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An assessment model for linking changes in pelagic habitat state to impacts on human wellbeing

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ABSTRACT

Plankton monitoring datasets help inform indicators for marine biodiversity assessments under the European Union Marine Strategy Framework Directive and United Kingdom Marine Strategy. These indicators are used to assess long-term changes in the state of the pelagic habitats of the Northeast Atlantic which then guide policy formation and implementation to achieve Good Environmental Status. Across all ecosystems, environmental change has the potential to impact upon human wellbeing by changing the quantity and quality of ecosystem services. Here, we develop a socio-ecological assessment model that can describe how variations in pelagic habitat state, evidenced by plankton indicators, can impact human wellbeing. We show that pelagic habitat state can influence human wellbeing through changing the availability of 'goods and benefits' (as made available via ecosystem services), such as the contribution of phytoplankton to climate regulation, but also through mediating the risks of 'ecosystem hazards'. Importantly, changes to pelagic ecosystem state will also drive changes to ecosystem services and ecosystem hazards in the wider marine food web, supported by ecosystem processes associated with plankton, such as the rate of primary production. Applying the proposed assessment model to plankton monitoring data highlights the potential for a greater depth of understanding of the human wellbeing impacts driven by state changes in pelagic habitats. Alongside making best use of the available plankton monitoring data, quantifying the human wellbeing impacts arising from changes to pelagic habitat state increases the evidence base for decision makers.

1. Introduction

Climate change and other human activities are driving substantial changes in the biodiversity and functioning of marine ecosystems [1,2], placing a range of human goods and benefits (ecosystem services) at risk [3]. Ecosystem-based management (EBM) approaches are being implemented internationally, with the aim of regulating these human activities to limit subsequent pressures on marine ecosystems [4]. EBM recognises that human wellbeing, including that related to health, social cohesion, cultural fulfilment, and economic prosperity [5,6], is dependent on healthy ecosystems. The relationships between humans and ecosystems are therefore addressed in EBM frameworks to encourage and support future sustainability [4]. The OSPAR (Oslo-Paris) Convention, European Union's Marine Strategy Framework Directive (MSFD) and United Kingdom's Marine Strategy (UKMS) have ensured biodiversity assessments of the Northeast Atlantic follow an EBM approach [7,8], to manage the ecosystem impacts of human activities in the Northeast Atlantic. OSPAR, MSFD and UKMS policy mechanisms are therefore informed by assessments of both ecosystem state and the potential for state changes to impact human wellbeing [7].

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Comprising the ocean's entire water column, covering 71 % of the planet's surface, and with an average depth of over three kilometres [9], pelagic habitats are a key component of marine EBM biodiversity assessments. Pelagic habitats are critical to the existence of life on Earth, supporting global food webs and driving fundamental biogeochemical processes [10]. A key biological component of pelagic habitats is the plankton. Plankton regulate the overall functioning of pelagic ecosystems, where phytoplankton drive over half of global primary production, underpin the global carbon pump, and support most marine food webs [11–15]. Plankton therefore underpin a range of ecosystem services, from fish caught for human consumption to genetic resources supporting medical research [16,17]. Notwithstanding the substantial benefits provided by plankton, they also present various hazards which have the potential to negatively impact human wellbeing or occasionally cause loss of life. Such hazards include shellfish poisoning incidents, driven by harmful algal blooms [18], and human injuries from certain jellyfish species [19].

However, plankton community composition is highly sensitive to environmental changes, including sea surface temperatures and nutrient concentrations [20]. The sensitivity of plankton to environmental change, coupled with their role in underpinning pelagic ecosystem functioning, has supported the development of a suite of plankton indicators that enable monitoring of changes to pelagic ecosystem processes [2,21]. Plankton indicators are informed by metrics extracted from plankton time-series datasets [22,23] and assess key changes to pelagic processes, such as primary productivity, overall biodiversity, and relationships between plankton functional groups [24]. Monitoring changes in the functioning of pelagic habitats through plankton indicators can provide a greater understanding of changes to the state of pelagic habitats under climate change and direct human pressures [23–25]. The MSFD and UKMS use descriptors of Good Environmental Status (GES) as a benchmark for ecosystem state [26]. By assessing whether pelagic habitats are in GES, plankton indicators can inform decisionmakers of the impacts of human activities and climate change on the marine environment [21,27].

Pelagic habitats face a range of direct and indirect pressures which drive changes to plankton indicators of state. Climate change exerts substantial pressure on pelagic habitats, for example through increasing temperatures, stratification, deoxygenation and ocean acidification, alongside increasing likelihood of extreme weather events, together driving changes in plankton biomass and community composition [28–32]. Direct pressures from human activities can also drive changes to the state of pelagic habitats, for example, nutrient input from agricultural activities can increase the primary productivity of coastal waters and impact the food web [33–35]. Multiple pressures on plankton may have compounding and synergistic effects, such that the total change in ecosystem state may be more than the sum of that predicted from individual pressures [36–38]. Consequently, recent assessments of the Northeast Atlantic marine environment [21,27] have highlighted that many plankton indicators show long-term negative changes, demonstrating that the state of pelagic habitats are not in GES. Changes to the state of pelagic habitats have identified changes to the overall functioning of pelagic ecosystems, impacting species composition, overall biodiversity, and food web functioning [21]. Failing to meet GES indicates that there are changes to ecosystem functioning that are likely to impact the provision of a range of human goods and benefits from the marine environment [27].

To inform decisionmakers of the societal consequences of not meeting GES, the DAPSIR (Drivers – Activities – Pressures – State changes – Impacts – Response) framework (Fig. 1) helps enable EBM by linking human activities (and their consequent environmental pressures) to ecosystem state changes and subsequent impacts to human wellbeing [39]. To assess the human wellbeing impacts of ecosystem state changes, the Natural Capital (NC) approach has been integrated into MSFD and UKMS marine biodiversity assessments [40]. NC approaches were designed as a management tool to account for the human goods and benefits at risk from ecosystem degradation [41], therefore overlapping with the goals and data requirements of EBM [40]. For marine biodiversity assessments under UKMS and MSFD, the Common International Classification of Ecosystem Services (CICES) [42] framework is used to assess the human wellbeing impacts arising from state indicator changes (Fig. 1) [39,40].

However, the components which should be included in ecosystem service frameworks, such as CICES, are debated. One such component is broader ecosystem processes, such as primary production and nutrient cycling, which were originally included in the Millennium Ecosystem Assessment as supporting services [43]. The Millennium Ecosystem Assessment [43] and UK National Ecosystem Assessment [44] distinguish supporting services from the provisioning, regulating and cultural services that contribute directly to human wellbeing, including through goods and benefits. CICES [42] excludes supporting services altogether, only providing classifications of 'final' ecosystem services. Supporting

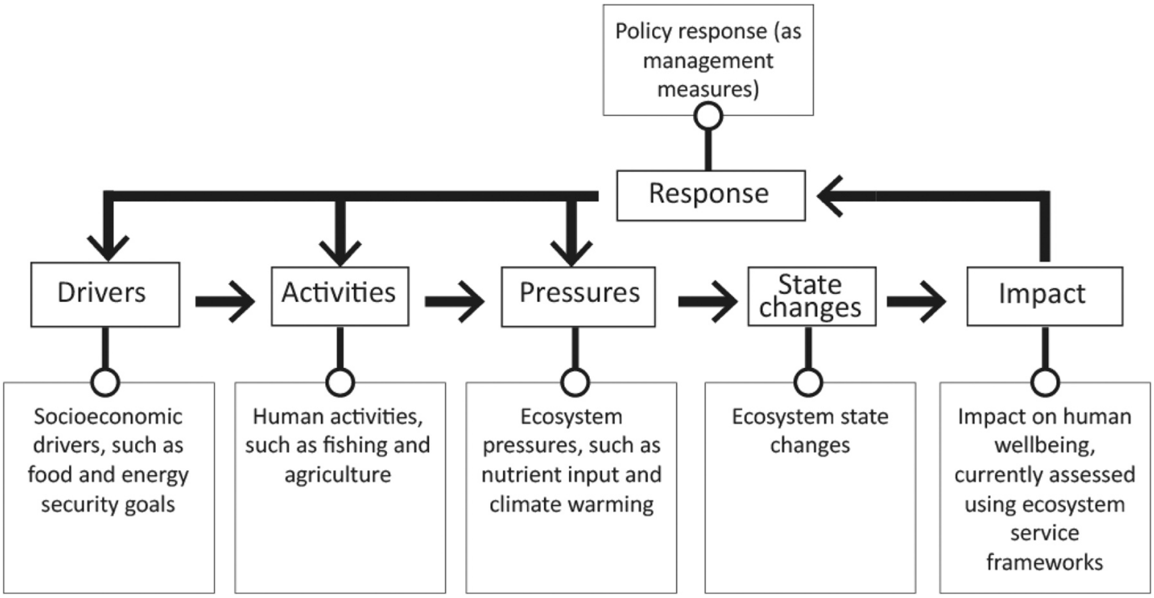

Fig. 1. DAPSIR framework underpinning OSPAR assessments (based on Elliott et al. [39]).

services are now generally excluded from NC accounting to mitigate the risk of double-counting the benefits from ecosystems [45]. Here we use the term 'ecosystem services' (ES) only for what these authors call 'final services', referring to everything else as 'ecosystem processes'. The exclusion of ecosystem processes from frameworks is highly relevant to plankton, where changes to pelagic ecosystem processes (assessed according to plankton indicators) could place a range of ES provided by the marine environment at risk [27,46]. Although the availability of non-plankton marine ES, such as wild fish catch for human food, are determined by a range of factors beyond plankton (e.g., environmental variability and fishing pressures) [47], the understanding of the complex relationship between plankton indicators and non-plankton ES is increasing [48].

In addition, the hazardous components of ecosystems are also excluded from ES frameworks [49]. Although the term 'ecosystem disservice' has been used to define the negative impacts of ecosystems to both human wellbeing and the wider environment [50,51], the term is not included within current frameworks [42,52]. Negative human wellbeing impacts have been excluded from the NC approach partly to avoid increasing the negative perceptions of some wildlife (e.g., sharks known to attack humans), which in turn may result in poor conservation outcomes [53]. However, the links between human-driven changes in the marine environment and emerging risks to human wellbeing have been well established [54–58], from selected regional harmful algal blooms driven by nutrient pollution [59] to increased shark attacks under climate-driven marine heatwaves [58,60]. The inclusion of negative human wellbeing impacts within pelagic EBM assessments would provide increased evidence to decisionmakers of potential consequences to human wellbeing resulting from changes in habitat state.

To ensure EBM biodiversity assessments accurately inform decisionmakers, a comprehensive understanding of the human wellbeing impacts arising from state changes in pelagic habitats is required. Therefore, our aim here is to conceptualise the relationship between pelagic habitat state and human wellbeing. We also aim to demonstrate the management benefits of monitoring hazardous ecosystem components alongside ES within the DAPSIR framework to support pelagic EBM. In this paper, we conceptualise an assessment model to comprehensively assess the human wellbeing impacts of changes to pelagic habitat state (Section 2). We then apply this framework to plankton and provide examples of how changes to plankton indicators can impact human wellbeing (Section 3). Finally, we explore what is required to progress towards assessing a range of ES and hazards, using plankton monitoring datasets to provide additional evidence to support EBM of pelagic habitats (Section 4).

2. Assessment model design

The conceptual framework below (Fig. 2) links pelagic ecosystem

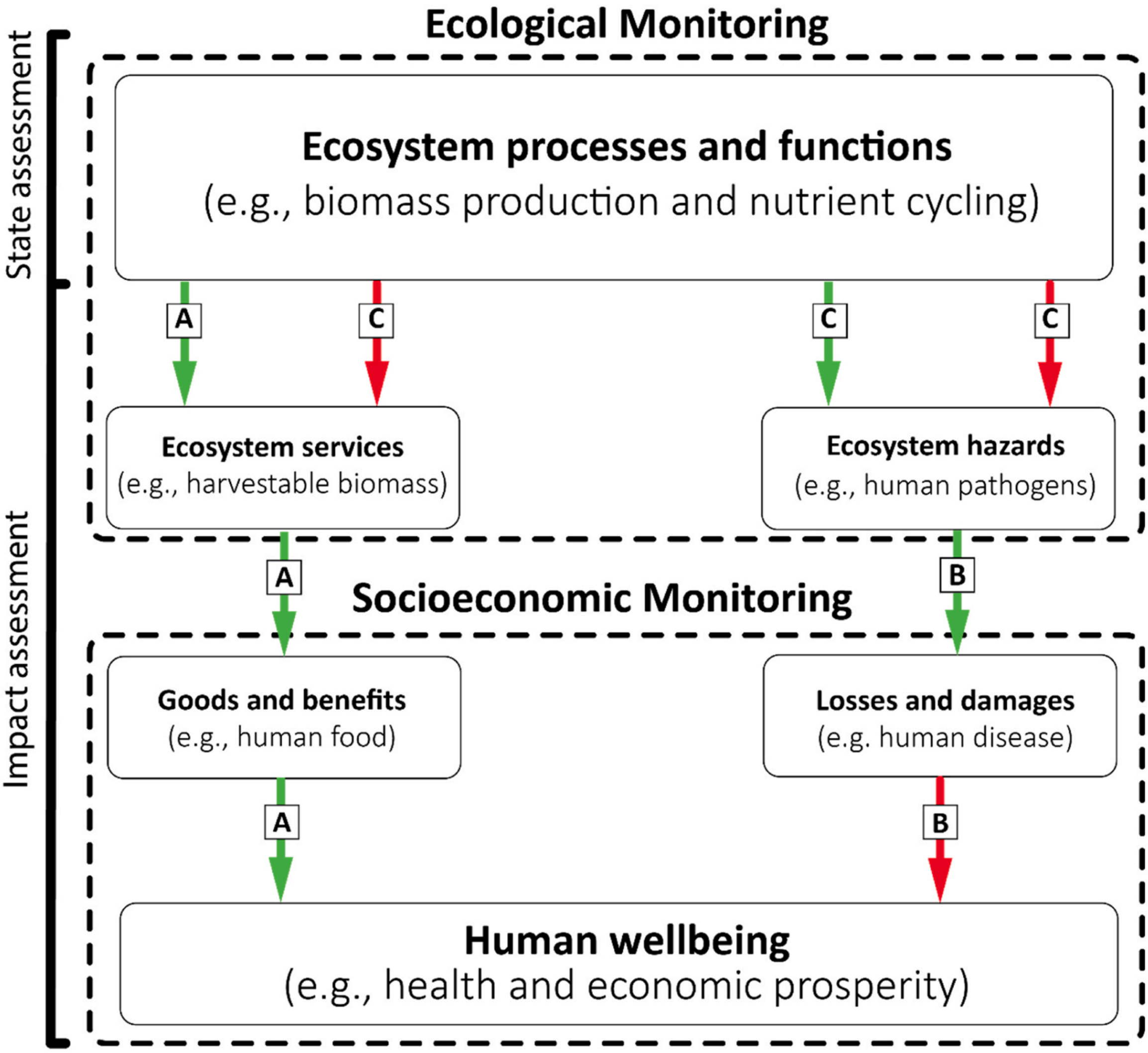

Fig. 2. – A conceptual framework of how pelagic habitats impact human wellbeing with supporting (green) and inhibiting (red) flows, combining concepts of a) ecosystem services (adapted from Potschin and Haines-Young [61]) with introduced concepts of b) ecosystem hazards and c) indirect impacts.

changes with human wellbeing. The framework identifies which socio-ecological components can be monitored with ecological monitoring data, to highlight options to better utilise available datasets. The framework is also split between the DAPSIR components assessing ecosystem state and human wellbeing impacts, to better conceptualise the impacts of state changes on human wellbeing. Existing concepts developed for socioecological systems, which define the flow of human goods and benefits from ecosystems through ES [61] (labelled a in Fig. 2), are combined with information that describes ecosystem hazards (b in Fig. 2). The indirect impacts of ecosystem processes and functions on human wellbeing, through support and inhibition of ES and hazards, are also detailed (c in Fig. 2).

2.1. Ecosystem services

The initial design of the conceptual framework built on existing ES concepts (a in Fig. 2), where the provision of ES is underpinned by ecosystem processes and functions [61,62]. Ecosystem processes include primary productivity and nutrient cycling [63]; ecosystem function is occasionally considered separately to ecosystem processes [61,62] but is widely understood to be a synonymous term [64]. ES then describes a subset of ecosystem processes which can be transformed into human goods and benefits [61,65]. So, whilst the production of plankton biomass is considered an ecosystem process, the available biomass of edible zooplankton (e.g., krill, *Calanus* copepods and some jellyfish species) can be considered as an ES [66]. Goods and benefits provided by ES provide direct support to human wellbeing [67]. The products derived from harvested zooplankton, such as omega-3 and collagen supplements [66], benefit human wellbeing in a range of domains, including supporting health and commercial activities. These ES can be directly monitored with ecological monitoring data (Fig. 2), whereas goods, benefits, and human wellbeing require alternative monitoring datasets [68].

2.2. Ecosystem hazards

The conceptual framework then adopts the term ‘ecosystem hazard’ to define a subset of ecosystem processes which directly inhibit human wellbeing through societal losses and damages (b in Fig. 2). Losses and damages are recognised in climate change policy to define the negative impacts to human health or property, along with social and economic disruption, arising from climatic hazards [69,70]. Ecosystem hazards are akin to climatic hazards (e.g., storms and droughts), but refer instead to the hazards posed by ecosystems, rather than the climate system. Assessing (climatic and ecosystem) hazards can inform adaptation and mitigation measures [71], which reduce the potential for losses and damages. Measures to adapt to pelagic ecosystem hazards could include deploying nets to protect bathers from jellyfish stings [72] and using bubble screens to prevent power plant cooling systems from being blocked by high-biomass jellyfish blooms [73]. Some ecosystem hazards, such as the presence of algal toxins in farmed shellfish, are already monitored by public and environmental health agencies to manage risks to society [74]. However, other hazards, such as those linked to jellyfish blooms, are not yet routinely assessed at the policy-level [75].

Many ecosystem hazards, such as harmful algal blooms, are natural [76] and thus occur within healthy ecosystems which are simultaneously providing valuable ecosystem services [77]. However, the intensity, likelihood and distribution of some pelagic ecosystem hazards, such as some specific types of harmful algal blooms, may be linked to climate change and human pressures on pelagic habitats (discussed in Section 3.2). The intensity and likelihood of these ecosystem hazards may therefore be reduced through effective ecosystem management. While public and environmental health agencies may be responsible for managing societal exposure and vulnerability to ecosystem hazards, EBM biodiversity assessments present a valuable opportunity to assess how human activities could be regulated to reduce ecosystem hazard likelihood and intensity. Ecosystem hazard risk assessments could therefore be made alongside ES assessments in DAPSIR assessments of human wellbeing impacts in EBM, to provide a more comprehensive understanding of the links between human activities, ecosystem state, and human wellbeing.

We have opted to move away from the ecosystem disservice term occasionally used to describe some ecosystem hazards. Disservices generally include both direct and indirect negative impacts [49]; from the conceptual framework here (Fig. 2), ecosystem disservices would include ecosystem hazards, alongside ecosystem processes that both inhibit ES and support ecosystem hazards (discussed in Section 2.3). Our definition of ecosystem hazard is therefore compatible with ES terminology, where both are underpinned by ecosystem processes and functions, along with having a direct impact on human wellbeing [61,62] (Fig. 2). In addition, ecosystem disservice terminology was developed within NC thinking [78], which aims to inform biodiversity conservation measures. Biodiversity declines are not inherently linked to ecosystem hazard risks in the same way as ES declines, potentially indicating why ecosystem disservices have had limited tangible impact on biodiversity decision-making. While ES availability can be effectively assessed through an asset valuation lens (as used in NC approaches), ecosystem hazards should be assessed through a risk-based lens.

2.3. Indirect impacts

The final component of the framework details the relationships between ecosystem processes and ES and hazards (c in Fig. 2), herein referred to as indirect impacts. Marine EBM typically takes a ‘whole-ecosystem’ approach [79,80], making these indirect impacts a critical component of assessments under the DAPSIR framework. Changes to ecosystem processes can act to support and inhibit both ES and hazards, in turn altering the magnitude of positive and negative impacts to human wellbeing (Fig. 2). Ecosystem processes which provide support to ES are widely referred to as supporting services in socio-ecological systems research (a in Fig. 2). However, as already discussed (see introduction), supporting services are not quantified in Natural Capital approaches and are therefore excluded from many frameworks such as CICES. The exclusion of supporting services from frameworks therefore prevents their assessment from ecological datasets in marine biodiversity assessments. Although marine ecosystem processes provide support to ES, such as plankton biomass providing trophic support to commercially harvested fish, the same processes can also provide support to ecosystem hazards (i.e., providing trophic support to potentially hazardous organisms, such as stinging jellyfish). Some ecosystem processes also inhibit ES and hazards (c in Fig. 2), such as wildlife pathogens which can reduce the population size of harvestable organisms (e.g., fish) and therefore inhibit ES availability (i.e., harvestable biomass for human consumption) [81]. Changes to ecosystem processes (detected from state changes) can therefore change the magnitude of support and inhibition of ES and hazards, yet remain excluded from the current DAPSIR implementation of assessing ‘direct’ ecosystem service provision with CICES [27].

The effects of changing ecosystem processes on ES availability are not always immediate. Spatiotemporal lags have been highlighted between state indicator change and subsequent impacts to ES [82,83]; similar lags are likely mirrored between state changes and ecosystem hazards. The presence of temporal lags highlights the potential for state indicator changes to act as a warning to future human wellbeing impacts. The indirect human wellbeing impacts of ecosystem processes changes, through supporting and inhibiting ES and hazards in the wider ecosystem, could therefore be monitored in EBM, to both highlight the full extent of human wellbeing impacts arising from changes to ecosystem state indicators and provide an early warning of future human wellbeing impacts.

2.4. Key impact assessment components

Based on the conceptual social-ecological framework (Fig. 2), we propose an alternative model for DAPSIR assessments of impacts to human wellbeing (Fig. 3). Quantifying changes to the availability of ES from plankton indicators is not enough to fully understand the extent of human wellbeing impacts resulting from pelagic habitat state changes. Instead, we recommend that ES and ecosystem hazards are both assessed within the human wellbeing impact section of DAPSIR. Further, the impact of any changes to the pelagic indicators of state on ES and hazards in the wider marine environment should be estimated as 'indirect impacts'. An alternative approach to solely assessing ES, additional assessment of ecosystem hazards and indirect impacts (Fig. 3) will provide more comprehensive evidence of the human wellbeing impacts arising from changes to pelagic habitat state.

3. Applying our assessment model to plankton

By applying our proposed model to currently available plankton monitoring data, we demonstrate its potential to comprehensively link pelagic habitat state with aspects of human wellbeing.

3.1. Ecosystem services

Recent research has identified a range of ES provided by plankton, with several examples of provisioning, regulation and maintenance, and cultural services [66,84–86]. Although plankton provide trophic support to wild fisheries [87], some plankton, including krill, copepods and some species of jellyfish, are also directly harvested for human consumption [66,88]. Plankton play a pivotal role in global climate regulation, where phytoplankton primary production drives the biological carbon pump, which helps reduce the build-up of atmospheric CO_2 [89, 90]. Plankton provide a range of cultural services, including tourism activities focussed on bioluminescence and jellyfish blooms [91–93]. Plankton are also important to traditional, indigenous and local knowledge systems, where box jellyfish are used as seasonal indicators by Aboriginal communities in Australia [66].

The ecological changes associated with pelagic habitat state changes will affect the availability of plankton ES. For example, increased temperatures and ocean stratification is projected to reduce overall phytoplankton primary productivity in many regions [32]. This reduction would be detected by the currently used pelagic state indicators [27]. While primary production is not an ES itself, reductions in phytoplankton primary production will reduce plankton contributions to global climate regulation (an ES) [89]. Although some cultural ES are more difficult to quantify [94], changes to a range of other plankton ES (i.e., Provisioning and Regulation & Maintenance services) could be directly quantified from plankton monitoring data.

3.2. Ecosystem hazards

Some types of plankton present ecosystem hazards. Some jellyfish species, for example, are known to cause sting injuries [19,95,96], with some stings so severe they can cause human fatalities [97–99]. Jellyfish can also cause severe disruption to industrial activities, including blockages at power station cooling facilities (potentially leading to power cuts), finfish mortality in aquaculture and unmanageable bycatch for fishers [100,101]. Similarly, bacterioplankton can be pathogenic [55,102] and some high-biomass phytoplankton blooms can also cause blockages in industrial water inlet pipes [103]. Other high-biomass blooms (e.g., *Noctiluca* and *Phaeocystis* spp.) can produce sea foams often perceived as unsightly, resulting in beach closures in tourist areas, or cause mass mortalities at aquaculture sites [104]. Finally, some phytoplankton produce toxins which can be aerosolised and act as severe irritants to users both in and close to the water [105–107].

Climate change and direct human pressures can increase the likelihood and severity (risk) of pelagic ecosystem hazards. Pelagic organisms adapted to a temperature range typically found in tropical regions are undergoing range expansions under warming [108], increasing the range of any associated ecosystem hazards into temperate regions. This is a particular concern with pathogenic *Vibrio* species, which alongside being adapted to tropical temperatures, thrive in high nutrient concentrations, increasing the spatial range of *Vibrio*-related diseases with both climate change and nutrient pollution [55,56,81]. The risk of other pelagic ecosystem hazards, such as those associated with jellyfish, have been identified as increasing in ecosystems experiencing human pressures [57,109]. Although the notion of global human-driven increases to jellyfish populations is disputed [110,111], several relationships

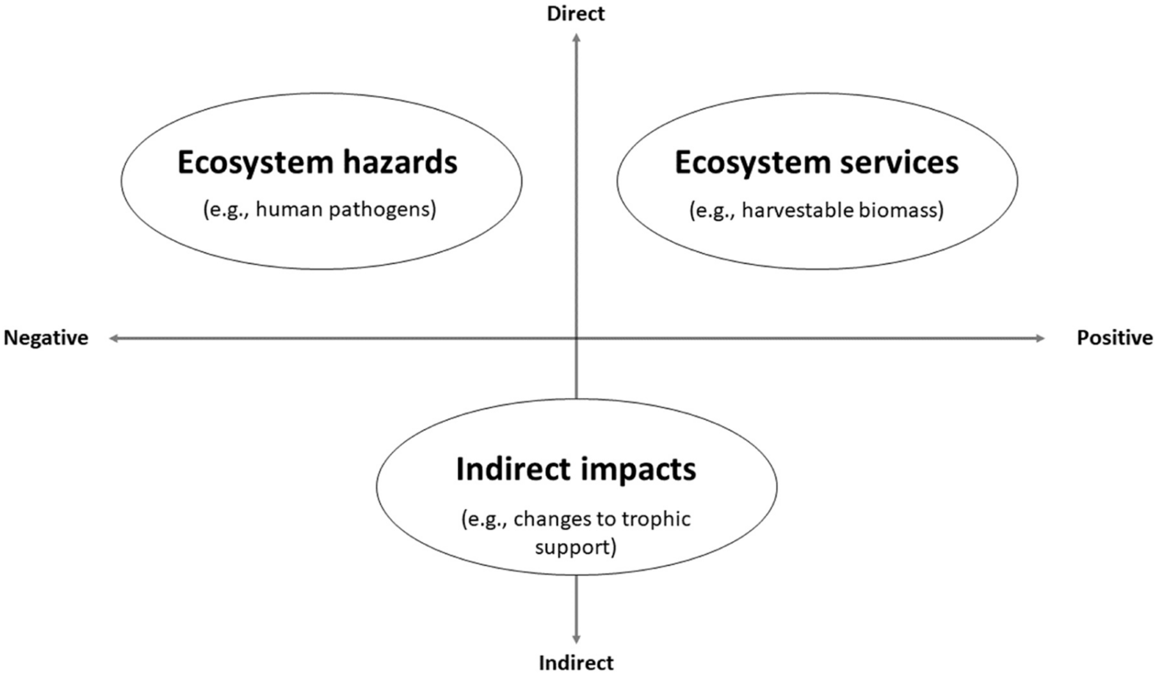

Fig. 3. – A proposed model for assessing the human wellbeing impacts arising from changes to the state of ecosystems in DAPSIR approaches to EBM assessments.

between human activities and increasing jellyfish populations have been hypothesised. The introduction of engineered hard structures enable polyps to settle [109], fishing activities reduce prey competition and predators [112], and reduced light penetration in eutrophic waters may allow predators which do not rely on visual ability (i.e., jellyfish) to outcompete those which do (e.g., fish) [113].

3.3. Indirect impacts

As discussed, plankton can impact human wellbeing indirectly, by supporting and inhibiting a range of non-plankton marine ES and hazards. Primarily, plankton are associated with the trophic support of most marine food webs, in turn underpinning the majority of biotic marine ES [11,12]. Plankton are therefore already monitored to understand the impacts of changing plankton communities on highly valued marine ES, such as the impact of changes in copepod biomass on commercial fisheries [114]. However, other plankton inhibit ES, where some bacterioplankton cause disease and mortalities in wild fish populations, reducing the harvestable population size [81]. Some plankton also support ecosystem hazards. Harmful Algal Blooms are widely discussed in the context of human health hazards, however only a small number of Harmful Algal Bloom genera, such as palytoxin producers (e.g., *Ostreopsis*), are a direct hazard to human health [115] (See Section 3.2). Shellfish toxin-producing phytoplankton do not produce toxins at a concentration sufficient to impact human health, but only pose a risk when toxins are bioaccumulated at higher trophic levels, such as in filter-feeding shellfish [115–117]. These toxin-producing phytoplankton, such as species in the genera *Pseudo-nitzschia*, *Dinophysis* and *Alexandrium*, indirectly impact human wellbeing by contaminating filter-feeding crustaceans and increasing the risk of shellfish poisoning [118], an ecosystem hazard.

Plankton community changes associated with pelagic habitat state changes therefore impact a range of marine ES [27] and hazards. Excessive coastal phytoplankton primary production (i.e., eutrophication) can inhibit several marine ES, including all of the services provided by seagrass (where phytoplankton biomass reduces light penetration and prevents seagrass growth) [119,120], tourism services (by reducing the aesthetics of the area) and recreational services, such as SCUBA diving activities (due to decreased visibility) [121]. Plankton community changes can also support marine ecosystem hazards, where the increased productivity associated with eutrophication has been linked to increased rates of shark attacks on humans around affected river mouths and beaches, likely driven by more availability of prey for sharks (i.e., fish and marine mammals) supported by increased plankton biomass [58]. A particular ES at risk from climate-driven decreases in phytoplankton primary productivity is food provision, where a decrease in the efficiency of pelagic food webs will likely reduce the supportable biomass of fish and result in reduced food provision [48]. Plankton monitoring datasets could support efforts to assess and model the impacts of pelagic state changes on a range of marine ES and hazards, providing valuable evidence of indirect human wellbeing impacts.

However, it is important to caveat that changes to plankton communities are not the only component determining the extent of non-plankton marine ES and hazards. Fisheries, for example, are vulnerable to a range of pressures which can determine the population of harvestable fish stocks [122]. Increasing temperature can act as a stressor to pelagic fishes, leading to changes in distribution, larval recruitment, and resilience of populations [123,124]. Although temperature increases have already supported the targeted fishing of new species, due to spatial range expansions [125], other fisheries have experienced lower catch rates [126]. Direct human pressures, particularly fishing pressures, also play a key role in determining the availability of harvestable fish biomass [127]. Plankton monitoring data should therefore not be solely relied upon to quantify the indirect human wellbeing impacts arising from changes to other marine ES and hazards, such as impacts to fisheries, but instead be used as an additional source of evidence for monitoring and modelling efforts [128].

4. Towards implementing our assessment model in biodiversity assessments

Recent pelagic habitat assessments in the Northeast Atlantic have graded the impact of changes to plankton state indicators on the provision of marine ES [27]. However, current methodologies are semi-quantitative and based on expert opinion, broadly linking overall state assessments (i.e. whether GES is met or not) to ecosystem services provided by pelagic habitats across the whole Northeast Atlantic [27]. Quantitative approaches which directly link ecological [128] and pressure [129] data to human impacts provide much more detailed evidence for decision-making, supporting the effective targeting of management measures. Although plankton have been linked to ecosystem services in the literature (see Section 3.1), a quantitative assessment of plankton ecosystem service provision has yet to be made for EBM. Changes to plankton ES availability could therefore be directly assessed from monitoring data, contributing additional insight into human wellbeing impacts from pelagic habitat state changes. ES frameworks, such as CICES, provide a basis for identifying which ES plankton provide. Future work should therefore establish metrics to support the development of plankton ES indicators from monitoring data.

In addition to ES assessments, our proposed assessment model also includes ecosystem hazards and indirect impacts (Fig. 3). Recent work has made direct estimates of the trophic support provided to commercially harvested fish from phytoplankton biomass (an indirect impact), allowing high-resolution mapping of impacts to fisheries goods and benefits, as plankton productivity changes with climate pressures [48, 128]. Due to the exclusion of indirect impacts in current DAPSIR approaches, quantitative assessments of these indirect impacts are currently excluded from EBM assessments. Future work should look beyond the fisheries impacts of plankton ecological changes, quantifying the indirect impacts to a broad range of ecosystem services provided by marine ecosystems, from seagrass to marine mammals and seabirds. Developing quantitative approaches to modelling links between plankton and the wider marine food web will provide a basis for assessing the indirect impacts of changes to plankton indicators of state in future EBM assessments of pelagic habitats.

In a similar way, some plankton ecosystem hazards have been quantified from various forms of plankton monitoring data [130,131]. For example, the risks of jellyfish blooms have been modelled in the Eastern Mediterranean Sea using citizen science datasets, to understand the likely distributions of stinging species [131]. Plankton monitoring surveys are also regularly used in environmental and public health domains to protect public health from the risk of shellfish poisoning incidents [74]. However, as ecosystem hazards are not currently assessed in the DAPSIR approach, EBM assessments have been prevented from linking these hazards to ecosystem pressures and informing management measures. Further work will be required to enable the quantification of ecosystem hazards from available plankton monitoring data. In a similar way to plankton ES assessments, metrics to quantify changes to ecosystem hazards directly from plankton monitoring need to be established. Further, an assessment protocol for quantifying changes to ecosystem hazards, such as a risk assessment framework, could be developed to support assessments using our proposed assessment model (Fig. 3).

5. Conclusions

The assessment model proposed here supports a holistic approach to assessing the human wellbeing impacts arising from pelagic habitat state changes. Recent assessments of pelagic habitats for EBM have recognised that pelagic habitats which are not in GES are likely to reduce the provision of several ES. However, here we demonstrate that ecosystem state changes may not only reduce the provision of human goods and benefits through ES losses but could also lead to increased risks of direct losses and damages through ecosystem hazards. In addition, changes to plankton state indicators are likely to drive wider changes in marine ecosystems and indirectly impact humans by regulating ecosystem services and hazards beyond plankton. Both ecosystem hazards and indirect impacts should therefore be assessed alongside ecosystem services to provide decisionmakers with comprehensive evidence of how pelagic habitat state changes are likely to impact society. With further work to develop appropriate metrics, our assessment model can make use of available plankton monitoring data to assess these human impacts in future EBM biodiversity assessments of pelagic habitats.

CRediT authorship contribution statement

Matthew Faith: Conceptualization, Writing – original draft, Writing – review & editing. **Sian Rees**: Conceptualization, Writing – original draft, Writing – review & editing. **Angus Atkinson**: Writing – review & editing. **Mike Best**: Writing – review & editing. **Eileen Bresnan**: Writing – review & editing. **Michelle Devlin**: Writing – review & editing. **Matthew Holland**: Writing – review & editing. **Holly Niner**: Writing – review & editing. **Clare Ostle**: Writing – review & editing. **Paul Tett**: Writing – review & editing. **Abigail McQuatters-Gollop**: Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

None declared.

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Data availability

No data was used for the research described in the article.

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