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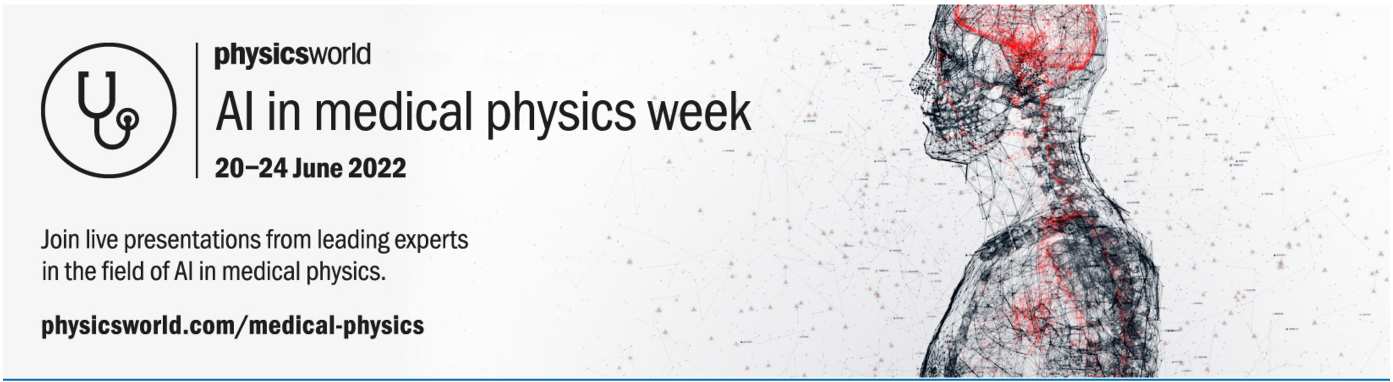

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TOPICAL REVIEW

An ecosystem-based natural capital evaluation framework that combines environmental and socio-economic implications of offshore renewable energy developments

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Abstract

There is about to be an abrupt step-change in the use of coastal seas around the globe, specifically by the addition of large-scale offshore renewable energy (ORE) developments to combat climate change. Developing this sustainable energy supply will require trade-offs between both direct and indirect environmental effects, as well as spatial conflicts with marine uses like shipping, fishing, and recreation. However, the nexus between drivers, such as changes in the bio-physical environment from the introduction of structures and extraction of energy, and the consequent impacts on ecosystem services delivery and natural capital assets is poorly understood and rarely considered through a whole ecosystem perspective. Future marine planning needs to assess these changes as part of national policy level assessments but also to inform practitioners about the benefits and trade-offs between different uses of natural resources when making decisions to balance environmental and energy sustainability and socio-economic impacts. To address this shortfall, we propose an ecosystem-based natural capital evaluation framework that builds on a dynamic Bayesian modelling approach which accounts for the multiplicity of interactions between physical (e.g. bottom temperature), biological (e.g. net primary production) indicators and anthropogenic marine use (i.e. fishing) and their changes across space and over time. The proposed assessment framework measures ecosystem change, changes in ecosystem goods and services and changes in socio-economic value in response to ORE deployment scenarios as well as climate change, to provide objective information for decision processes seeking to integrate new uses into our marine ecosystems. Such a framework has the potential of exploring the likely outcomes in the same metrics (both ecological and socio-economic) from alternative management and climate scenarios, such that objective judgements and decisions can be made, as to how to balance the benefits and trade-offs between a range of marine uses to deliver long-term environmental sustainability, economic benefits, and social welfare.

1. Introduction

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 (Battisti and Naylor 2009, Barange *et al* 2014, Molinos *et al* 2016). Such interactions are further exacerbated by spatial and temporal variation of the ecosystem and its components

(Polis *et al* 1996, Hunsicker *et al* 2011, Doney *et al* 2012). Stressors such as, climate change, fishing, and resource exploitation have also been shown to modify the driving forces in ecosystems (Blanchard *et al* 2012, Cheung *et al* 2019; Lotze *et al* 2019). In fact, the effects of fishing may have been exacerbated by climate warming and climate-induced changes in primary production, leading to impacts on demersal fish and seabirds in the North Sea (Lynam *et al* 2017). One of the more likely solutions to combat climate change is the introduction of large-scale offshore renewable energy (ORE) developments (wind, tidal and wave) of 100s of gigawatts (GW) (IRENA 2019). Such developments will not only reduce reliance on importing fossil fuels, and reduce emissions, but will also provide socio-economic benefits and job creation. However, the introduction of so many new structures and the extraction of so much energy either from wind, wave or tides will have cumulative effects within the world's shallow seas and therefore will also influence whole ecosystems with potentially far-ranging societal consequences (White *et al* 2012, Hooper and Austen 2013, Dalton *et al* 2015, Hooper *et al* 2015, Boon *et al* 2018, De Dominicis *et al* 2018, Sadykova *et al* 2020). There are significant gaps in our understanding of the socio-economic impacts of physical and biological changes, associated with both climate change and ORE developments (Mooney *et al* 2009, Polasky *et al* 2011, Seppelt *et al* 2011).

In 2019, the UK parliament passed legislation: The Climate Change Act 2008 (2050 Target Amendment[5]) to reduce the UK's net emissions of greenhouse gases by 100% relative to 1990 levels by 2050 (Net zero). The UK is the current global leader in offshore wind with 8.5 GW currently installed and a commitment to increase its capacity to 40 GW by 2030[6]. However, that level has just recently been increased to 50 GW (UK Energy Security Strategy, UK GOV[7]) with an accompanying dramatic shift to planning reforms to cut the approval times for new offshore wind farms from 4 years to 1 year. In the U.S., the Biden Administration has released an executive order[8] targeting 30 GW of offshore wind energy capacity by 2030, with an additional target of 110 GW by 2050, and all coming from a current capacity of 42 megawatts (MW). Achieving these lofty goals in the UK, U.S., and the many other countries with offshore wind energy ambitions will require a significant transition in our economy and society, if they are to be deployed at the scale needed to have a meaningful impact on climate change. Many trade-offs will need to be evaluated rapidly for the future sustainable management of marine ecosystems between different uses of our seas, e.g. ORE developments, fisheries, commercial transport, and marine protected areas (MPAs). Moreover, the diversity of economic drivers of change, such as changes in costs, technology, trade, substitute goods, and demand, can make assessments of socio-economic impacts problematic, especially when projecting out into the future (Fernandes *et al* 2017). To ensure management is sustainable and meeting desired societal goals, and to avoid unintended consequences, it is essential to move toward identifying and measuring all environmental, social, and economic impacts, both short and long term (Daily *et al* 2000).

1.2. Decision frameworks

Given the various ambitions for ORE as a source of clean energy, economic development, job growth, national security enhancement, and more, all, while managing environmental issues and use conflicts in already crowded waters, decision making needs to account for a wide array of factors to meet goals and avoid unintended outcomes. Multicriteria analysis (MCA) is the most widely decision framework used to assess trade-offs in settings like this, and includes a process of scoring, ranking, or weighting the importance of different objectives to provide a numerical basis on which to select between different options (Britain 2009, Hooper and Austen 2013). Examples include the development of fisheries management plans, which are also part of the management strategy evaluation[9] (MSE), in which stakeholders and managers identify and score risks to the delivery of ecological, social, and economic objectives (Fletcher *et al* 2010), and mapping areas of optimal resource, overlapping with technical constraints, environmentally sensitive sites, and potential conflicts with other marine users to aid wave energy development (Nobre *et al* 2009).

An increasingly important part of the multicriteria decision processes for offshore wind energy in many countries is to measure cumulative environmental effects. In the UK, cumulative effects of ORE developments need to be evaluated through cumulative impact assessments (CIAs). CIAs are defined as: 'An assessment of potential cumulative impacts arising from a proposed development or activity, usually completed as part of an environmental impact assessment (EIA)' (Broderick *et al* 2013). The UK Marine Policy Statement (UK-MPS), in line with the Sustainability Appraisal, sets the process for developing marine plans, which should be based on an ecosystem approach and obliges decision-making bodies to ensure that

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[5] www.legislation.gov.uk/uksi/2019/1056/contents/made.

[6] www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future.

[7] www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy.

[8] www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/.

[9] www.pewtrusts.org/-/media/assets/2019/07/harvest-strategies/hs_mse_update.pdf.

potential cumulative effects are considered and managed by setting targets or limiting development (MMO 2014, Woolley 2015). In the U.S., the Bureau of Ocean Energy Management (BOEM) is charged with investigating cumulative impacts by the National Environmental Protection Act. However, despite the recent increase in ORE deployments, countries have been slow in measuring cumulative impacts of ORE developments (Diaz and Soares 2020, Gusatu *et al* 2020, 2021). In the U.S., BOEM conducted a qualitative classification of potential avenues for cumulative impact on the North Atlantic continental shelf, but no attempts were made to measure these[10]. Some of the challenges with this work include different assessment methodologies, the mismatch between spatial scales at which ecosystems function, the different time scales of the ORE-related impacts, the need for a long-term monitoring of effects across the ORE development timeline, and the differences between how regulatory agencies operate (Willsteed *et al* 2017, Gusatu *et al* 2020).

As a result, decisions presently lack accurate information for assessing marine animal populations and large-scale ecosystem changes. This ultimately exacerbates uncertainties regarding ORE developments, climate change and other anthropogenic impacts on marine ecosystems and their societal implications, which in turn fails to inform future ORE developments (Therivel and González 2019). When uncertainties regarding the effects of marine activities 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 complexity of ecosystem dynamics (Burdon *et al* 2018, Gissi *et al* 2018, Willsteed *et al* 2018), thus they are insufficient to reach broader ambitions to implement an ecosystem approach for the sustainable management of marine waters (Willsteed *et al* 2017).

Measuring the change in societal well-being from ORE policy is also a critical factor for consideration in an MCA. Cost-benefit analysis (CBA) is a structured valuation technique that provides a quantification of all the costs and benefits (including non-market goods) associated with projects or policies to establish their likely impact (Pacific Community Policy Brief 2017). It has been widely used in policy deliberations in the UK (Atkinson *et al* 2018), including siting MPAs and as part of the Marine Strategy Framework Directive, and has been a critical part of policy in the U.S. since President Ronald Regan's Executive Order 12291 of 1981, which mandated its use as part of major federal decision making. Rarely is CBA used as the sole factor in decisions, even for measuring human well-being; rather it is often considered alongside other important criteria, such as job growth, changes in gross value added (GVA) or gross domestic product (GDP), economic impact analysis, distributional impact analysis, and a wide array of other decision aids (Harrison *et al* 2018, OECD 2018). For example, in Australia CBA is regularly used to choose between policy alternatives in natural resource management, whilst in fisheries and aquaculture, its use is less systematic (Coglan *et al* 2020). The use of social indicators in an CBA approach has been identified as important to ensure sustainability in the use of marine resources and other environmental contexts (Olander *et al* 2018, Oleson *et al* 2020, Schaar and Cox 2021).

1.3. Natural capital and ecosystem services

Natural capital is a concept that borrows from the traditional framing of built capital and other forms of capital to frame the environment as a scarce, but regenerative, life supporting asset with value to society (Daily *et al* 2000, Beaumont *et al* 2007). By accounting for the quantity, quality, function, and value of environmental assets and the goods and ecosystem services that flow from them, decisions can be oriented towards ensuring the sustainable use of natural resources through time and other social objectives (Guerry *et al* 2015, Hooper *et al* 2019). The modelling tools and approaches that support measurement of these stocks and flows rely on the concept of marginal changes, also often referred to as scenario analysis, to measure how an action or decision manifests from an ecological change into changes in ecosystem goods and services that people value, and finally measures that change in value itself (Olander *et al* 2017). As coupled human-natural systems models, these assessments produce both environmental and socio-economic change estimates, measured in monetary terms and other benefit relevant indicators, and as a result are generally more encompassing than other decision aids like EIAs (Hooper *et al* 2017, 2018). Such information can support communication with other sectors, such as the conservation and financial sectors, and guide policy decisions and planning (Arkema *et al* 2014, 2015, Reyers *et al* 2015, Schaefer *et al* 2015, Posner *et al* 2016). The notion of using ecosystem-level processes and how they are affected by economic activity has recently been introduced in the ways in which we should account for nature in economics and decision-making: The Economics of Biodiversity: The Dasgupta Review[11]. In the UK, the Environment White Paper (HM Government 2011) reaffirmed the use of the natural capital approach within UK environmental policy, and

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[10] www.boem.gov/sites/default/files/environmental-stewardship/Environmental-Studies/Renewable-Energy/IPFs-in-the-Offshore-Wind-Cumulative-Impacts-Scenario-on-the-N-OCS.pdf.

[11] www.gov.uk/government/publications/final-report-the-economics-of-biodiversity-the-dasgupta-review.

more recently the 25 Year Environmental Plan (HM Government 2018) explicitly stated that 'over the coming years the UK intends to use a 'natural capital' approach as a tool to help us make key choices and long-term decisions'. However, existing frameworks are best fit to terrestrial environments and there are an array of research gaps remaining with these approaches for decision support in the marine environment (Milon and Alvarez 2019).

To minimize negative impacts and secure wider environmental benefits, a marine net gain (MNG) approach, based on the value of the marine environment to people via ecosystem services and natural capital, is essential. The developing thinking on natural capital accounting is important to MNG as it provides a framework for articulating, defining, and measuring the impacts of energy related installations on environmental benefits and their relative importance in provision of wider ecosystem services. Natural capital accounting also supports the implementation of economic mechanisms, such as incentives or market-based approaches to securing MNG. The MNG approach will enable future marine energy planning as part of national policy assessments. The MNG approach improves transparency, allowing practitioners to objectively understand the full benefits and trade-offs between marine uses (including fisheries, MPAs and energy), improving decision making when balancing energy needs, and environmental, social, and economic impacts.

In this paper, we examine the prospect of combining an ecosystem-based modelling approach that measures changes in natural capital to illuminate how ecosystem changes manifest into the socio-economic outcomes to support decision-making of ORE developments in the marine environment in the context of climate change. By allowing for interactions from the physical environment up through top predators (seabirds and marine mammals) and their links with delivery of ecosystem services, natural capital and socio-economic benefits, the proposed framework provides a data-driven whole system approach which supports identifying and assessing MNG. We describe the framework and the mechanisms needed to apply such a framework, with the potential changes from displacement of fisheries, as an example of direct and indirect changes, and a range of ORE deployment scenarios to assess and evaluate the usability of the framework for marine spatial planning. Through the use of scenario analyses, the framework can provide a dynamic assessment of alternative marine use management (e.g. ORE developments and changes in fishing catch) and climate change outcomes across spatial and temporal scales, given the interaction between changes in the physical environment up through the marine ecosystem, including impacts in a natural capital and ecosystem service context. In this way, the framework can produce outcomes in a range of comparative ecological (e.g. stock biomass in kilograms) and socio-economic (e.g. monetary value) metrics throughout different habitats within the North Sea, and their associated ecosystem-level changes over time. Such predictive outcomes would allow the exploration of trends (increase vs decrease) of ecosystem-level, natural capital, and socio-economic changes to be able to provide strategic advice on potential future response to natural and/or anthropogenic drivers. The usefulness of the potential outcomes from the framework has been discussed with respects to supporting marine spatial management but also in the context of reducing climate change and delivering sustainable use of our seas with socio-economic benefits and MNG. The UK has been chosen for its advantageous policy environment; however, we also bring localized examples from Scotland and international examples from the U.S. The study concludes with a discussion on whether the framework is fit for purpose for the marine environment, including key challenges, whether alternative approaches are possible and suggestions for future steps forward.

2. An ecosystem-based natural capital evaluation framework

2.1. Case study: fisheries displacement

The introduction of ORE developments will bring environmental and socio-economic benefits, but it may bring potential negative impacts to coastal communities, which have the greatest dependence on traditional marine uses, such as recreational and commercial fishing (Hooper *et al* 2017, Twigg *et al* 2020). It is suggested that ORE developments might cause disturbance or loss of traditional fishing grounds and 'industrialization' of marine open space (Haggett *et al* 2020, Stelzenmüller *et al* 2020). The spatial redistribution of fishing effort (fisheries displacement effect) to areas outside of the ORE development can potentially lead to increased competition among fishermen and to adverse effects on other less impacted habitats (Murawski *et al* 2005, De Backer *et al* 2019), which is also an argument made against the 30 by 30 ocean campaign goals of marine protection (Kubiak 2020, Hilborn and Sinclair 2021). Understanding the availability and ecology of alternative fishing grounds is important to determine whether displacement will have environmental and socio-economic impacts, or not (Gill *et al* 2020).

Currently, in the UK, fishing in the confines of static (non-floating) offshore wind farms is only prohibited during construction or maintenance phases, however trawling is not generally resumed during the operational phase, due to liability and safety issues as a lack of cooperation and knowledge exchange between the two industries prevents fishermen from entering the wind farm array (Hooper *et al* 2015, Gusatu *et al* 2020). However, two of the currently operational windfarms in the north-east coast of Scotland (Beatrice and Moray East) are conducting over-trawl ability trials where they are testing trawling over cables. Such trials are to ensure the comprehensive utilization of sea space and continuous safe operation of fishing activities. There are ongoing efforts to set up commercial fisheries monitoring by Scottish government (Marine Scotland) to look into any signs of displacement and changes to fishing patterns, concurrent with efforts performed by the EIA processes (Stelzenmüller *et al* 2020).

Floating windfarms will not permit any mobile fishing practises within wind farm arrays, due to the safety concerns of mobile cables and infrastructure throughout the water column. This is a concern, as for example, the UK fishing fleet (4,491 active fishing vessels) landed 620 000 tonnes of fish and shellfish in 2019 with a total revenue of £1 billion and a profit of £240 million (Seafish 2019). Economic performance of the UK fishing fleet is measured in terms of GVA, calculated as the sum of operating profit and crew share. Total fishing income of the fleet was £980 million in 2019, with a GVA of £498 million (Seafish 2019). In 2019, Scotland-registered vessels landed the largest weight (384 000 tonnes landed) and value (£570 million) of fish and shellfish (Seafish 2019) by registered home nation. Scottish-registered vessels also created the highest GVA in 2019 at £302 million (Seafish 2019).

Currently, there are no UK policies or procedures in place that address the interactions between ORE developments and existing fisheries activities (Schupp *et al* 2021). Conflicts between the fishing industry and ORE (wind in particular) industry have risen across Europe and the U.S., with some approaches being introduced to resolve such conflicts, e.g. compensation funds, cooperative research strategies, lease stipulations, and participatory decision-making (Dupont *et al* 2020). Therefore, there is a need for an integrated framework that would enable a holistic assessment of trade-offs between different uses of natural resources to support the communication with multiple sectors and guide policy decisions and planning.

2.2. Section one: Bayesian ecosystem model

The ecosystem-based natural capital evaluation framework (figure 1) builds on a Bayesian modelling approach, that uses long-term historical data on physical (e.g. temperature), biological (e.g. fish stock biomass) and anthropogenic marine use (e.g. fisheries catch) components to model ecosystem status (Trifonova *et al* 2021). These components will change with climate change and the very large extraction of energy (100s of GW) from ORE developments (van der Molen *et al* 2014, Wakelin *et al* 2015, Holt *et al* 2016, Boon *et al* 2018, De Dominicis *et al* 2018, Sadykova *et al* 2020). The model is a spatio–temporal ecosystem approach that provided further insights into the best physical and biological indicators within four different habitat types that will contain different types of ORE extraction: shallow (<50 m; static wind), deep (>50 m; floating wind), or oceanic influenced (with either high tidal or wave energy resources) of shallow seas and their associated ecosystems. This unique approach works across a range of spatial and temporal scales and allows for interactions amongst different ecosystem components to be incorporated. At the same time, the approach can accommodate expert elicitation, alongside observed data (Uusitalo 2007). The approach holds the ability of investigating scenarios to investigate the effect of ORE developments to explore the likely outcomes of alternative management and climate scenarios (such as the business-as-usual climate scenario), and for evaluating trade-offs among sectors and services (Trifonova *et al* 2017; table 1). As applied in ecology, Bayesian networks represent probabilistic dependencies among species and their surrounding environment in an intuitive, graphic form (Jensen and Nielsen 2007), therefore different experts can have a quantitative indication of the range of possible scenarios consistent with the data to give strategic advice on potential ecosystem response. The visual nature of Bayesian networks can help communicate modelling results and they allow a variety of perspectives of natural and anthropogenic effects to be represented (Levontin *et al* 2011). The usefulness of scenarios in supporting environmental resource management is becoming increasingly recognized internationally (e.g. Marine Ecosystem Assessment, Scenarios Assessment[12]) and in the UK (Pinnegar *et al* 2006, Fernandes *et al* 2017). For example, one could ask, what is the probability of seeing a change in the stock biomass of herring, given that we have observed a change in the probability distribution of fisheries catch, due to changes caused by displacement from wind farms, sea temperatures and the prey of herring? Through the developed scenarios, we can explore the specific trends (increase vs decrease) of multiple species and functional groups of lower trophic groups (such as zooplankton) throughout the ecosystem in response to change in drivers and examine potential trade-offs between herring as well as other important (highly protected) species, such as seabirds and marine mammals, which are the common predators of herring.

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[12] www.millenniumassessment.org/en/Scenarios.html.

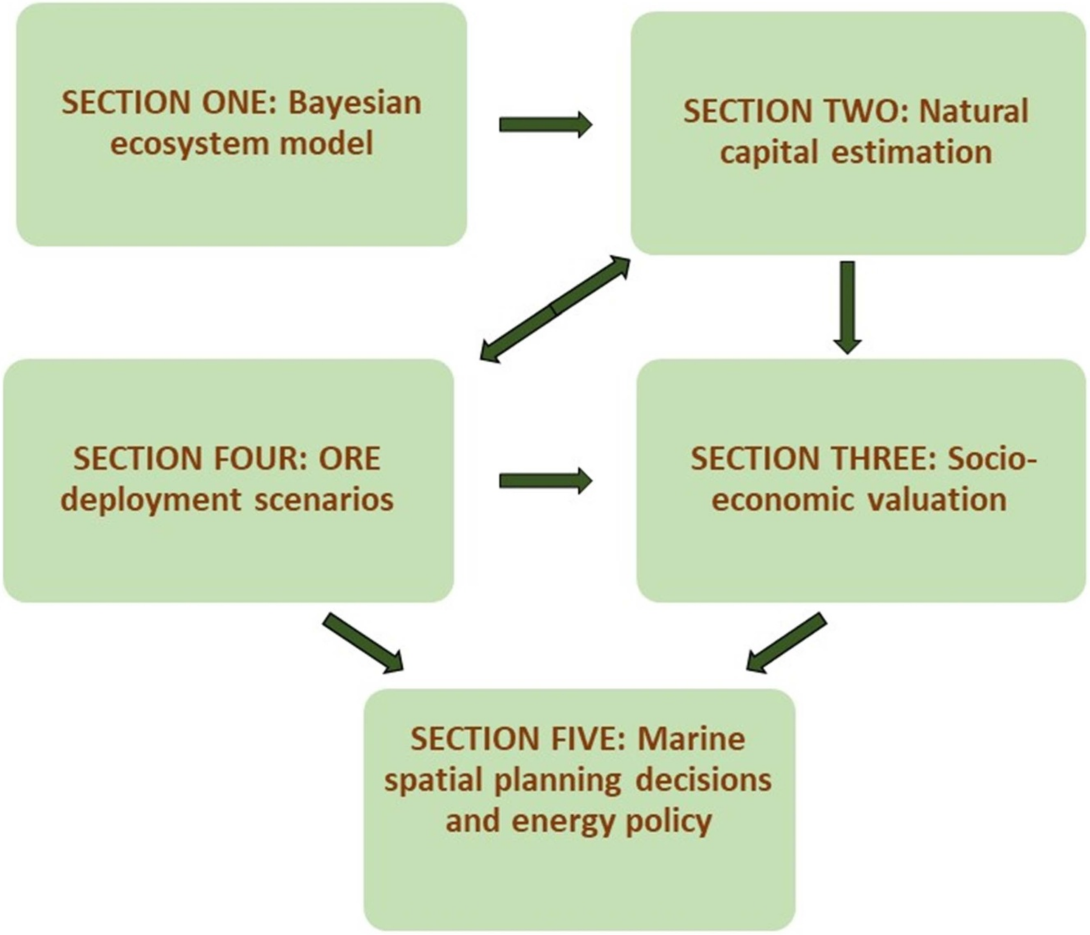

Figure 1. Graphical representation of the sequence of sections that form the ecosystem-based natural capital evaluation framework. The arrows represent flow of information within the sections of the framework necessary for incorporating ecosystem-level knowledge and natural capital into marine spatial planning decisions and energy policy.

Table 1. Sections of the ecosystem-based natural capital evaluation framework and their methods and potential examples of ecological and socio-economic outcomes and their metrics in response to alternative natural (e.g. climate change) and anthropogenic (e.g. increase or decrease in fishing catch) scenarios.

Sections	Methods	Outcomes
Bayesian ecosystem model	Natural (e.g. climate change) or anthropogenic (e.g. increase or decrease in fishing catch) Bayesian modelling scenarios	e.g. increase or decrease in fish stock biomass (in kilograms)
Natural capital estimation	Natural (e.g. climate change) or anthropogenic (e.g. increase or decrease in fishing catch) Bayesian modelling scenarios	e.g. increase or decrease in fish landings (in kilograms)
Socio-economic valuation	IO analytical model, MCA, CBA	e.g. increase or decrease in economic activity (e.g. ORE deployment costs) and social welfare, both in monetary (GVA change) and non-monetary terms
ORE deployment scenarios	ESME tool, supply chain scenarios	Amount of energy (GW)
Marine spatial planning and energy policy	Communicate findings of the framework through publications, policy briefs. Dissemination and discussion of findings through engagement with science, industry, and policymakers	Ecosystem (e.g. species and locations within the marine environment); economic activity (e.g. job creation); social welfare (e.g. consumer and producer surplus from fishing)

2.3. Section two: natural capital estimation

Next, the Bayesian modelling outcomes, i.e. species trends of increase or decrease via a particular fish species (e.g. herring) and the changes in stock biomass (in kilograms), will be used in a scenario analysis to estimate the change (increase vs decrease) in natural capital value of the fish population in terms of the service it provides (e.g. food provision for human consumption) (figure 1; table 1). Using the Bayesian modelling approach, we can estimate how the herring landings can change in section two, by examining changes in the physical (e.g. temperature), biological (e.g. zooplankton abundance, i.e. prey for herring) and/or anthropogenic (fisheries catch) components and their effects on herring stock biomass from section one. For example, what is the probability of seeing a change in the total herring landings, given the change (decrease) in areas of catch from ORE developments, but an increase in bottom temperature, and a decrease in zooplankton prey from climate change? In this way, we can explore the trend (increase vs decrease) of the herring landings, given a change in drivers, that we know are important for herring stock biomass, given the outcomes from previous ecosystem network analysis of the last 30 years (Trifonova *et al* 2021). It is important to note that with using such scenarios, we are not attempting to indicate levels of plausibility but rather explore the predictive results of relative differences of species and ecosystem-level responses and the changes associated with well-being that arise from natural and anthropogenic change. Such outcomes would allow the dynamic assessment of choices, which should be able to provide strategic advice on potential system response to different and cumulative levels of drivers.

2.4. Section three: socio-economic valuation

In section three, given the outcomes of increase or decrease in the amount of fish landed for human consumption from section two, we can estimate its change in value. In the sphere of economic valuation, there is a distinction between valuing the stock of natural capital or the flow of ecosystem services. In practice, most environmental goods and services are measured in flow terms, estimating the value change for a given (current) period. Measures like GVA, which represents the annual sum of operating profit and labour income, and other components of national accounts, such as GDP, are typically used as a tracking index through time. Other measures like change in net or gross revenue or change in annual household willingness to pay are also measures of the change in ecosystem service flow value. The marginal change in a natural resource can also be measured as the change in dynamic value through time, accounting for rates of time preference and induced long term stock changes that affect future service provision (Fenichel and Abbot 2014). This allows for resource valuation that more accurately reflects that resource stocks are likely not in equilibrium and assuming a constant stream of ecosystem service flow through time is misleading.

Approaches for valuing ecosystem service flows are widely available, even if in practice studies often stop short of measuring values and settle for changes in biophysical terms (Mandle *et al* 2021). Natural capital concepts are almost exclusively used for public and private decisions for marketed goods like fish, timber, water, oil, and gas, though there have been some recent advances in applying them to non-marketed goods, like storm protection (Bond 2017). Given the dynamic nature of the Bayesian model applied in sections one and two, the proposed natural capital evaluation framework is suitable for stock or flow value measurement, depending on decision needs.

2.5. Section four: ORE deployment scenarios

The framework also holds the potential to link ecosystem-level effects and ecosystem service value changes through the use of ORE deployment scenarios that present the potential economic benefit, for example in GVA terms, of deploying innovative ORE developments in domestic and international waters (Supergen ORE Hub Policy Paper, Policy and Innovation Group, University of Edinburgh, 2021[13]; figure 1). Section four is founded on deployment scenarios, where cost, performance and systemic conditions are defined, for example, by the 2030 levelized cost of energy targets in the UK Strategic Energy Technology Plans for ORE (wave, tidal stream, and floating offshore wind) technologies. Deployment modelling obtained from the Energy Systems Catapult[14] and the International Energy Agency[15] can be utilized alongside an Input Output analytical model (Leontief 1986) for valuation (section three).

The time series of the installed capacity are coupled with deployment costs, leakage rates, and GVA effects to obtain GVA results associated with the different project phases and components. For example, a Low Ambition scenario vs High Ambition scenario generates £16.4 bn in GVA vs £41.4 bn in GVA for the UK economy, respectively, both derived from 57 GW (floating offshore wind, wave and tidal) ORE deployment by 2050. The proportion of the total spending associated with the domestic and international deployment

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[13] www.supergen-ore.net/uploads/What-is-the-value-of-innovative-ORE-deployment-to-UK-economy.pdf.

[14] https://es.catapult.org.uk/reports/innovating-to-net-zero/.

[15] www.iea.org/reports/energy-technology-perspectives-2020.

retained in the UK is dependent on the relative strength of the UK supply chain. For example, an increase of 151% in GVA from domestic deployments has been modelled due to more ambitious retention assumptions reflecting a stronger supply chain. This highlights the significant potential value to the UK if the UK government invests in developing the local supply chain ahead of these deployments. Such an economic benefit from ORE developments will bring multiple benefits, such as decreased consumption of fossil fuels and job opportunities in various sectors of the economy. Such deployment scenarios can be investigated with Input Output analytical model, as well as how the ORE industries will benefit economically remote coastal communities and assess the value of ORE deployments in the context of reducing climate change.

The Input Output analytical model has been successfully applied for the local community in Orkney, Scotland, where a socio-economic impact assessment of a renewable wave device, Aquamarine Power's Oyster project, evaluated the impacts on employment and GVA (Yuille 2009). Another study outlined the potential economic benefits of developing an ocean energy industry in Ireland, including a roadmap for the development of the sector (Connor 2010). In the U.S., an impact study using the Input Output method explored the impact on the economy of expenditure on ORE projects out to 2050 (Pollin *et al* 2009), whilst a study by Hoagland *et al* (2015) evaluated the economic impacts and social welfare changes to both coastal and non-coastal communities from displacement of commercial fishing by offshore wind. By using the knowledge from the deployment scenarios on the amount of GW and GVA benefit, the framework holds the potential of estimating the amount of space and locations within the marine environment needed for such developments and how existing marine uses (e.g. fisheries activities) will interact with the planned ORE developments.

2.6. Section five: framework outcomes to support marine spatial planning decisions and energy policy

Using knowledge on the amount of GW and GVA benefit, combined with the scenario outcomes on the ecosystem and natural capital changes from sections one and two, the framework will be able to identify ecosystems (i.e. locations) in which ORE developments and other stressors (climate change) and marine uses (e.g. fisheries activities) might have the strongest impacts (increase or decrease) on fish stock biomass, landings, and fisheries production. These outcomes will be used to estimate any socio-economic impacts in both monetary and non-monetary terms, using the valuation techniques and decision frameworks from section three, thus minimizing negative effects and prioritizing locations and management plans accordingly (figure 1; table 1). The framework provides a dynamic assessment of alternative management and climate scenarios across spatial and temporal scales, given the interaction among multiple marine uses in the context of climate change. By identifying highly sensitive vs more robust ecosystems and their locations, and how changing the location and extent of the most impactful uses, the framework can assess changes in flows of ecosystem services and offers changes in stock values of natural capital that will allow us to make judgements and decisions about the environmental, social, and economic benefits and trade-offs within spatial scales, among sectors, and between users. This could also be linked to non-consumptive values from marine species, such as sightseeing and recreational activities, and non-market values people hold for species' existence.

Such information will ideally support the communication with other sectors, in particular the fishing industry, and assist the development of marine spatial planning, marine policy statement, MNG and energy policy. Improved research outcomes on ecosystem-level changes and their well-being outcomes, associated with spatial variation in the design and location of ORE developments, builds on a growing scientific capability to incorporate these into policy (Jacobson *et al* 2014, Samoteskul *et al* 2014, Griffin *et al* 2015). This improved understanding would ideally enable the integration of fisheries activities in order to better assess issues, such as potential fisheries displacement and encourage involvement of the industry at the beginning of the CIA processes.

The framework will provide us with better assessment of the changes resulting from climate change, ORE developments, and changes in fishing on the marine system which will inform the optimum development arrangement (i.e. size and array design) and locations within the marine environment to maximize MNG, energy sustainability and support multiple benefits. A core part of achieving the UK Energy Security Strategy will be to consider environmental considerations more strategically and the proposed framework is perfectly aligned to contribute to this aim. Indeed, the framework will provide an approach to measuring the relative value of MNG interventions in terms of wider natural capital accounting, in line with the UK Environmental Accounts such as those produced by the Office of National Statistics and could support the basis of any future economic consideration of MNG including market-based approaches. Progressing understanding of ecosystem services and market-based approaches could inform developing a sustainable fisheries policy, including climate change adaptation policies in marine plans, and supporting the development of adaptive capacity of marine sectors. 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 Year Environmental Plan (HM Government 2018), the UK Marine Strategy[16], as well as the Sustainable Development Goals[17].

3. Framework potential with other ecosystem service examples and their issues

The proposed framework holds the potential to identify, quantify and map ecosystem-level changes and natural capital in the context of multiple ecosystem services to highlight spatial, temporal, and socio-economic differences, and explore trade-offs. As ORE developments continue to grow, changes in biodiversity could affect the provision of ecosystem services through the associated processes and functions (Gill 2005).

3.1. Primary production

As an example of important ecosystem service, changes in primary productivity have been recorded around wind turbines in shallow sea regions (<50 m), which are likely to have positive effects on the availability of food to higher trophic levels and may well have knock-on effects to food provision and cultural experience of iconic species, such as birds and marine mammals (Causon and Gill 2018). However, results from the few studies that have included analyses of the wind farm and/or tidal turbine impacts on primary production, differ among regions, due to their unequal topographic and oceanographic conditions and consistent outcomes are lacking to allow informed decision-making. The introduction of devices and their energy extraction will inevitably affect the timing, distribution, and composition of plankton communities, causing food availability displacement (van der Molen *et al* 2014, Ludewig 2015, 2016, Schultze *et al* 2020, Wolf *et al* 2021). Such changes are likely to be strongly linked with storage of organic carbon and bottom-up effects on climate regulation (Causon and Gill 2018). Yet, at present, the extent to which regulating ecosystem services (e.g. climate regulation) maybe altered by ORE developments is unknown. There is the need for empirical measurements of the vertical distribution of chlorophyll-a (as a measure of primary production) and nutrient concentrations on and around ORE developments. Quantifying the value of climate regulation requires an understanding of carbon sequestration, including the mechanisms for sequestration: e.g. export, burial, and resuspension rates (Busch *et al* 2012). Because of a lack of data, values related to carbon sequestration by marine ecosystems are not included in the current estimates. Therefore, data are needed on the amount of standing stock biomass for phytoplankton, zooplankton, and higher trophic levels, as any changes to the benthic ecosystem, due to ORE developments, can have profound implications for the provision of valuable ecosystem services, including those related to sea mammals, birds, and fish (Wilding *et al* 2017).

3.2. Wildlife tourism: marine mammals

Marine mammals have traditionally been part of Scottish marine heritage and utilized economically (Parsons *et al* 2003). Whale-watching has become a fast-expanding tourist attraction and the number of commercial tourism enterprises has grown significantly (Thompson 1994). The value to the Scottish economy of wildlife tourism is £127 million per year, specifically, dolphin watching, for example, on the east coast of Scotland generates £4 million for the local economy each year (Bryden *et al* 2010; NatureScot Heritage[18]).

Given top predators' geographic distribution and high mobility, there is a high potential for interactions between seabirds and marine mammals and ORE developments, even including those in development (Skeate *et al* 2012). ORE developments are thought to have several effects on marine mobile animal populations, although the extent to which these are biologically significant at the population scale remain uncertain (Dierschke *et al* 2016, Gasparatos *et al* 2017, Joy *et al* 2018, Skov *et al* 2018, Gill *et al* 2020). The effect of ORE developments on marine animal populations is difficult to establish, also due to the influence from other factors (e.g. climate change), including the ambiguity around complex behavioural movement, breeding/haul-out sites, migratory and feeding routes, but also species- and site-specific differences (Teilmann *et al* 2006, Lindeboom *et al* 2011, Mangi 2013). Any negative effects on wildlife as a result of ORE developments may also have social and economic implications for nature-based tourism (Maunsell and Metoc 2007). For example, changing migration patterns and the redistribution of species have the potential to change the length and nature of wildlife-based tourism seasons (Lambert *et al* 2010, Coles 2020). Empirical evidence is needed to estimate the scale of the effects of ORE developments on mobile marine animal populations and consequently on the services they provide. Recognizing the relevance of scale in relation to ORE interactions with both lower and higher trophic level species, can aid understanding of population-level changes and inform regulators in applying more species-specific regulations (Wilding *et al* 2017).

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[16] www.gov.uk/government/publications/marine-strategy-part-one-uk-updated-assessment-and-good-environmental-status.

[17] https://sdgs.un.org/goals.

[18] www.nature.scot/sites/default/files/2019-07/Valuing%20naure%20based%20tourism%20in%20Scotland.pdf

3.3. Climate change: carbon emissions

Moreover, the introduction of ORE developments will have positive effects on other service values, such as the value of avoiding carbon emissions (A Sustainable Ocean Economy for 2050, World Resources Institute[19]; Bang *et al* 2019, Barthelmie and Pryor 2021; Ørsted ESG Performance Report 2020[20]; Spyroudi *et al* 2020). It can also potentially help mitigate hurricane damage by diminishing hurricane wind speeds and storm surge (Jacobson *et al* 2014) and can effectively protect the coast from heavy rains during hurricanes (Pan *et al* 2018). However, even the wide social acceptance of ORE developments (Henderson *et al* 2003, Haggett 2011, Hattam *et al* 2015), there will be some societal challenges. Some of these challenges, due to visual proximity, include the perceptions of coastal communities towards offshore wind farms (Lacroix and Pioch 2011, Ladenburg and Möller 2011, Chen *et al* 2015), changes in recreation value (Ladenburg and Dubgaard 2009, Landry *et al* 2012) and house values (Ladenburg and Dubgaard 2007, Krueger *et al* 2011, Ek and Persson 2014).

3.4. Maritime transport

Another critical interaction is the one between ORE developments and maritime activities, such as shipping and navigation costs (Samoteskul *et al* 2014, Mehdi *et al* 2018). It has been discussed that offshore wind farms can pose risk to navigational safety, leading to increased traffic density and risk of collision (Mehdi and Schröder-Hinrichs 2016, Wright *et al* 2016). Since more efficient use of offshore space increases social welfare by providing more with less impact, it is a desirable policy goal and should be fostered where possible (Griffin *et al* 2015). The co-location of multiple marine uses to examine benefits and trade-offs can potentially increase the production and enjoyment of our seas, while limiting impacts and should play a key role as part of marine spatial planning.

4. Coordination needed to move towards an ecosystem-based natural capital evaluation framework

4.1. Levels of local, regional, and international cooperation

Although, interactions between fisheries and energy industries present challenges, through coordination, cooperative research, and iterative engagements, there is the potential for an inclusive approach to decision-making (Twigg *et al* 2020). Successful examples of bringing together fisheries and ORE developments and providing a range of management recommendations to support decision-making, in relation to the multiple marine use in the same area, have been illustrated for Scotland and Germany (Schupp *et al* 2021). For example, since 2015, the Forth and Tay regional advisory group (FTRAG Group 2015[21]) and the Moray Firth regional advisory group (MFRAG Group 2015[22]) in Scotland act as mechanisms for developers in these regions to pool resources, and work collaboratively with government, NGOs, and Statutory Nature Conservation Bodies, in order to prioritize and progress strategic research areas. Such groups enable monitoring and feedback into impact assessments and can act as a template for undertaking strategic research to inform future developments, but have not, so far, led to research at the ecosystem scale. The International Council on the Exploration of the Sea (ICES) is advancing transboundary, collaborative offshore wind and marine research through working groups that consider ORE, benthic interactions with ORE developments, and, most recently, fisheries and offshore wind (Gill *et al* 2020).

Improved spatially explicit fisheries data, along with onsite continuous monitoring, will be advantageous, to obtain better understanding of how species and ecosystems would respond to ORE introductions, as well as the socio-economic responses of fishing industry and local communities (Methratta and Dardick 2019, Gill *et al* 2020). In addition, it is important to distinguish effects in the context of existing long-term trends of species dynamics, in relation to fishing and environmental variables, and evaluate resources within and out of managed areas (Addison *et al* 2015). Given the uncertainties caused by climate change, the complexities associated with species abundance and distribution, must be considered by ORE impact assessments (Perry and Heyman 2020). Thus, taking a holistic ecosystem-level and ecosystem service valuation approach to explaining the changes and value of the fisheries and other marine resources to support understanding of the economic and societal impacts of the ORE developments is needed to assist energy policy development, planning, decision-making, and potential mitigation suggestions (Hooper *et al* 2017, Gill *et al* 2020).

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[19] https://oceanpanel.org/sites/default/files/2020-07/Ocean%20Panel_Economic%20Analysis_FINAL.pdf.

[20] https://orsted.com/esgperformance2020.

[21] https://marine.gov.scot/ml/forth-tay-regional-advisory-group-ftrag.

[22] http://marine.gov.scot/ml/moray-firth-regional-advisory-group-mfrag.

4.2. Formalizing natural capital and ecosystem service linkages within energy system models

By placing a monetary valuation on the environmental impacts, decision makers will be able to examine ecosystem service issues and their impact on economic activity and social welfare. In addition, monetary outcomes can be used in collaboration with energy system models (e.g. UK TIMES[23] and Scottish TIMES model[24]) that are used for energy technology assessment and aim to minimize total energy system cost. The monetary valuation of environmental impacts can be used to inform the energy system models to investigate the economic, social, and technological trade-offs between long-term divergent energy scenarios, which will lead to a greater ability to launch interdisciplinary studies between ecologists and economists. Specifically, by promoting such collaboration, the energy system models will be able to identify areas where investment may not just enhance human well-being but also nature.

4.3. Incorporating ecosystem modelling linked to habitat risk in an ecosystem-based framework

An ecosystem-based approach using a habitat risk assessment dynamic Bayesian network (HRA-DBN) is another alternative (Declerck *et al* 2021). The approach brings together the dynamic data-driven Bayesian spatio–temporal ecosystem approach (Trifonova *et al* 2021) and a Habitat Risk Assessment (HRA) model, which is one of the InVEST[25] (Integrated Valuation of Ecosystem Services and Trade-offs) models, created by Stanford University (Natural Capital Project[26]). Thus, the model will calculate the cumulative vulnerability, generated by several stressors for each habitat or trophic key ecosystem component and facilitate the identification, as well as the testing of innovative compensatory measures. This will help identify potential mitigation and compensatory measures at correct spatio–temporal scales to maximize future ecosystem value and functioning to enhance marine spatial planning processes.

The notion of ecosystem services and the value they bring to human well-being has been recognized in other existing frameworks, such as the one from Olander *et al* (2017), who reported on best practice for integrating ecosystem services into federal decision making in the U.S. and has been successfully applied to advance natural and nature-based solutions to coastal protection (Arkema *et al* 2017). It is an assessment framework build on causal chains that link change in ecosystem structure and function to the ecosystem services that benefit people. For example, a decision to invest in habitat restoration can lead to change in habitat structure (e.g. presence of oyster reef and/or width of saltmarsh buffer), which in turn can lead to a change in biophysical conditions (e.g. wave attenuation) and changes in the services provided to people (e.g. reduction in erosion or flooding of coastal property).

There are a few recent examples attempting to develop coupled environmental and socio-economic approaches, such as a Bayesian belief network approach that was developed for the Basque coast to identify trends in the strength and spatial distribution between natural capital dependencies and maritime activities to identify the potential socio-economic impacts of management decisions and contribute towards ecosystem-based spatial planning (Gacutan *et al* 2019). Another example of movements in this direction are an analytical tool to help understand the positive connection between the environment and human well-being which has been developed by the Joint Nature Conservation Committee (JNCC) for terrestrial environments (Howard *et al* 2016) and two separate frameworks that are currently being developed for the marine environment by JNCC and the Centre for the Environment, Fisheries, Aquaculture Science (CEFAS). The purpose of such tools is to ensure that planning and management of the environment considers the diverse ways in which it supports human well-being.

However, both tools assume that the connections between ecosystems and human well-being are ‘static’. 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), which threatens the provision of ecosystem services and can impact human well-being in a negative way (Campagne *et al* 2021). On the contrary, our proposed framework provides a dynamic assessment of the ecosystem components (e.g. physical environment through to seabirds and marine mammals) and the multiplicity of their interactions across spatial and temporal scales to be able to assess changes in flows of ecosystem services and in stock values of natural capital. An added value of the proposed approach is that the outcomes can also be used as inputs to the current ‘static’ framework approaches of JNCC and CEFAS.

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[23] www.ucl.acuk/energy-models/models/uk-times.

[24] https://archive2021.parliament.scot/S5_Environment/General%20Documents/20160922_Scottish_TIMES_model_-_an_overview.pdf.

[25] https://naturalcapitalproject.stanford.edu/software/invest.

[26] https://invest-userguide.readthedocs.io/_/downloads/en/3.8.5/pdf/.

5. Conclusion

A step-change is occurring in the use of coastal seas globally, specifically by the addition of large-scale ORE developments, to combat climate change and achieve sustainable affordable green energy. Considering the relationship between species distribution, population dynamics and physical habitats, and to ensure the compatibility of ORE developments with other marine management sectors, it is evident that a holistic approach, to account for cumulative impacts of ORE at an ecosystem scale, is an essential goal to address baselines for consenting and decision processes (Wolf *et al* 2021). Using ecosystem models at ecologically meaningful scales to understand how ecosystems respond to multiple stressors will support the cumulative assessment process and the inherent multi-objective decision process of integrating ORE into the marine environment (Piroddi *et al* 2015). To address that and to incorporate both direct and indirect effects on the ecosystem, ecosystem models need to be linked with a hydrodynamic-biogeochemical-sediments modelling system (Schuchert *et al* 2018, Wolf *et al* 2021). Under business-as-usual scenarios, climate conditions in 2050 are predicted to have even 10 times more of an effect on marine habitats than very large-scale energy extraction (De Dominicis *et al* 2018, Sadykova *et al* 2020). These modelling results highlight the need to make a policy including climate change effects as a part of the consenting process.

By placing both monetary and non-monetary values on ecosystem goods and services, natural and anthropogenic impacts can be measured using similar metrics. This approach would make the connection between marine ecosystems and human well-being more explicit and make benefits and trade-offs easier to compare. The potential use for ORE developers and marine planning policy makers is obvious, as it allows the examination and comparison of all uses of marine space and any consequent environmental and/or socio-economic impacts. Currently, ecosystem service values are underrepresented in UK and U.S. national policy level assessments (Atkinson *et al* 2018), so this proposed framework can help bridge that gap and bring ecosystem-level changes into the socio-economic analysis of ORE developments. Communicating results of the environmental, social, and economic impact of marine renewable developments together, in the context of climate change, and other marine activities, such as, fisheries, will inform practitioners about the location and design of ORE developments when making decisions to balance environmental sustainability, economic activity, and social welfare.

Data availability statement

No new data were created or analysed in this study.

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