spezia, Italy.	April 18	M1
T Webb et al	Marine Space and Management, oral presentation and panel discussion	Oral presentation	MERP Stakeholder Symposium, The Royal Society	London, April 2018	All
James Waggitt	SEA ALARMS: Preparedness and Response to Marine Emergencies	Workshop Attendance	Hamburg, Germany.	Mar 18	
Jason Holt	Priorities for physics improvements in CO configurations	Oral presentation	North-West European Shelf Monitoring and Prediction Service (NOWMAPS) project meeting, Exeter	5-6 March 2018	M6
T Webb	Comparative Macroecology	Invited seminar	Queens University Belfast	Feb 2018	M1
Somerfield PJ,	*The NERC/Defra Marine Ecosystems Research Programme*	Oral	Coastal Futures 2018, London,	January 2018.	All
T Webb	Linking Occurrence, Traits, and Environment to Map the Diversity of Marine Life	Workshop	LifeWatch.be Stakeholder Meeting and User Event, Ostend	Jan 2018	M1
T Webb	Comparative Macroecology	Invited seminar	University of York	Jan 2018	M1
Jason Holt	Shelf scale modelling	Oral presentation	Land Ocean Carbon Transfer (LOCATE) project meeting, Nottingham	February 2018	M6
James Waggitt	Patterns in top-predator diversity: taxa-specific responses to environmental gradients in the north-east Atlantic Ocean	Oral Presentation	British Ecology Society Conference, Ghent, Belgium	Dec 17	M1
James Waggitt	Understanding and predicting European marine mammal distributions at seasonal and	Oral Presentation	Mammal Society Autumn Symposium, ARUP, London	Nov 17	M1

	decadal scales				
Peter Evans	Three talks on: white-beaked dolphin species review, common dolphin conservation plan, harbour porpoise North Sea conservation plan	Oral, presenting seasonal distribution maps	UNEP/ASCOBANS Advisory Committee meeting, Le Conquet, France	5-7/9/17	1
Wanless, S	Forty years of Auks on the Isle of May	Oral presentation	Scottish Ornithologists' Club Annual Conference	September 2017	1
F. Daunt	Ecosystem service trade-offs between wildlife recreation and industrial activities	Defra Policy Meeting	Defra Policy Meeting	27/9/17	1, 5, 6
Lindeque, P	Molecules and morphology: integrative taxonomic analysis of marine planktonic assemblages	Theme session proposal for ICES Annual Science Meeting	ICES Annual Science Meeting Hamburg	Sept. 2017	2
Jorn Bruggeman, Gabriel Yvon-Durocher, Katrin Schmidt, Thomas Mock	Modelling the evolution of thermal tolerance in phytoplankton	poster (also member of scientific steering committee)	3rd workshop on trait-based approaches to ocean life, Bergen, Norway	21 Aug 2017	6
AM Queirós	Placing ecology in macroscale models without getting lost in translation: An ecologist's point of view	Presentation	FILAMO workshop. Bergen (Norway)	18th-19th August 2017)	WP1-7
Nager	Long-term changes in resource use of gulls in the British Isles	Invited symposium contribution	Waterbird Society Annual Meeting 2017	8-12 August 2017	M1
Evans PGH	UNEP Meeting with Marine Stewardship Council on fisheries bycatch risk assessment	skype based meeting	UNEP Meeting	20 July, 2017	
Miriam Grace and Tom Webb	Cumulative effects of pressures and management in marine ecosystems	Poster	BES Macroecology Annual Meeting, London	July 2017	8
Tom Webb	Marine Biodiversity Data in R	Invited oral presentation	BES Macroecology Annual Meeting, London	July 2017	1
A G Rossberg	Third author meeting of the regional assessment of biodiversity and ecosystem services for Europe and Central Asia	Lead Author in IPBES regional assessment	Prague	July 24-28, 2017	5
AM Queirós	Hosted the president of The Ocean Foundation to visit the MERP T2.2 experimental setup	Networking event	Plymouth Marine Laboratory	14th July 2017	WP2
Evans PGH	marine mammal by catch issues in relation to reforms to the Common Fisheries Policy	Talk	European Parliament , Brussels	11 July, 2017	
Heath, M., Wilson, R. & Speirs, D.	Modelling the whole-ecosystem impacts of trawling	Oral presentation	AMEMR Conference Plymouth	3 July 2017	4
Sevrine Sailley	Zooplankton diversity modelling, combining size and trait based approaches	Oral	Advances in Marine Ecosystem Modelling Research (AMEMR) conference, Plymouth	3-6 Jul 2017	6
Gennadi Lessin, Jorn Bruggeman	Modelling the temporal coupling between phytoplankton and benthic fauna in shelf seas	poster	Advances in Marine Ecosystem Modelling Research (AMEMR) conference, Plymouth	3-6 Jul 2017	6
Mike Spence, Paul Blackwell	A dynamic multi-model ensemble for ecosystem simulators	Oral	Advances in Marine Ecosystem Modelling	July 2017	4

and Julia Blanchard			Research, Plymouth		
Mike Spence and Alan Turtle	Making the most of survey data: incorporating age uncertainty when fitting growth parameters	Poster	Advances in Marine Ecosystem Modelling Research, Plymouth	July 2017	4
Natalia Serpetti	AMEMR and EwE workshop	Attended a meeting and presenting: poster and presentation at the workshop	AMEMR, Plymouth	3-6 July	3/4
Sarah Wakelin	The effects of model resolution on the ecosystem of the Celtic Sea	poster	Advances in Marine Ecosystem Modelling Research conference, Plymouth	3—6 July 2017	6
Sheila JJ Heymans	AMEMR and EMB policy meeting	Co-chaired the EMB policy meeting on End-to-end marine modelling	Towards end-to-end Marine Ecosystem Modelling: R&D needs for ecosystem-based management	2-7 July	4-8
Paul Blackwell and Mike Spence	Marine ecosystem modelling: shaping future research agendas	Contributions to plenary and break-out discussion	Full day workshop organised by European Marine Board	July 2017	4
A G Rossberg	Simulating marine with thousands of species and their responses to changing fishing pressure	Poster	Centre for Computational Biology networking day, London	5 July 2017	Mod 3,4
Michaela Schratzberger	Marine nematology: Meeting the challenges created by a changing world	Invited keynote presentation illustrating how discrete pools of scientific and contextual knowledge of organisms at the bottom of marine food webs can be used to inform decision-making	Third International Symposium on Nematodes as Environmental Bioindicators, Institute of Technology, Carlow, Ireland	28-29 June 2017	All
John Pinnegar	Climate change and UK fisheries: potential impacts, adaptation and mitigation - overview of current scientific knowledge and cutting-edge developments	Presentation and discussion with fishing industry stakeholders	Seafish Common Language Group, Friend's House, London	22 June 2017	2
Broszeit, Stefanie	*"Marine ecology and ecosystem services"*	Soapbox Science event	City centre, Exeter	24/06/2017	M5
Peter Evans	Seasonal distribution mapping	Informal contribution presenting MERP results (by skyoe)	UNEP/ASCOBANS Common Dolphin Conservation Plan steering group meeting, Galway, Ireland	14-15/6/17	M1
Michaela Schratzberger	Marine nematology: Meeting the challenges created by a changing world. - illustrating how discrete pools of scientific and contextual knowledge of organisms at the bottom of marine food webs can be used to inform decision-making	Invited keynote presentation	Third International Symposium on Nematodes as Environmental Bioindicators, Institute of Technology, Carlow, Ireland	28-29 June 2017	All
John Pinnegar	Climate change and UK fisheries: potential impacts, adaptation and	Presentation and discussion with	Seafish Common Language Group, Friend's House,	22 June 2017	7

	mitigation - overview of current scientific knowledge and cutting-edge developments	fishing industry stakeholders	London		
Evans PGH	Chaired this and made a presentation	Oral	ASCOBANS European Harbour Porpoise Conservation Plan Steering Group meeting	19-20 June, 2017	2
Sheila JJ Heymans, Natalia Serpetti	Ecopath with Ecosim	Introductory CPD course – 3 days.	Ecosystem Based Management using Ecopath with Ecosim	27-29 June 2017	4
Jorn Bruggeman	DEB for any species Making the most of existing knowledge	Oral	Fifth international symposium on Dynamic Energy Budget theory, Tromsø, Norway	2 Jun 2017	6
Helen Parry	Fish larvae at L4	Oral	What's in the sea at L4. Salisbury Road Primary School Year 5.	Various, May 2017	2
Waggitt JJ, **Evans PGH.**	A collation of European at-sea surveys identifies and explains persistent areas of cetacean diversity and abundance at regional and decadal scales.	Oral	30th European Cetacean Conference, Middelfart, Denmark.	1st – 3rd May 2017	2
Evans PGH	Opening talk on cetacean research	Oral	Bangor University Marine Mammal Society Conference	5 May, 2017	2
Kenter, Martino, & Heymans	Scenario workshop for the Marine Ecosystems Research Programme (MERP)	Facilitated workshop to assess views of West of Scotland marine stakeholders under different socio-economic scenarios	Scenario workshop for the Marine Ecosystems Research Programme (MERP) University of Strathclyde, Glasgow, 10.30 – 15.30	16th May	8
Sheila JJ Heymans, Natalia Serpetti	Modelling mackerel in the NE Atlantic	Attended a meeting on how to model a migratory stock such as mackerel in the NE Atlantic	Mackerel in the NE Atlantic – Aberdeen	29 May - 1st June	4
Howarth, L.M., **Somerfield, P.J., Blanchard, J.L. and Hiddink, J.G**	Top-down or bottom-up? Investigating the effects of primary productivity and fishing pressure on benthic size spectra	Talk	PICES early career conference in Busan, South Korea.	30 May 2017	2
Waggitt JJ, **Evans PGH et al**	Quantifying top-predators' use of hydrodynamic features in coastal regions; applied and ecological consequences	Talk	PICES early career conference in Busan, South Korea.	30 May 2017	2
Waggitt JJ, **Evans PGH**	Understanding and predicting spatio-temporal dynamics in marine top-predator communities at regional and decadal scales.	Poster	PICES early career conference in Busan, South Korea.	30 May 2017	2
Nager	Spatio-temporal variation in the diet of two auks	Tweets	3rd World Seabird Twitter Conference	12-14 April 2017	1
Gennadi Lessin, Jorn Bruggeman, Yuri Artioli, Momme	Modelling temporal and spatial dynamics of benthic fauna in North-West-European shelf seas	Oral	European Geosciences Union General Assembly 2017, Vienna, Austria	8-13 Apr 2017	6

Butenschön, and Jerry Blackford					
J van der Kooij	Habitat drivers of small pelagic fish in the Celtic Sea	Presentation and discussion	ICES Working Group on Fisheries Acoustics, Science and Technology (WGFAST), Nelson, New Zealand	4-7 April, 2017	2
Peter Evans	Mapping cetacean bycatch risk	Informal contribution presenting MERP results (by skype)	UK Wildlife & Countryside Whales Group meeting, London	20/4/17	WP3, T2
Tom Webb	Linking & Enriching Biodiversity Data for Marine Management	Oral presentation	MERP Briefing for Scotland, Scottish Government, Edinburgh	March 2017	1, WP3
Evans PGH.	MERP presentation	Oral	North Wales Marine Mammal Society	20 March 2017	
Jorn Bruggeman, Katrin Schmidt, Thomas Mock	Capturing species succession and evolution in large scale biogeochemical models	Oral	ASLO Aquatic Sciences meeting, Honolulu, Hawaii	3 Mar 2017	6
AM Queirós	Multi-model projection of spatial planning and climate conflicts in the North East Atlantic	Poster	2nd UNESCO 2nd International Conference on Marine Spatial Planning, Paris (France)	15-17 March 2017	WP6,7
Jorn Bruggeman, Susan Kay, Yuri Artioli, Karsten Bolding	Higher trophic level modelling at PML	Oral	2nd workshop of the EC Network of Experts for ReDeveloping Models of the European Marine Environment, Brussels	23 Mar 2017	6
Peter Evans	Seasonal distribution mapping	Informal contribution presenting MERP results (by phone)	Natural England Biodiversity 2020 meeting, Natural England, Peterborough	29/3/17	Module 1
A G Rossberg	How loss of fish biodiversity affects marine ecosystem functioning	Presentation	Centre for Ecology and Evolution, UCL, London	4 April 2017	
Sheila JJ Heymans	MSP Challenge game	Attended a meeting on the MSP Challenge Game and gave a talk about Ecopath and its uses for MSP	MSP Challenge Game – NHTV Breda, the Netherlands	9-11 April 2017	7
Tom Webb	Biological traits in biodiversity research	Invited oral presentation	EMODnet Biology Phase 3 launch meeting, Ostend	April 2017	1
F Daunt	Drivers of North Sea seabird breeding success	Oral lecture	University of Edinburgh undergraduate lecture	1/2/17	1
A G Hirstt, M Lilley et al	Plankton Provide New Perspectives on Metabolic Rates	Lead author talk	ASLO meeting, Hawaii	Feb 2017	Mod 3
AM Queirós	Networking	Networking	Preparatory meeting for the United Nations Conference on Sustainable Development Goal 14, New York (USA)	15-16 February 2017	WP2, WP7
Michaela Schratzberger & Paul Somerfield	Incorporating functional characteristics into the derivation of biodiversity metrics	Collaboration with members of the ICES Working Group on Biodiversity Science to develop life-history-trait-	Annual meeting of the ICES Working Group on Biodiversity Science, University of Venice, Italy	6-10 February 2017	1 and 2

		based biodiversity indicators			
Evans PGH.	ICES Working Group on Marine Mammal Ecology	(contributed remotely)	ICES Working Group, University of St Andrews	6-9 Feb	
Howarth, L.M., **Somerfield, P.J., Blanchard, J.L. and Hiddink, J.G**	Top-down or bottom-up? Investigating the effects of primary productivity and fishing pressure on benthic size spectra	Talk	ASLO 2017	Feb 26th 2017	
Peter Evans	Mapping cetacean bycatch risk	Oral, presenting seasonal distribution maps	UNEP Convention on Migratory Species (joint ASCOBANS-ACCOBAMS) meeting on Unacceptable Interactions and bycatches in marine mammals, UN Campus, Bonn, Germany	22/2/17	WP3, T2
Peter Evans	Mapping risk of noise disturbance to cetaceans	Informal discourse on MERP results	JNCC Workshop on Noise Management within Marine Protected Areas, Edinburgh	27/2/17	WP3, T2
L Howarth	Top-down or bottom-up? Investigating the effects of fishing pressure and primary productivity on benthic size spectra	Oral	ASLO 2017, Hawaii	27/02/2017	M2
M. A. Spence	Report of the Working Group on Multispecies Assessment Methods (WGSAM)	report		February 2017	M4
Sheila JJ Heymans	WKIRISH meeting	Attended a ICES meeting on the Irish Sea and gave a talk on Modelling	WKIRISH3 – Stock assessment workshop for the Irish Sea Stocks	30 January – 3 February	4
Waggitt	When, where and why: mapping and understanding the distribution of European Cetaceans	Oral	Meeting of the Bangor University Marine Mammal Society, Bangor, UK.	30/01/2017	M1
Waggitt		Invited Participant	Seabirds and Renewables Workshop, Glasgow, UK.	18/01/2017	M1
J van der Kooij	Disseminating survey derived biomass estimates of pelagic fish	Presentation and discussion (in absentia)	ICES Working Group on International Pelagic Surveys (WGIPS), Reykjavik, Iceland	16-20 January 2017	2
Waggitt	Life in the fast line: Seabirds and Tidal Energy	Oral	Meeting of the CoCoast Project, Bangor, UK.	14/01/2017	M1
A G Rossberg	The Nash Equilibrium for Two Fleets Exploiting One Stock	Presentation	Defra, London	11 January 2017	Mod 3, 5
A Farcas and A G Rossberg	Effective management measures to achieve MSY are different from current fisheries policies	Presentation	Defra, London	11 January 2017	Mod 3, 5
Axel G. Rossberg, Adrian Farcas and Robert Thorpe	Meeting with Defra staff to advise on multispecies fisheries management in the Brexit context.	Briefing meeting	Defra, London	11/01/2017	M3
R. Vergnon	Rmerp/merpWS/merpData	R packages and accompanying documentation	Github	Dec 2016 - Jan 2017	M1
M. A. Spence	Ageing elephants from the sky: lessons from fisheries	oral	Behavioural ecology seminar - University of Sheffield	20/01/17	M4
A Rossberg, A	How to achieve maximum	Oral presentation	In Thematic Topic Session:	11-14/12/16	M3

Farcas	sustainable yield from interacting fish stocks		"What will sustainable fisheries look like in 2025?" at British Ecological Society annual meeting, Liverpool, December 2016		
Daunt, F. & K. R. Searle	Integration of research into effects of offshore renewable developments on breeding seabirds	Meeting and report provided to Scottish Government (Liam Kelly)	CEH Edinburgh	December 2016	M1
Mel Austen	Valuing marine ecosystems	Oral (remotely via webex)	JPI Oceans Ecosystem Goods and Services workshop, Brussels	24/11/2016	M5
Jose Fernandes	Communicating results and uncertainty to policy makers and stakeholders	Oral	ICES, Copenhagen, Denmark	23/11/2016	M5
Sarah Wakelin	The effects of model resolution on the Celtic Sea ecosystem	Poster	The 2nd Challenger Society Coastal Ocean Special Interest Group workshop, UK Met Office, Exeter	22-23/11/2016	M6
A Rossberg, M Heath, S Heymans, N Serpetti, D Speirs, M Spence, P Blackwell	MERP policy brief on predicted times to achievement of improved environmental status after implementation of CFP reform	Policy brief		10/11/16	M3 &4
M Austen	Marine science and policy: match and mismatch	Opening Keynote	North Sea Science Conference, Ostend,	08/11/2016	M5
S Broszeit	How to assess ecosystem services?: Using conceptual models to capture complexity	Seminar	Sheffield University, Department of Animal and Plant Sciences	09/11/2016	M5
J van der Kooij	Disseminating survey derived biomass estimates of pelagic fish pelagic	Presentation and discussion	ICES Working Group on Acoustic and Egg Surveys for Sardine and Anchovy in ICES Areas VII, VIII and IX (WGACEGG), Sicily	14-18 Nov 2016	All
J. Bruggeman	Modelling plankton adaptation: from the individual to the world ocean	oral	Dialogue on methods for ecology, University of Cambridge, UK	15 November 2016	6
AM Queiros (Presented by Carol Turley, PML)	Building resilience to Ocean Acidification: Blue carbon and C-farming	Presentation (COP22 report attached)	United Nations Climate Change Conference (22nd Conference of Parties, Marrakech, Morocco). "Small Island Developing States" event, Oceans Action Day.	12 Nov 2016	M2
J van der Kooij	Habitat drivers of small pelagic fish in the Celtic Sea	Presentation and discussion	Challenger Society Conference, Liverpool	5-8 Nov 2016	All
Serpetti et al.	Predicting cumulative effects of fishing and rising temperature on a marine ecosystem	Oral presentation	SAMS – PIES seminar	4/11/16	M4
AM Queiros. M Burrows, N O'Connor	Blue Carbon + Climate-ready Conservation = Climate Action	Presentation (COP22 report attached)	United Nations Climate Change Conference (22nd Conference of Parties, Marrakech, Morocco). "Climate readiness –Ocean based adaptation and mitigation" event, UK pavilion.	10/11/16	M2
M Austen		Oral participation	Government Office for	24/10/16,	M5

			Science Ocean Foresight Project Advisory Group meetings	15/12/16	
G. Lessin	Modelling benthic processes and benthic-pelagic coupling in shelf seas: understanding interactions and predicting potential change	oral	Workshop on Modeling on Coastal and Shelf Ecosystems, East China Normal University, Shanghai, China	24-25 October 2016	6
J. Bruggeman	FABM-ERSEM: a model toolbox for water and sediment biogeochemistry	oral	Workshop on Modeling on Coastal and Shelf Ecosystems, East China Normal University, Shanghai, China	24-25 October 2016	6
M. A. Spence	A dynamic multi-model ensemble for ecosystem simulators	Oral	WG-SAMS	10/10/16	M4
Atkinson	UK Pelagics MSFD assessment workshop,	Phytoplankton and zooplankton time series and traits Partially developed within MERP) to complete the UK MSFD assessment	Plymouth Marine Laboratory	10-11 October.	M1 M2
Howarth LM, Blanchard JL, Somerfield PJ, Hiddink JG	Top-down or bottom-up: investigating benthic biomass size spectra across gradients of fishing pressure and primary production	Oral presentation	British Ecological Society Macroecology Meeting, London,	September 2016	M2
S Wanless	Forty years of Auks on the Isle of May	Oral presentation	Scottish Ornithologists' Club Annual Conference	September 2016	1
K Searle, F Daunt & S Wanless	Use of SMP count data to test how intrinsic and extrinsic processes combine to drive patterns of seabird population dynamics in UK coastal waters	Oral presentation	Seabird Conference, Edinburgh	Sept 2016	1
R. Nager	Spying on Scottish Seabirds at their Dinner Table	Invited talk	Scotland's Ornithologist Club Annual Conference	23/09/2016	M2
M Austen		Oral participation	Canadian Healthy Oceans Network CHONE 2 Directors meeting, Montreal	16/09/2016	M5
T Webb	State of Nature	Report	State of Nature 2016	Sept 2016	M1
Atkinson	Oral paper: A view from the south: use of composite time series data to understand how recruitment and mortality govern populations size	Session co-convenor for Session "The role of zooplankton in exploited ecosystems: the role of top down and bottom up controls on pelagic	ICES Annual Science Conference, Riga, Latvia	Sep 2016	M2, M6
M. A. Spence	A dynamic multi-model ensemble for ecosystem simulators	Oral	ICES ASM	20/9/16	M4
Sarah Wakelin	The effects of model resolution on hydrodynamic-biogeochemical interaction in the Celtic Sea	Poster	Challenger Society 2016 Conference, University of Liverpool	08/09/2016	M6
Waggitt	Understanding and predicting spatio-temporal variations in marine top-predator distributions in European Waters, at regional and decadal scales.	Poster	13th International Conference Of The Seabird Group, Edinburgh, UK,	08/09/2016	M1
J Waggitt	Quantifying top-predators' use of hydrodynamic features in coastal regions; applied and ecological	Oral	Biannual Challenger Society Conference, Liverpool, UK.	06/09/2016	M1

	consequences.				
Searle, K. R.	Predator-prey interactions affecting Scottish fisheries	Organised 2 day workshop with Fisheries Innovation Scotland and other stakeholders	FIS Predator-Prey Interactions workshop St. Andrews	24-25th August 2016	1,5,6
M Heath	Modelling the whole ecosystem impacts of trawling	Oral	Fisheries Innovation Scotland Annual Symposium, St Andrews	22-23 August 2016	M3 & M4
M Austen		Oral participation	Sir Charles Hendry Tidal Lagoon Inquiry Round table, UKERC London	26/07/2016	M5
M Austen		Oral participation	Expert workshop for the Foresight Future of the Sea project, London	27/07/2016	M5
Somerfield PJ, Dashfield S	The structure and organisation of marine benthic communities in relation to body size	Poster	16th International Meiofauna Conference, Heraklion, Greece	July 2016	M2
L. Polimene, S. Sailley, D. Clark, S. Kimmance, A. Mitra, I. Allen	Are we able to model the microbial carbon pump? Current state and future prospective	Poster	Gordon Research Conference on Ocean Biogeochemistry, Hong Kong, CN	12-17 June 2016	M6
M Austen	Marine ecosystem services: Linking indicators to their classification	Oral	DEVOTES-EUROMARINE Summer School San Sebastian	07/06/2016	M5
M Austen	Predicting ecosystem service change in the future: the developing role of socio-ecological modelling	Oral	DEVOTES-EUROMARINE Summer School San Sebastian	09/06/2016	M5
S. Sailley		[participation only]	ICES Working Group on Integrated, Physical-biological and Ecosystem Modelling (WGIPEM) meeting, Brest, FR	6-8 June 2016	M6
TJW	Comparative Macroecology	Oral	Invited seminar, University of Nottingham	June 2016	M1
TJW	Integrating biological traits in biodiversity research	Oral	EMODnet biological traits workshop	June 2016	M1
M Lilley, A Atkinson, R Harmer, A McEvoy and A Hirst	Do abundance time series identify the same Hydromedusae bloom events as biomass estimates?	Oral presentation	5th International Jellyfish Blooms Symposium, Barcelona	30/5/16-3/6/16	Mod 2
Lilley MKS, Atkinson A, Harmer R, McEvoy A, Hirst AG	Do abundance time series identify the same Hydromedusae bloom events as biomass estimates?	Oral presentation	5th International Jellyfish Blooms Symposium in Barcelona	30 May- 3 June 2016	M2
Mel Austen		Oral participation	Valuing Nature Programme Advisory Group meeting	26/05/2016	M5
M Heath		Oral presentation	Meeting with Fisheries Innovation Scotland to discuss ecosystem approach to fisheries, Glasgow	11 May 2016	M3 & 4
Lilley MKS, Hirst AG, Glazier D, Atkinson D	Steep body mass scaling of biological rates in macrozooplankton supports a Surface Area dependent model	Oral presentation	ICES 6th International Zooplankton Symposium, Bergen	9-13 May 2016	M1
S Sailley, L	Stoichiometry and	Oral	ICES 2016 Zooplankton	9-13 May	M6

Polimene, J Bruggeman, JI Allen	microzooplankton: How one predator answer to food quality impacts the ecosystem around him		production symposium, Bergen, NO	2016	
F Daunt	Isle of May long-term seabird research	Oral presentation	Scotland's Big Nature Festival (Edinburgh)	22/5/16	M1
SWakelin		Breakout group discussions on marine predictions and next-generation biogeochemical models.	National Partnership for Ocean Prediction Science workshop, Bristol	25-27 April 2016	M6
S Broszeit	Marine ecosystem services and coastal development	Presentation	ECORES workshop Ravenna, Italy	4 May 2016	M5
J van der Kooij	Integrated Pelagic Ecosystem Survey	Platform presentation	Southwest Marine Ecosystem Survey	8 April 2016	M2
Mel Austen et al	Linking ecosystem change & economics	Presentation	MSCC/MASTS Bioeconomic modelling & policy workshop	03 May 2016	M5
TJ Webb		Attendance at event, networking	NOC Association Annual Science Meeting	5 May 2016	All
J van der Kooij	First Lyme Bay sprat stock assessment	Presentation and discussion (in absentia)	Herring Assessment Working Group (ICES)	1-4 April 2016	All
PJ Somerfield	Seeing the bigger picture: Models of systems or systems with models?	Oral presentation	National Partnership for Ocean Prediction inaugural meeting	25-27 April 2016	All
J Waggitt	Understanding the drivers of top-predator distributions: implications for the designation of Important Marine Mammal Areas (IMMAs)	Oral Presentation	European Cetacean Conference, Madeira	20 March 2016	M2
S Sailley	Modelling fish and their environment. How, when, where and what?	Oral Presentation	Presentation to the CEO of the Atlantic Salmon Trust, Plymouth, UK	4 March 2016	M6
F Daunt, M Heath, A Rossberg, M Schratzberger, P Somerfield and T Webb	MERP briefing to Defra: The Marine Ecosystems Research Programme: better understanding connections to address evidence needs.	Policy briefing	Defra, Nobel House, London, UK	23 Feb 2016	All
N Beaumont		Discussion included reference to MERP activities.	RESILCOAST meeting, Cardiff. Including Welsh academics and environmental managers	18th – 19th Feb 2016	5
N Beaumont	Enabling Ecosystem-Based Management through improved understanding of ecosystem services related to marine mammals	Oral presentation including MERP	North Atlantic Marine Mammal Commission, Joint Meeting of the Management Committees Oslo, Norway. Invited speaker	9 feb 2016	5
M Schratzberger	MERP indicator-based activities	Informal presentation to members of the ICES Working Group on Biodiversity with particular view of using MERP-sourced data sets	AZTI-Tecnalia, Pasaia, Spain	8-12 Feb 2016	All
TJ Webb, HJ Bannister		Participation in workshop	MSCC/MASTS bioeconomic modelling workshop	3-5 February 2016	1, 4, 5
S Wakelin		Breakout group discussions on the	MSCC/MASTS bioeconomic modelling workshop, Didcot	3-4 February 2016	6

		role of models in marine policy and management and the implementation of plans for fisheries under the common fisheries policy.			
J van der Kooij	Integrated monitoring surveys: studying the pelagic ecosystems of the south west of the UK	Platform presentation	Coastal Futures Conference	20 Jan 2016	2
TJ Webb	Harnessing open environmental data	Talk	openDefra event, Sheffield	15 January 2016	1
Francis Daunt	Population ecology of North Sea seabirds	Oral presentation	RSPB	20 January 2016	1
J Bruggeman, K Bolding, S Ciavatta, Y Artioli, I Allen	Towards custom built models for water and sediment biogeochemistry based on reusable components	oral	EU network "ReDEveloping Models of the European Marine Environment", EC, Brussels, BE	19-21 January 2016	6
M Austen, I Allen		Discussion included reference to MERP activities	Cross-RC Coastal workshop	07/01/2016	5,6
TJ Webb, R Vergnon		Co-organised workshop	OBIS data hack	7-11/12/15	1
TJ Webb		Attendance at event, networking	National Biodiversity Network Conference	20/11/15	1
J van der Kooij	Disseminating survey derived biomass estimates of pelagic fish	Presentation and discussion	ICES Working Group on Acoustic and Egg Surveys for Sardine and Anchovy in ICES Areas VII, VIII and IX (WGACEGG)	16-20 Nov 2015	All
Nicky Beaumont		Discussion included reference to MERP activities. International audience	High Seas Symposium. Global Ocean Commission. Somerville College, Oxford	12th-13th November 2015.	5
M Austen, M Emmerson, P Somerfield, I Allen, TJ Webb		Participation in workshop	MMO/MERP workshop	4/11/15	All
P G Blackwell	Predictions of marine ecosystems - from one model and from many	Seminar	University of Tasmania	17/12/2015	4
R Nager	Change in between- and within-individual variation in resource utilisation in gulls over the last 4 decades	Oral Presentation	2nd World Seabird Conference, Durban South Africa	27/10/2015	1