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BRITISH ECOLOGICAL SOCIETY Ecological Solutions and Evidence

PERSPECTIVE

The Global Energy Transition: Ecological Impact, Mitigation and Restoration

Fishing, offshore wind energy, climate change and marine spatial planning: Is it possible to plan for a best use of space?

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Abstract

1. The significant expansion of offshore wind farms (OWF) is a core element of the world's decarbonisation strategy. However, in the urgency to meet Net Zero, care must be exercised to avoid exchanging one environmental crisis for another. A primary aim of this paper is to set out a methodology roadmap to ensure that future marine management and renewable energy policy is sustainable and evidence based. Marine ecosystems are complex, and the current lack of understanding makes it difficult to predict the effects of introducing thousands of wind turbines and extracting hundreds of gigawatts of wind energy that would have otherwise influenced our shelf seas ecosystems. It is difficult to predict the subsequent wider ecosystem effects of the combined changes in spatial use, such as displacement of fisheries out of OWF, along with possible attraction of fish into OWF developments.
2. Therefore, to proceed with any reasonable level of certainty, we need to be able to rapidly estimate the safe upper limit of whole ecosystem effects of OWF. As an example, this perspective paper sets out the challenges which OWF pose to fishing industries within the context of existing nature conservation policies. We propose modelling approaches that can incorporate both the ecological effects of large-scale fisheries displacements as well as ecosystem level changes to fish populations from OWF developments. The ecosystem models can also predict the effects on future trends of fish populations within climate change forecasts.
3. *Practical implication*. To improve decision making when balancing environmental and socio-economic benefits and trade-offs, we then propose methods that use Marine Net Gain, which is a conservation approach that ensures human activities in marine environments result in a measurable net positive impact on biodiversity. The focus is on the United Kingdom and North Sea; however, the proposed roadmap holds the capability to be transferable to other shelf sea systems with similar types and levels of pressures. This perspective provides a methodology

roadmap that considers the link between, and the need for, both food and energy security from our oceans and provides a route to increased certainty in our current choices for the long-term sustainable use of our oceans.

KEYWORDS
climate change, cumulative effects, energy transition, marine ecosystem, whole system approach

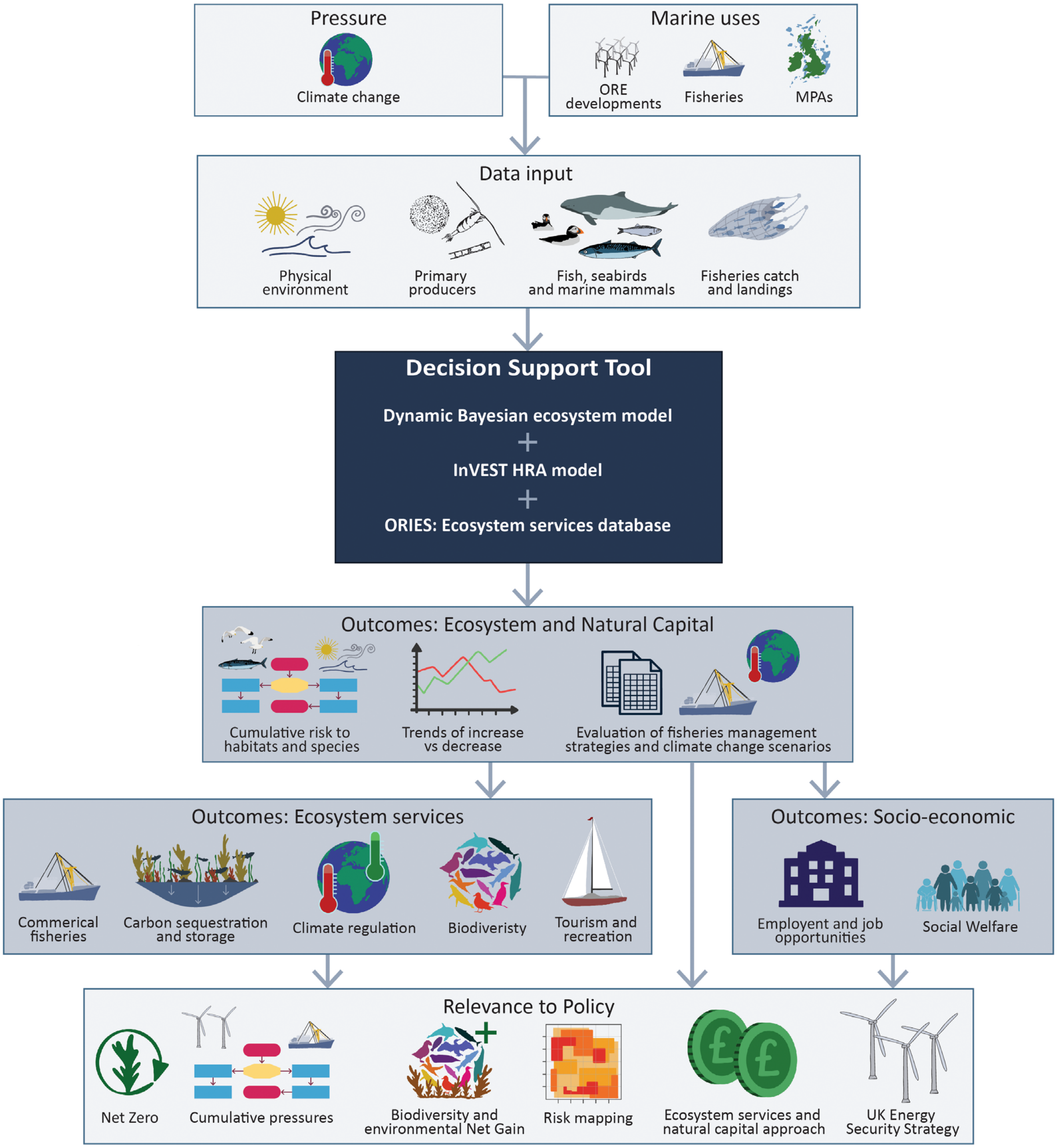
1 | INTRODUCTION: WHAT ARE THE CHALLENGES AT PRESENT

1.1 | Complexity of marine ecosystems

Marine ecosystems consist of complex dynamic interactions among species and the environment, the understanding of which has significant ecological and societal implications for predicting nature's response to changes in climate and biodiversity (Molinos et al., 2016). The complexity of such interactions is further exacerbated by spatial and temporal variation of the ecosystem and its components (Polis et al., 1996). Stressors, such as climate change and fishing exploitation, have also been shown to modify the driving forces in ecosystems (Cheung et al., 2019).

A key solution to combat climate change is the introduction of large-scale offshore renewable energy (ORE) developments (wind, tidal and wave) (IRENA, 2019). The United Kingdom is the second largest world leader in offshore wind farms (OWF) with 12.7 GW currently installed and a commitment to increase its capacity to 50 GW by 2030 with at least 5 GW of floating wind (UK Energy Security Strategy, 2022). There has been an accompanying shift to planning reforms to cut the approval times for new OWF from 4 years to 1 year. In Europe, approval times in some areas are being cut from 4–6 years to 1–2 years (REPowerEU Plan, 2022) which will create considerable challenges to ensure developments are meeting nature positive targets. Large-scale developments will not only reduce reliance on importing fossil fuels and reduce emissions but will also provide social and economic benefits, for example, job creation and regeneration of the local coastal communities. However, this implementation of OWF will require a rapid increase in the use of complex information to identify trade-offs between both direct and indirect environmental impacts, as well as spatial conflicts with other marine uses like food production (fisheries) and conservation efforts (marine protected areas, MPAs). The introduction of so many new structures and the extraction of so much energy from wind will have cumulative effects within the ecosystems of the world's shelf seas with potentially far-ranging societal consequences (Dalton et al., 2015). The expansion of large-scale OWF into deeper waters has the potential to alter local and regional shelf-sea hydrodynamics and subsequently bio-physical processes, particularly in seasonally stratified areas that play a vital role in regulating prey availability for higher trophic levels (Dorrell et al., 2022). Changes in hydrodynamic regimes (i.e. levels of mixing, surface wave energy and upwelling) could affect the nutrient supply to the euphotic layer and change its spatial pattern, with important knock-on effects for primary and secondary production (Daewel et al., 2022; Floeter et al., 2017). It is also difficult to predict the subsequent effects of the displacement of fisheries (Kafas et al., 2018; Stelzenmüller et al., 2022) and some seabird species (Peschko et al., 2020), as there is also the possibility of attraction of some fish species (Williamson et al., 2021) and marine mammals (Russell et al., 2016), all of which will have accompanying marine ecosystem services impacts (Watson et al., 2024). Achieving a high level of understanding given the rapid pace of OWF development will necessitate a shift towards being able to predict more explicit ecosystem-wide cumulative effects on marine habitats and populations along with actual praxis in policy and regulatory frameworks (Declerck et al., 2023). All these issues will require prioritising hypothesis-driven studies of ecosystem processes (e.g. bottom-up: temperature and top-down: fishing), that include species' populations and trophic level interactions at spatial and temporal scales relevant to all these processes and effects of ORE.

In this perspective, we suggest that ecosystem models with data input from the physical environment, primary producers, higher trophic levels (e.g. seabirds) through to fisheries catch and landings can be used to identify good indicators of habitat and ecosystem change following the effects of pressures, such as climate change and multiple marine uses (e.g. ORE developments) (Figure 1; Trifonova et al., 2021). We show that machine learning approaches, such as dynamic Bayesian network models, can be used to predict trends (increase vs. decrease) for species' populations in different regions under different climate and/or anthropogenic scenarios (Figure 1; Trifonova & Scott, 2023). We demonstrate that outputs (e.g. indicator species of ecosystem change) from the dynamic Bayesian network model can be integrated into finer-scale spatial risk assessment models (i.e. the Habitat Risk Assessment model (HRA) from the InVEST software). Finally, we discuss that the outputs from the latter two models are converted into ecosystem services and socio-economic outcomes using information in the Offshore Renewable Impacts on Ecosystem Services (ORIES) database. Using an example of the effects of fishing displacement, we show these types of approaches can provide the environmental evidence base to support holistic cumulative effects assessments, as well as inform marine spatial planning (MSP) and management strategies (Figure 1).



Here, we present the strategic approach of a methodology roadmap, that integrates the joint use of three support tools (i.e., dynamic ecosystem model with the output driving a spatial Habitat Risk Assessment (HRA) model and a conversion into ecosystem services using information in the Offshore Renewable Impacts on Ecosystem Services (ORIES) database) to provide outcomes in a natural capital, ecosystem services and socio-economic context. The ecosystem model allows for dynamic interactions from pressures and multiple marine uses and their bottom-up and top-down effects on the bio-physical environment and up through top predators (seabirds and marine mammals). The ecosystem model allows for predictive outputs (i.e., trends of increase vs decrease) across a range of spatio-temporal scales at which changes can occur that can then be integrated with the HRA model (Declerck et al., 2023). In this way, the tools support the interlinked connections between ecosystems and ecosystem services and can measure the cumulative risk (i.e., risk mapping) generated by multiple pressures for a range of habitats and species in response to alternative management and climate change scenarios. The predictive outputs from the latter two models are converted into ecosystem services and socio-economic outcomes using information in the ORIES database which can help assess the environmental and socio-economic benefits and trade-offs in response to the same alternative management and climate change scenarios. In this way, the proposed strategic approach will maximise future ecosystem value and functioning and provide empirical evidence-base to support Marine Spatail Planning processes and policies (e.g., Net Zero, Biodiversity and Net Gain).

FIGURE 1 Schematic representation of the proposed strategic approach of a methodology roadmap.

1.2 | Policy and nature conservation

An increasingly important part of the decision processes for OWF across Europe is to measure cumulative environmental effects through cumulative impact assessments (CIAs) (Stelzenmüller et al., 2023). In the United Kingdom, the UK Marine Policy Statement (UK-MPS) in line with the Sustainability Appraisal (SA) sets the process for developing marine plans that manage the seas to encourage a sustainable environment, society and economy, whilst considering an ecosystem approach. The obligation for the decision-making bodies is to ensure that potential cumulative effects are considered and managed by setting targets or limiting development (Woolley, 2015). However, despite the recent increase in OWF deployments, decision-making bodies have been making slow progress in measuring cumulative impacts (Díaz & Soares, 2020). As a result, project decisions, including design, deployment and location, presently lack evidence-based information for assessing cumulative impacts on marine animal populations and large-scale ecosystem changes. This ultimately exacerbates uncertainties regarding impacts on marine ecosystems and their societal implications, which in turn fails to inform future ORE developments and is one of the main reasons for the extended time needed for planning decisions (Therivel & González, 2019). When uncertainties arise, the UK-MPS prescribes a risk-based decision-making approach but without providing any methodological guidelines (Woolley, 2015). The tools currently available tend to neglect future climate changes and the dynamic complexity of marine ecosystems, thereby oversimplifying marine ecosystem processes and functioning (Willsteed et al., 2018). This contributes to uncertain assessments with a limited understanding of ecosystem-scale impacts. It is therefore important to develop CIAs to be able to integrate predicted ecosystem effects across the range of spatio-temporal scales at which changes can occur (Declerck et al., 2023).

Understanding how ecosystem changes interact with and impact/are impacted by the wider socio-economic landscape is also critical. To minimise negative impacts and ensure human activities in marine environments result in measurable net positive impact on biodiversity, a Marine Net Gain (MNG; Natural England, 2022) approach, based on the value of the marine environment to people via ecosystem services and natural capital, is essential. It requires that any environmental losses caused by development or other activities are not only offset but exceeded by ecological gains, leading to an overall improvement in marine ecosystem health. The ongoing advancements in natural capital accounting play a crucial role in defining MNG by providing a structured framework to assess and measure the impacts of ORE installations on environmental benefits and their contribution to broader ecosystem services. By evaluating trade-offs between different marine uses—including development and conservation—through ecosystem service assessments and benefit valuation, decision-making processes can become more efficient and transparent, ensuring that trade-offs are clearly understood and considered (e.g. Watson et al., 2022).

There are some existing spatial decision support tools for the marine environment (e.g. in the United Kingdom: SMMART Tool, Le Quesne et al., 2021; MSPACE & ORIES from Plymouth Marine Laboratory). The purpose of these tools is to ensure that planning and management of the environment considers the diverse ways in which it supports human well-being, to evaluate spatial management options, incorporating multiple activities and ecosystem components in the context of a natural capital ecosystem assessment. While their practical application in MSP is still evolving, they provide a strong foundation for more effective, data-driven decision-making in the future. These tools provide valuable insights, although there is an opportunity to further enhance them by incorporating the spatial and temporal dynamics of the interconnected relationships between ecosystems and ecosystem services (Pınarbaşı et al., 2017). Addressing this shortfall in the broader understanding of the environmental and socio-economic implications of ORE developments requires an inclusive, holistic and pragmatic ecosystem-based approach that considers the dynamic and spatial nature that ORE will have on all the uses of our seas (e.g. food, energy and conservation).

1.3 | Example of fisheries displacement

Commercial fishers have to manage spatial conflicts with other fishers, structures (oil rigs/pipelines), aggregate extraction activities, MPAs and maritime transport, in addition to ecological impacts on target species, such as fluctuations in stock or distribution changes, due to climate change. OWF causes displacement of fishing effort, either by the placement of structures or by exclusion zones that restrict their ability to enter an OWF area (Stelzenmüller et al., 2022). Some fishers might be permitted within the OWF area but may choose not to fish there due to subsea pipelines and cables that can cause snagging risks to fishing gear (Rouse et al., 2017). Although earlier studies of fishers' attitudes to OWF developments had been fairly positive (Reilly et al., 2015), the increased spatial squeeze has changed this (ABPmer, 2022; Szostek et al., 2025). It has been suggested that fishers can adapt to spatial conflicts by fishing in different areas and/or changing their target species (which may also involve modifications to the vessel and gear used). In reality, there are multiple factors that impact the ability to alter fishing practices. Displacing fishing effort from one area to another has large ecological implications with increasing pressure and environmental impacts in the area where fishing effort is relocated (Halpern et al., 2004). The move to other grounds will likely cost more, not only in fuel, but also in time (i.e. effort) (Chaji & Werner, 2023). Fuel costs in the United Kingdom range from ~5% of annual income for under 10m vessels to >25% for large (>250kW) beam trawlers (UK Seafish Industry Authority). The full economic cost of fisheries displacement should be quantified through combining known annual fuel costs per gear with high-resolution vessel monitoring system data, rather than only assessing the percentage loss of fishing grounds.

Economic implications for fishers include reduced catches if displacement from preferred fishing grounds occurs, with cumulative impacts of increasing numbers of OWF highly likely (Berkenhagen et al., 2010). Offshore structures, such as wind turbines, can attract fish; however, barriers to fishing in or near turbines include safety and insurance considerations (Chaji & Werner, 2023). Many fish species are subject to quotas; therefore, switching from a non-quota stock would require the availability of quota and funds for purchase. Modifying a vessel from mobile gear (trawl or dredge) to static gear (pots/creels) is more feasible than the other way around; however, there is already significant competition for fishing grounds between existing static gear fishers. Any changes to gear or related vessel modifications are likely to come at significant cost, and it is uncommon for existing vessels to be suitable for both static and mobile gear types (Gus Caslake, pers. comm.). In relation to the socio-economic impacts of OWF on fisheries, there remain key gaps in understanding that should form priority research questions, including economic data, indirect economic impacts (e.g. to support businesses) and better models and methods to quantify impacts on the industry, fishing communities and fish populations (Chaji & Werner, 2023). Currently, there are no UK policies or procedures in place that address the interactions between OWF and existing fisheries activities (Schupp et al., 2021). Conflicts between the fishing industry and OWFs have risen across Europe, with some approaches being introduced to resolve such conflicts, for example, compensation funds, cooperative research strategies, lease stipulations and participatory decision-making. However, there is no consistency, leading to fisheries being an obvious case that needs an integrated approach to enable a holistic assessment of trade-offs between multiple sectors.

2 | METHODOLOGY ROADMAP: PLANNING FOR THE BEST USE OF SPACE

2.1 | Ecosystem-based approach

Significant progress has been made in developing ecosystem models that use traditional statistical approaches to understand the relationships between several variables (Lynam et al., 2017), including 'end-to-end' dynamic ecosystem models to predict impacts of environmental change on the structure and function of marine food webs and the services they provide (Heath et al., 2021; Spence et al., 2018). However, all these models assume that the underlying relationships are in a steady state. This assumption might not be true, as ecosystems are known to sometimes undergo relatively fast structural changes that have a major effect on the ecosystem dynamics (Möllmann et al., 2008). Further, it is possible that the changes are driven by unobserved components, that is, ecosystem variables that we do not have data on. Thus, it is recommended that ecosystem models develop a richer non-mechanistic appreciation of ecological interactions across space and over time due to changing pressures at different levels of the trophic chain (Uusitalo et al., 2018).

Therefore, we propose an ecosystem approach based on a dynamic Bayesian network model (Figure 1; Trifonova et al., 2021) that will not only provide a methodology to assess the dynamic impacts and trade-offs of the main uses of our seas but also provide a pragmatic solution to the new need for such a rapid assessment of offshore planning issues. Such probabilistic models allow predictions to be made across different spatial and temporal scales in response to multiple stressors while simultaneously including a range of indicator individual species or functional groups to represent all trophic levels (i.e. data input: from the physical environment up through to top predators, Figure 1). The probabilistic presentation of the interactions is one of the key advantages of the method that allows for the estimation of uncertainties better than models that only account for expected values (Uusitalo, 2007). Pragmatic Bayesian network models can also readily be used to explore a range of 'what-if?' scenarios to investigate the effect of OWF and explore the likely outcomes of alternative fisheries displacement (e.g. increase vs. decrease in fishing) and climate change scenarios (e.g. 'business-as-usual' scenario) of multiple trophic levels in response to such changes (Trifonova & Scott, 2023).

For example, one could ask, what is the probability of seeing a change in the stock biomass and landings of herring, given the change (decrease) in areas of fishing caused by displacement from OWF, and both increases in sea temperatures and decreases in the prey of herring from climate change (i.e. multiple pressures and marine uses, Figure 1)? In this way, we can explore the trend (increase vs. decrease) of the herring stock biomass and landings, given a change in multiple pressures. Similarly, through the developed scenarios, we can explore the specific trends (increase vs. decrease) of other species within the ecosystem in response to change in pressures on herring (e.g. ecosystem outcomes: trends of increase vs. decrease shown in Figure 1). Highly protected species, such as seabirds and marine mammal species, which are common predators of herring. Therefore, we can estimate both the ecosystem-level, as well as natural capital impacts through measuring the predicted population changes of important commercial fish species. The natural capital value of the fish population is estimated in terms of the service it provides to society, for example, food supply for humans and how that might change with the size and location of an OWF deployment, climate change and fisheries displacement scenarios.

Crucially, the dynamic Bayesian ecosystem model will allow the evaluation of sustainable strategies by identifying highly sensitive vs. more robust species and/or locations (i.e. habitats) based on ecosystem features (e.g. shallow mixed coastal areas vs. deeper highly stratified regions; Trifonova & Scott, 2023). Using the Bayesian network approach, an understanding of the reactive responses across all trophic levels can be improved, adding the dynamic aspect of the interaction of stressors at the level of the ecosystem and therefore vastly improving the accuracy of the CIA process. This in turn will allow for ecosystem-wide cumulative effects to be predicted under multiple scenarios, at scales relevant to Environmental Impact Assessments (EIA).

2.2 | Ecosystem services and risk-based approaches

Outputs (e.g. indicator species of ecosystem change) from the ecosystem model can be integrated into finer-scale models, such as the Habitat Risk Assessment model (HRA) from the InVEST software (Figure 1). The HRA model produces risk maps (i.e. cumulative risk to habitats and species, Figure 1) where the habitat risk assessment and MSP approach (Arkema et al., 2015) are combined with the outputs of the ecosystem-level Bayesian network model such that ecosystem services provisioning is added as a descriptor, introducing the ability for dynamic inputs/outputs to the current InVEST/HRA approach. This unique approach will make it possible to assess the cumulative risk posed to habitats and species at much finer scales (1–10 km) than the ecosystem model alone can provide and can directly address implications for biodiversity and the co-location of marine uses.

The UK Energy Research Centre (UKERC) recently undertook a critical analysis of the United Kingdom and global evidence-base around OWF research to provide scientific evidence on the environmental and societal effects of OWF on biodiversity and ecosystem services and has developed a decision support tool (ORIES; Figure 1) to help summarise the effects of OWF development phases (constructions and operation) on ecosystem services (Szostek et al., 2024; Watson et al., 2024). Key features of the ORIES decision support tool are: assessment of ecosystem services, spatial and temporal evaluation, scenario analysis and decision-making support. The tool helps assess both the direct and indirect impacts of ORE developments on various marine ecosystem services. ORIES incorporates spatial and temporal dynamics, helping to assess the potential impacts on ecosystems not only in terms of location but also over time, allowing for a more comprehensive understanding of long-term effects. The tool supports scenario testing, allowing planners to explore different development options and their relative impacts on the marine environment. It can be used to compare the effects of multiple renewable energy projects on ecosystem services. By integrating ecosystem service considerations into spatial planning processes, the ORIES tool helps stakeholders make informed decisions that balance energy generation with the need for sustainable marine resource management.

The predictive outputs from the dynamic Bayesian network model and HRA model can be combined with information from the ORIES ecosystem service database and can be used to provide assessments of trade-offs in both ecological and socio-economic values following alternative fisheries management and climate change scenarios (Figure 1; e.g. changes to financial outcomes, such as gross value added [GVA]) (Trifonova et al., 2022) and cumulative effects (Declerck et al., 2023). Specifically, to follow-up from the above example, we can measure economic changes (positive and/or negative) to GVA (in £) by calculating changes in herring landings from commercial fisheries, following the same scenarios. The tool helps assess both the direct and indirect impacts of offshore renewable energy developments on various marine ecosystem services, alternative management and/or climate change scenarios. Focus can be placed on the understanding of where uses of the environment and ecosystem services align in space and 'what-if?' scenarios can be used to examine trade-offs in a range of currencies: natural capital (units of biomass in kilograms, Figure 1), ecosystem services (e.g. commercial fisheries, Figure 1) and socio-economic (e.g. GVA in £, number of jobs and social welfare, Figure 1). In this way, the MNG or loss would be evaluated to determine whether placement of OWF has had an effect on fish catch and fisheries production. Determining the resultant changes and value of the fisheries and other marine resources is needed to assist MSP, marine policy statement, MNG and energy policy (Figure 1). The user will be able to make evidence-based judgements and decisions, including quantified estimates of the trade-offs between environmental and socio-economic benefits at regional (strategic) and single OWF development scales. This will in turn support improved integrated marine spatial management in the context of reducing climate change and delivering sustainable use of our seas with socio-economic benefits, including interventions related to indicators/outcomes under the 25 YEP, the UK Marine Strategy, as well as the Sustainable Development Goals.

3 | CONCLUSION: IS IT POSSIBLE TO PLAN FOR THE BEST USE OF SPACE?

Meeting marine energy, food and conservation policy targets will require a significant transition in our economy and society. A core part of achieving ecologically sustainable change will be to consider the dynamic interactions between marine uses (e.g. fisheries and OWF) to attain these targets more strategically. The proposed methodological roadmap (Figure 1), with the central use of a Bayesian network ecosystem model, accounts for the dynamic interactions of the effects of OWF, changes in fishing and climate change and produces predictions of trends of populations at all marine trophic levels as well as the levels of ecosystem services provided. The outputs and resulting range of assessments of location-specific dynamic interactions between uses of the seas are able to support marine spatial planners to balance and minimise conflicts and tensions among existing and future planned marine uses of natural resources. The model also provides an approach to integrating the relative value of MNG interventions in terms of wider Natural Capital Accounting. This will further progress understanding of ecosystem services and market-based approaches and should be combined with the use of decision support tools such as ORIES (Figure 1) which will enable stakeholders to access and compare global studies on the environmental and socio-economic outcomes of OWF. Current policy targets also aim to review how spatial aspects, Habitat Regulation Assessments (HRAs), are undertaken and the proposed methodology produces indicators that can then be used at finer spatial scales such that it will also support spatial decision-making: namely where to site OWF to reduce their negative impacts and maximise their positive outcomes for biodiversity (MNG). Together, the outcomes delivered by the proposed strategic approach will provide a major contribution to ensuring that energy, food and conservation policies can be developed in a coherent manner for the maximal benefit of society. Recently, the Offshore Renewable Energy (ORE) Catapult laid out a new Regional Ecosystem Monitoring Programme (REMP) approach to environmental monitoring and consenting within the United Kingdom offshore wind sector. The proposed roadmap from the study here was used in this report. If the REMP approach is accepted by policy and OWF developers, outputs from the dynamic Bayesian network ecosystem model will be directly utilised by the newly suggested approach which would assess the environmental impacts of offshore wind projects at a regional level rather than the current project-by-project approach.

Although we focus on the United Kingdom and North Sea, the proposed roadmap serves as an effective baseline and holds the capability to be transferred to other marine systems globally and to be used within planning considerations of the relevant implications of multiple uses of natural resources by estimating both ecological and socio-economic changes. It has already been demonstrated that the proposed roadmap, specifically the integration of the dynamic Bayesian network model outputs with the HRA model, can be implemented into European processes, enabling an ecosystem-based approach for CIAs (Declerck et al., 2023).

AUTHOR CONTRIBUTIONS

Neda Trifonova: Conceptualization and writing; Beth E. Scott: conceptualization, review and editing. Stephen C. L. Watson, Claire Szostek, Morgane Declerck and Nicola Beaumont: review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

No data was used.

RELEVANT GREY LITERATURE

You can find related grey literature on the topics below on Applied Ecology Resources: Marine ecosystem, Energy transition, Climate change.

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