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A cumulative impact assessment on the marine capacity to supply ecosystem services

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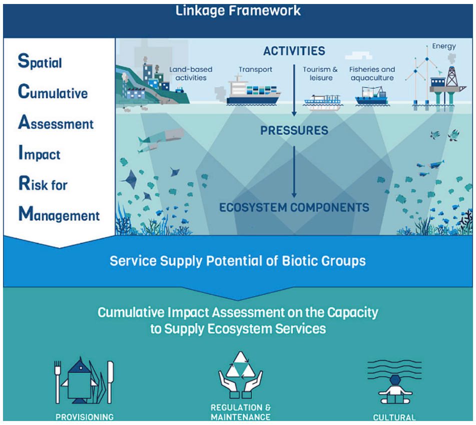
HIGHLIGHTS

- Assessment of main anthropogenic threats to the supply of ecosystem services.
- Method applies quantitative metrics based on a review of potential indicators.
- The metrics for ecosystem functioning were obtained from a foodweb model.
- The societal preferences were incorporated through expert-judgement.

GRAPHICAL ABSTRACT



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ABSTRACT

Ecosystem services link the status of biodiversity and its functioning to societal goods and benefits contributing to human wellbeing. As such, they can play a key role in preserving the environment and managing natural resources and ecosystems to conserve nature's contributions to people. Identification of the main threats acting on the natural environment, and how these may impact its capacity to supply ecosystem services, is fundamental to the maintenance of these services. To that end, we present a novel approach based on a cumulative impacts assessment that 1) covers all relevant human activities and their pressures, 2) links impacts to the biotic groups that make up biodiversity and 3) provides an estimation of the Service Supply Potential based on the functioning of these biotic groups. Key proxy metrics to estimate this Service Supply Potential were identified from a literature review and quantified using a food web model (Ecopath with Ecosim). In addition to this quantitative information, the assessment of the capacity to supply ecosystem services was supplemented with expert judgement-based information to reflect the societal preferences that drive the allocation of human capital and turn these services into societal goods and benefits. As a proof of concept, the method was applied to the North Sea ecosystem. Results showed that, overall, the capacity of the North Sea to supply Cultural ecosystem services

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was most threatened, with an average potential decline of 50 % compared to an undisturbed situation. This was followed by the Provisioning ecosystem services with 46 % and the Regulation & Maintenance with 38 %. The main anthropogenic threats (excluding climate change) to the North Sea capacity to supply ecosystem services come primarily from fishing contributing to 51 % of the overall threat. Of the remaining 18 sectoral activities another 23 % was contributed by mining, non-renewable energy, tourism, and agriculture.

1. Introduction

Ecosystem recovery and the sustainable exploitation of marine resources are important for the conservation of nature's contributions to people (e.g. MA., 2005; IPBES, 2018). Ambitions to quantify nature's contribution to people (NCP) has given rise to the concept of 'natural capital', a concept that explores the flows of ecosystem services in the context of human benefits, and how management scenarios may be able to sustain or improve flows in the future. Ecosystem accounting is a key analytical tool to provide insights for managing natural capital (EEA, 2018). The System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA EA) (UN, 2014) adapts the concepts developed for the estimation of ecosystem services, such as the cascade model (Haines-Young and Potschin, 2010; Potschin and Haines-Young, 2011), and can be placed within the conceptual framing of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al., 2015). Within this framework, the ecosystem asset is a key concept that refers to the individual spatially defined statistical units (spatial perspective), the ecological functional units (the ecological perspective) and the supply or producing units that deliver ecosystem services and associated benefits (the societal benefit perspective). In an accounting context, the concept of ecosystem capacity embodies the link between the ecosystem asset extent and condition, and the ecosystem services supply and use (UN, 2021). This study therefore focusses on the concept of ecosystem capacity.

The complex problems we are currently facing, such as climate change and biodiversity loss, require integrated assessments of all anthropogenic threats and ecosystem-based management, supported by inter- and transdisciplinary science that considers the whole social-ecological system (Biggs et al., 2012; Liquete et al., 2013; Maes et al., 2012; Mee et al., 2015). This requires the development of approaches that bridge the gap between the ecological system and the social system. Ecosystem services are such a concept as they are being used in the cascade model (Haines-Young and Potschin, 2010; Potschin and Haines-Young, 2011) to link biophysical structure, processes, and functions (together making up the environmental system) with their goods and benefits and how these are valued in the socio-economic system (Burdon et al., 2022; von Thenen et al., 2020; Drakou et al., 2017; Guerry et al., 2015). Potential threats to biodiversity and ecosystem integrity thus affect the capacity of ecosystems to supply ecosystem services (Müller and Burkhard, 2007; Quintessence, 2016) and their contribution to human well-being (Costanza et al., 1997, Mace et al., 2014). As such, the future developments of environmental assessments are usually limited to estimating impacts on biodiversity, and there is a large need to bridge the gap with the social system through the application of ecosystem services. These extended assessments would then cover all aspects of sustainability, i.e. environmental, social, and economic, thereby improving their relevance for ecosystem-based approaches to management (Berkes, 2012; Borgström et al., 2015). It is expected that such extended assessments would better guide advancements towards, and assess trade-offs between, diverse co-occurring objectives such as those that require us to safeguard human and ecosystem health, enable food security, support the sustainable growth of marine economies, and expedite biodiversity recovery (Judd and Lonsdale, 2021).

In this study, our focus is on the assessment of the ecosystem capacity to supply ecosystem services (CtSES), thus focussing on the ecological system and, specifically, the ecological functional units, i.e. biotic groups (the assets in an accounting context), that produce the ecosystem services. This focus suggests that the goods and benefits and hence the socio-economic system are excluded from this assessment. However, we assert that a proper assessment of the CtSES cannot avoid to consider the expected goods and benefits these ecosystem services are supposed to supply as these determine the potential interactions of the biotic groups with the built, human, and social capital in order to provide those good and benefits (Burdon et al., 2022; Elliott, 2023). After all, ecosystem services are intended to link ecosystem structure and functioning to human well-being through those good and benefits (Potschin and Haines-Young, 2011). To identify the threats that may impact the CtSES, we apply a Cumulative Impact Assessment (CIA) (Culhane et al., 2019a, 2019b; Piet et al., 2023) which estimates how the cumulative pressures of all human activities impact the biotic groups that make up marine biodiversity, with an estimate of the Service Supply Potential (SSP) (Teixeira et al., 2019; Culhane et al., 2019a, 2019b) representing the relative contributions of the biodiversity components in terms of their functioning. This SSP can be quantified using a set of proxy metrics from a review of indicators intended to operationalize ecosystem services assessments (von Thenen et al., 2020).

Changes across food webs, through direct and indirect interactions between species, the environment, and human use, are key to understand and account for ecosystem dynamics in management decisions (Belgrano et al., 2019). Food web modelling approaches, such as Ecopath with Ecosim (EwE) (Christensen and Walters, 2004; Coll and Steenbeek, 2017; Horn et al., 2021), are used to provide information on ecosystem dynamics (Craig and Link, 2023). In the context of this study, EwE quantifies the functioning of the various biotic groups in terms of their contribution to the supply of ecosystem services. The biotic groups that make up marine biodiversity are central to this CIA method, as they connect the impact from human activities and their pressures through their SSP to an overall assessment of the cumulative impact on the CtSES. The assessment is conducted for the North Sea as a proof of concept, but the method outlined in this paper can be applied in any marine ecosystem where comparable information is available. In less data-rich situations the application of expert-judgement to estimate specific parts of the method (e.g. SSP), is always an option. The current study uses the cascade model to define and explore several options for the estimation of SSP and how these may affect the outcome of the assessment to provide guidance for the development of the knowledge base required to assess the cumulative impacts on the CtSES.

2. Material and methods

The approach to assess the CtSES is illustrated in Fig. 1 showing that it is based on an understanding of how all the different anthropogenic stressors interact with the biotic groups as represented in the so-called linkage framework. A cumulative impact assessment, i.e. SCAIRM (Spatial Cumulative Assessment of Impact Risk for Management) (Piet et al., 2023), is then applied to estimate the risk that those biotic groups are impacted while the SSP represents the contribution of the functional biotic groups to the CtSES. Together this provides an estimation of the cumulative impacts of all anthropogenic stressors on the CtSES.

2.1. *Linkage framework*

To assess the impact of human activities on North Sea biodiversity, we adopted an evolving linkage framework which forms the basis of previous CIA (Knights et al., 2015; Piet et al., 2015, 2017a, 2019;

Borgwardt et al., 2019), with its latest iteration described by Piet et al. (2023). This linkage framework consists of impact chains linking human activities, via pressures, to ecosystem components in order to assess the main threats to biodiversity. The ecosystem components are aligned to the Marine Strategy Framework Directive (MSFD) (EC commission decision (EU), 2017) for policy relevance. For the purposes of this assessment this linkage framework was extended to include ecosystem services using known linkages between specific biotic (or functional) species groups and ecosystem services from Culhane et al. (2018a, 2018b, 2019a, 2019b). To that end the ecosystem components were matched to the biotic groups identified by Culhane et al. (2018a, 2018b) as the most relevant ecosystem services providing units. This was straightforward for the species groups (e.g. fish & cephalopods, mammals or birds), but involved several connections for those ecosystem components which are essentially communities associated to habitats in the MSFD (e.g. phytoplankton or zooplankton with the pelagic water column and benthic invertebrate infauna with several seabed habitats).

A key requirement for a CIA, and hence this linkage framework, is that it should comprehensively encompass all of the relevant activities and pressures that may affect all ecosystem components/biotic groups that make up biodiversity and the ecosystem services it supplies. The selected activities, pressures, and ecosystem components/biotic groups with applied typologies are adequately described in the previous CIA studies on which this study builds (Knights et al., 2015; Piet et al., 2015, 2017a, 2019; Borgwardt et al., 2019; Culhane et al., 2019a, 2019b) but are also shown in the Supplementary Material (SM1). The ecosystem services and their typology were based on CICES 5.1 (Haines-Young and Potschin, 2013; Potschin-Young et al., 2018; Haines-Young and Potschin-Young, 2018), which is the de facto standard reference classification for ecosystem services. Moreover, it is aligned with other ecosystem services classification systems (UN, 2021), such as those used by the Millennium Ecosystem Assessment (MA., 2005) and The Economics of Ecosystems and Biodiversity (TEEB) (Ring et al., 2010). For the linkage framework, the ecosystem services are distinguished at the Class level resulting in 45 types of ecosystem services comprehensively covering Provisioning, Regulation & Maintenance, and Cultural services (Haines-Young and Potschin-Young, 2018)). Every biotic group that can be expected to contribute to the supply of a specific ecosystem service group is then linked to it using Culhane et al. (2018a, 2018b) without any consideration of its relative contribution. In a subsequent step, this relative contribution is weighted through its SSP.

2.2. *Cumulative impact assessment*

For the CIA of the ecosystem and its components, i.e. biotic groups, we applied the SCAIRM model (see Supplementary Material SM2) as this is probably among the most sophisticated risk-based approaches available for CIA and has the advantage that impact is expressed as the "potential change in state compared to an undisturbed situation" (Piet et al., 2023) which can be easily transferred to an understanding of how the CtSES may potentially change. The model is developed for the North Sea and consists of 23,744 impact chains that link 106 human activities and their operations through 28 pressures (see Supplementary Material SM1) to a set of eight ecosystem components consisting of species groups and habitats according to the MSFD (EC, 2008) which were then matched to the 12 biotic groups (see Supplementary Material SM3 for cross-linkage). This model estimates the cumulative Impact Risk as a potential change in state, expressed as a relative change in equilibrium abundance of each ecosystem component compared to an undisturbed situation.

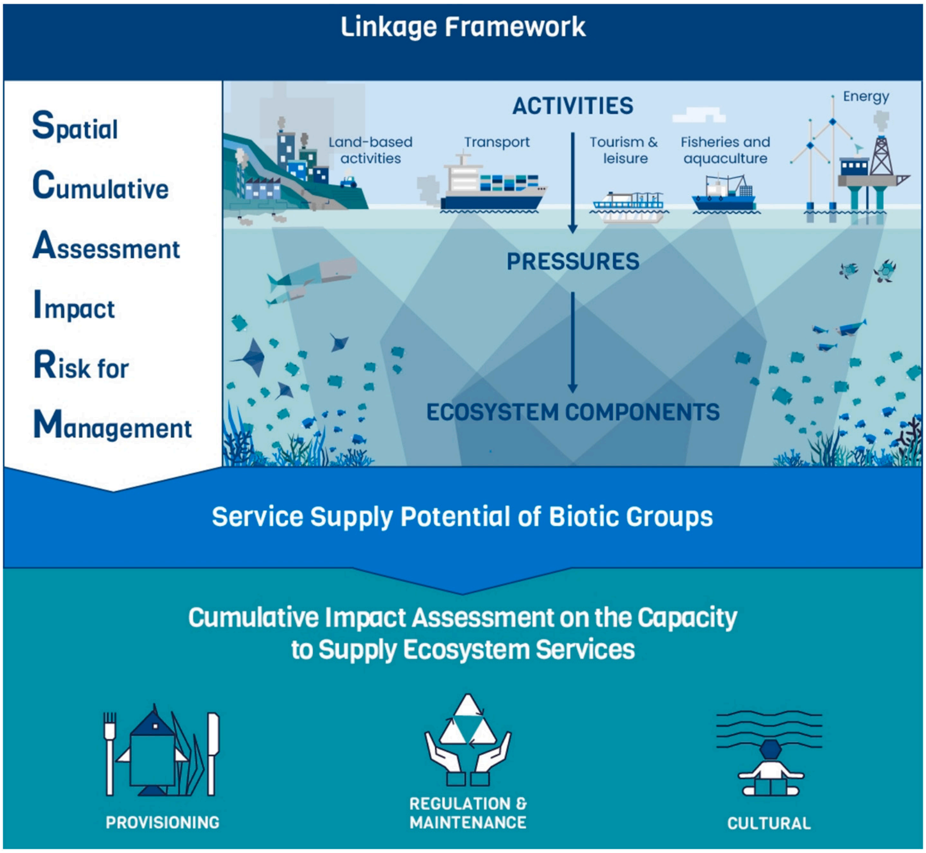

Fig. 1. Outline of the material and methods where the Cumulative Impact Assessment on the Capacity to Supply Ecosystem Services is calculated from the combination of the existing North Sea SCAIRM method and an estimation of the Service Supply Potential of the functional biotic groups. The North Sea linkage framework is represented in Fig. 6, the estimation of the Service Supply Potential is elaborated in Table 1.

2.3. Service supply potential

The present study works from the cascade model (Potschin and Haines-Young, 2011) which links the environmental system and its biophysical structure, i.e. biodiversity, to the socio-economic system and its goods and benefits contributing to human well-being through the flow of ecosystem services. Some studies distinguish within the environmental system between the *capacity* underpinned by the biophysical structure and processes which determine the functioning, and which then turns into the (flow of) *services* if they can be expected to contribute to the goods and benefits (Liquete et al., 2013; Potschin-Young et al., 2017; von Thenen et al., 2020) (see Table 1). Thus, in estimating the SSP we distinguish the capacity, in terms of its biophysical structures, processes and functions, from the ecosystem services where only those biotic groups are considered that are known to be part of, or have contributed to, the goods and benefits according to the links identified by Culhane et al. (2018a, 2018b) (Table 1, Option S1). The relative contribution of those biotic groups to the supply of ecosystem services is then determined by their structural or functional characteristics in relation to the nature of those goods and benefits as represented by appropriate metrics (Option S2) as well as their likelihood to contribute based on current societal preferences (Option S3).

Simply applying the linkage framework and subsequently only looking at the threat posed to each of the biotic groups, would suggest that all selected biotic groups contribute equally to the CtSES of specific ecosystem services. As this is known not to be the case, we worked from Teixeira et al. (2019) and Culhane et al. (2019b) to determine the biotic groups with a Service Supply Potential (SSP) for specific ecosystem services (S1 in Table 1) but instead of the expert judgement-based qualitative valuation used there (i.e. 0, 1, 2; to reflect the importance of a biotic group's contribution to the supply of ecosystem services) we developed an alternative, and more quantitative estimation of the SSP. This ultimately estimates SSP from the perspective of a social-ecological system (Culhane et al., 2019b): in the ecological system the supply of ecosystem services is determined by the amount of each of the biotic groups and their functioning but societal preferences determine how human capital is likely to interact with these biotic groups in order to generate the goods and benefits. Any monetary evaluation of these goods and benefits was considered beyond the scope of the present study (Table 1). The calculation of the SSP thus consists of an interpretation of how the *capacity* of the ecosystem, i.e. biophysical structure and their processes and functions of the biotic groups results in the supply of *services* (S2 in Table 1), the likelihood of contribution assumed to be reflected by current use (S3 in Table 1) which together should provide the best estimation of SSP (S4 in Table 1). The biotic group's functioning was estimated using metrics that could be calculated with existing models. This, however, was not possible for the likelihood of contribution based on societal preferences and thus expert judgement-based values needed to be applied.

To estimate the biotic group's functioning (Option S2 in Table 1) the structured indicator pool developed by von Thenen et al. (2020) to operationalize ecosystem services assessments (see Table 2 and SM4) was used to select appropriate proxy metrics that can be easily estimated. To that end three criteria were applied:

1) The metric adequately captures how the functioning of the biotic group contributes to the SSP of a specific ecosystem services,
2) The metric can be estimated from information that is readily available and
3) The metric is sufficiently consistent among all the biotic groups that contribute to the ecosystem services.

With the principal objective to investigate the impact of human activities on the CtSES, we aimed to estimate SSP (1st criterion) using indicators and indicator themes that represented either "Capacity" or "Services" according to von Thenen et al. (2020), while also ensuring metric selection met the 2nd and 3rd criteria. This resulted in the selection of six proxy metrics that covered the essence of most of the indicators and indicator themes, while being broad enough to facilitate the use of available data and consistency in the estimation among all the

Table 1
Options for the estimation of the Service Supply Potential (SSP) per biotic group according to Culhane et al. (2018a, 2018b) to contrast the default is the assumption that SSP is equal (=1) across all possible linkages. These options' sources of information are based on interpretations (Martinetto et al., 2020; von Thenen et al., 2020) of the cascade model (Potschin and Haines-Young, 2011) which now runs from top (biodiversity as the basis) to bottom. The Capacity to Supply ecosystem services is determined by the SSP in the environmental system.

Cascade model		Selection Criterion	SSP estimation	Option
Environmental system	Capacity	Biophysical Structure	Capacity of all possible linkages is determined by their biophysical structure as represented by the Biomass key proxy metric	
		Processes and Functions	Capacity of all possible linkages is determined by their functioning as represented by the Productivity key proxy metric	
	Services	Selection of biotic groups known to be part of, or have contributed to, the goods and benefits	SSP only based on the selected biotic groups as represented by the filled cells in Table 3	**S1**
		According to their structural or functional characteristics as represented by their appropriate key proxy metric, i.e. Biomass or Productivity, depending on the nature of those goods and benefits	SSP only based on the selected biotic groups weighted by their functioning as represented by the appropriate key proxy metric (Table 2)	**S2**
		Societal preferences determined by biotic group characteristics	SSP only based on the selected biotic groups weighted by their likelihood of contribution based on current use. See Table 3	**S3**
		Ultimate estimation based on the combination of the above		**S4**
Socio-economic system	Goods & Benefits	Not considered in this study		

Table 2

Proxy metrics, the information required from the study area and corresponding indicators from von Thenen et al. (2020). Often these may apply to specific biotic groups. The key proxy metrics applied to estimate the SSP are a selection from this.

Proxy metric	Information	Corresponding indicators
Production	The rate (e.g. time^{-1}) of generation of biomass in (a selection of) a biotic group	Primary production (gross, respiration and net), Leaf litter production, Eelgrass productivity, Assimilative/bioremediation capacity, Sequestration potential, algal production rates
Biomass	The mass (e.g. kg) of (a selection of) a biotic group	Biomass of sessile epifauna, Mangrove biomass, Aboveground biomass
Abundance or Density	Count of individuals in (a selection of) a biotic group	Abundance of seagrasses, Density of bioturbators, Abundance of suspension and surface deposit feeder, Depletion in the number of suspension feeders
Extent of habitat	Surface area of a biotic group (e.g. km^2)	Coral extent and condition, Substrate cover, Diversity and abundance of cold-water corals, Extent of selected emerged/submerged/ intertidal habitats, Seagrass extent, Mangrove extent, Number of operational taxonomic microbic units, Plant cover
Presence	The presence or absence of (a specific selection of) a biotic group	Presence of bioturbator organisms, Presence of floodplains/wetlands/estuaries/ mangroves, Benthic invertebrate species, Presence of nitrophilous macroalgae in catchment basin, suspension feeders, degrading microorganisms, biogenic habitat, four coralline algae, seagrass meadow
Composition	The composition of a biotic group in terms of size- or age-classes, traits, species richness or other biodiversity indices	Size-frequency distributions of corals, Submerged and intertidal habitats diversity, Topographic complexity of corals, Benthic biodiversity, Species composition and area covered with wetlands, Feeding modes, Food web structure and robustness (various properties), Functional variation of predatory performance, Marine food chain, Connectivity/diversity/trophic composition, Consumption of organisms by fish/foodchain relationships, Species richness

biotic groups.

The proxy metrics in Table 2 represent the main aspects of the biotic groups in terms of how much their functioning can be expected to contribute to the CtSES. They also cover the distinction used in ecosystem capital accounting between 'assets' and 'flows' (Maes et al., 2013), where *Production* represents the flow while the others (e.g. *Biomass*) represent the asset in terms of quantity or quality. Our selection of key proxy metrics was based on previous studies, which stated that ecosystem services are often (but not always) best represented by flows (Maes et al., 2013; Burdon et al., 2022). This resulted in the choice of *Production* as the preferred flow-type key proxy metric to represent the SSP for most biotic group-ecosystem service linkages. The choice of this metric is the consequence of putting more emphasis on the 2nd and 3rd criteria while acknowledging that other indicator themes from the von Thenen et al. (2020) review may be more applicable for the SSP of specific ecosystem services such as those under the division 'Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting'. In addition, we propose several asset-type proxy metrics that are less elaborate to calculate, and therefore more often available, as the fall-back options in case *Production* is not available: *Biomass* was selected as the other key proxy metric as it was considered to represent the CtSES better than *Abundance* of species or *Extent* of habitats which, in turn, are more informative than simply *Presence*. In addition to these metrics, a complementary metric was included that captures the *Composition* of the asset, e.g. in terms of size- or age-classes, traits, species richness or other biodiversity indices. As the indicators in Table 2 and SM4 show, the biotic group is often represented by an asset-type metric of a specific selection or subset within that biotic group considered to better estimate the capacity to supply a specific ecosystem services through what is essentially the combination of two complementary aspects (i.e. amount and composition) of the asset. For example, the selection of bioturbators within the benthic infauna and epifauna (Beauchard et al., 2023) in the case of 'Mediation of wastes or toxic substances of anthropogenic origin by living processes'.

For estimation of the SSP by option S2, we worked from the assumption that, for all the Provisioning services and most of the Regulation & Maintenance services, the production of the biotic group is probably the best proxy for its SSP. This was assumed to be different for the Cultural services where the "Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting" services were assumed to be best represented by biomass, whereas the "Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting" services were assumed to be independent from their actual status in the ecosystem as long as they were perceived as still present and for which biomass is also a good enough proxy.

The likelihood of contribution (Option S3 in Table 1) was introduced to reflect a full (High: 100 %) or limited (Medium: 1 % or Low: 0.1 %) contribution of the biotic group to ecosystem services as can be expected based on the key proxy metric alone. For now we applied a common sense approach based on the current and past contributions deemed adequate to reflect that societal preferences are likely to determine the outcome of such assessments and should be explicitly incorporated.

Here we assumed that, for the “Biomass” Division of the Provisioning ecosystem services, all biotic groups not commonly fished/harvested/reared/cultivated are assumed to contribute much less (an assumed 0.1 %) compared to those that are (i.e. fish, shellfish, cephalopods, macroalgae). This did not apply for the “*Genetic material*” Division of the Provisioning ecosystem services. For all Regulation & Maintenance ecosystem services we assumed a distinction between High and Medium/Low was not appropriate and the default 100 % contribution (weighting factor = 1) was applied. For the Cultural ecosystem services Division “*Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting*” we distinguished between the two ecosystem services Groups. For the Group “*Physical and experiential interactions with natural environment*” we assumed that all biotic groups that are not directly visible (i.e. too small for the naked eye and/or hidden from sight) contributed less (an assumed 1 %) than biotic groups that can be observed without a microscope and/or extraction from their environment. For the other ecosystem services Group “*Intellectual and representative interactions with natural environment*”, as well as the whole ecosystem services Division “*Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting*”, all biotic groups were assumed to contribute an equal 100 %.

Finally, the ultimate and most elaborate calculation of the SSP (Option S4 in Table 1) combines the functioning and likelihood of contribution of the different biotic groups from the perspective of the full social-ecological system.

2.4. Using Ecopath with Ecosim to calculate key proxy metrics

To estimate the SSP for those biotic group-ecosystem service linkages based on the proxy metrics, i.e. production or biomass, we used the estimates of the functional groups as they occur in the North Sea EwE model and matched the output to the biotic groups used in this ecosystem services context. EwE models the foodweb by quantifying biomass (carbon) and energy flows. It is used globally to simulate the ecosystem impacts of fishing and other activities, possibly under various management scenarios, as well as environmental drivers such as climate change on the structure and function of marine ecosystems (Christensen and Walters, 2004). The North Sea EwE model was initially built by Mackinson and Daskalov (2007) and subsequently updated and presented to the International Council for the Exploration of the Sea (ICES) Working Group on Multispecies Assessment Methods (WGSAM) to be used as an ICES advice product (ICES, 2013). The North Sea model was updated for the purpose of this work, bringing simulations to 2020 by updating the underlying time series data. The EwE model comprises 69 functional groups consisting of a single species, multiple species, or an age-stanza of a species that were aggregated into biotic groups ranging from plankton and benthos to fish, seabirds, and marine mammals.

We used the mass-balanced (Ecopath) and time-dynamic (Ecosim) components of EwE to extract estimates of production ($t \cdot km^{-2} \cdot year^{-1}$) and biomass ($t \cdot km^{-2}$) for each functional group in each year of the models duration (1991 to 2020). EwE was identified as an appropriate tool as it can simulate the dynamics of the functional groups as defined in the parallel ecosystem service linkage framework. EwE can provide quantitative estimates for functional groups that are well supported by data as well as those that are more data deficient (which it can acknowledge through parameter uncertainty routines) and it is able to simulate the retrospective and future impacts of cumulative pressures (Craig and Link, 2023). Functional group production rates in EwE are driven by their fishery catch rate, predation mortality, consumption rates, other mortality, migration, and biomass. Biomass dynamics (growth rates) are expressed in Ecosim through a series of coupled differential equations which account for functional group consumption rates (based on the foraging arena concept; Ahrens et al., 2012), fishing, predation, and other sources of mortality, as well as migration (see Christensen and Walters, 2004). Annual estimates of biomass and production were used to build a range of ‘observed ‘or ‘plausible’ metrics for each functional group based on retrospective dynamics and changes in fisheries exploitation.

2.5. Threats to the capacity to supply ecosystem services

This assessment uses an estimation of Impact Risk to quantify the threat of the anthropogenic stressors (i.e. human activities and their pressures) on the CtSES. To that end, SCAIRM was applied to estimate the Impact Risk per ecosystem component/biotic group which could then be converted using the SSP estimates of each of those biotic groups to an Impact Risk to the capacity to supply each of the specific ecosystem services.

The different options in the estimation of the SSP make explicit the knowledge demands that apply when calculating how the CtSES is affected by anthropogenic threats in any particular ecosystem. This North Sea proof of concept then also shows how the outcome of the assessment of the cumulative impacts on the CtSES is affected by such options. A Sankey diagram is used to depict the flow of Impact Risk through the linkage framework connecting the anthropogenic stressors to the CtSES through “*activity-pressure-biotic group-ecosystem services*” chains.

3. Results

3.1. Linkage framework

The linkage framework for the assessment of cumulative impacts of human activities on the North Sea CtSES was constructed from the linkage framework in Piet et al. (2023). This framework consists of nodes representing activities, pressures and ecosystem components and all 1005 relevant links between the various nodes within these three levels. The ecosystem components were matched to functional biotic groups and extended with the linkages to ecosystem services according to CICES 5.1. Table 3 shows that 327 linkages exist between the 12 biotic groups and the 45 ecosystem service classes.

3.2. Key proxy metrics to estimate the ecosystem service supply potential

Functional group estimates from the North Sea EwE model for each year of the simulation’s duration (1991–2020) were extracted to provide average and 95th percentile estimates for biotic groups biomass and production estimates (Fig. 2). To that end functional groups as they occur in the EwE model were aggregated into the biotic groups required for this ecosystem services assessment (Fig. 2 and Table 4). Data could not be aggregated to provide biomass and production estimates for microphytobenthos, macroalgae, or macrophytes as these biotic groups are not explicitly modelled in the North Sea EwE model. Focussing on the functional groups occurring in the North Sea EwE model: various shark and seabird groups were the least productive, while phytoplankton, zooplankton, bacteria, and benthos (epifauna and infauna) groups were among the most productive groups (Fig. 2A). The highest biomass was attributed to individual infauna and epifauna functional groups, followed by copepods and phytoplankton, while various shark and seabird functional groups had the lowest simulated biomass for the North Sea (Fig. 2B). When aggregated into biotic groups as used in this ecosystem services assessment the outcome remains largely the same, with phytoplankton and bacteria being the most productive biotic groups and epifauna and infauna supporting the greatest overall biomass (Table 4). The aggregated fish group had the third highest biomass of the biotic groups, greater than the aggregated biomasses of phytoplankton and zooplankton.

3.3. Service supply potential

The SSP per biotic group determined by the weighting options

Table 3
Existing linkages and their likelihood of contribution to the marine capacity to supply ecosystem services (according to CICES 5.1) per functional biotic group. The three codes indicate High (1), Medium (0.01), or Low (0.001) contribution. Empty cells indicate no contribution. For option S1 (Table 1) only the none-empty cells apply.

Section	Division	Group	Class	Bacteria	Phytoplankton	Zooplankton	Microphytobenthos	Macroalgae	Macrophytes	Infauna	Epifauna	Cephalopods	Fish	Birds	Marine mammals
Provisioning	Biomass	Cultivated aquatic plants for nutrition, materials or energy	Plants cultivated by in- situ aquaculture grown for nutritional purposes					H							
			Fibres and other materials from in-situ aquaculture for direct use or processing (excluding genetic materials)		L		L	H	L						
			Plants cultivated by in- situ aquaculture grown as an energy source		L		L	H	L						
		Reared aquatic animals for nutrition, materials or energy	Animals reared by in-situ aquaculture for nutritional purposes							L	H		H		
			Fibres and other materials from animals grown by in-situ aquaculture for direct use or processing (excluding genetic materials)			L				L	H	L	H	L	L
			Animals reared by in-situ aquaculture as an energy source										H		L
		Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition		L		L	H	H						
			Fibres and other materials from wild plants for direct use or processing (excluding genetic materials)		L		L	H	H						
			Wild plants (terrestrial and aquatic, including fungi, algae) used as a source of energy		L		L	H	H						
		Wild animals (terrestrial and aquatic) for nutrition, materials or energy	Wild animals (terrestrial and aquatic) used for nutritional purposes			L				H	H	H	H	L	L
			Fibres and other materials from wild animals for direct use or processing (excluding genetic materials)			L				H	H	H	H	L	L
			Wild animals (terrestrial and aquatic) used as a source of energy										H		L
	Genetic material from all biota	Genetic material from plants, algae or fungi	Seeds, spores and other plant materials collected for maintaining or establishing a population		H		H	H	H						
			Higher and lower plants (whole organisms) used to breed new strains or varieties		H		H	H	H						
			Individual genes extracted from higher and lower plants for the design and construction of new biological entities		H		H	H	H						
		Genetic material from animals	Animal material collected for the purposes of maintaining or establishing a population			H				H	H	H	H	H	H
			Wild animals (whole organisms) used to breed new strains or varieties			H				H	H	H	H	H	H
			Individual genes extracted from organisms for the design and construction of new biological entities	H	H	H	H	H	H	H	H	H	H	H	H
Regulation & Maintenance	Transformation of biochemical or physical inputs	Mediation of wastes or toxic substances of anthropogenic origin by living processes	Bio-remediation by micro-organisms, algae, plants, and animals	H	H	H	H	H	H	H	H				
			Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals	H	H	H	H	H	H	H	H	H	H	H	H
			Smell reduction	H						H	H			H	
			Visual screening	H						H	H			H	
	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	Control of erosion rates				H	H	H	H	H				
			Buffering and attenuation of mass movement				H	H	H	H	H				
			Hydrological cycle and water flow regulation (Including flood control, and coastal protection)				H	H	H	H	H				
		Lifecycle maintenance, habitat and gene pool protection	‘Gamete’ dispersal								H		H	H	
			Seed dispersal										H	H	
			Maintaining nursery populations and habitats (Including gene pool protection)	H	H	H	H	H	H	H	H	H	H	H	H
		Pest and disease control	Pest control (including invasive species)	H	H	H	H	H	H	H	H	H	H	H	H
			Disease control	H	H	H	H	H	H	H	H	H	H	H	H
		Regulation of soil quality	Decomposition and fixing processes and their effect on soil quality	H	H	H	H	H	H	H	H	H	H	H	H
		Water conditions	Regulation of the chemical condition of salt waters by living processes	H	H	H	H	H	H	H	H	H	H	H	H
		Atmospheric composition and conditions	Regulation of chemical composition of atmosphere and oceans	H	H	H	H	H	H	H	H	H	H	H	H
			Regulation of temperature and humidity, including ventilation and transpiration		H		H	H	H						

Section	Division	Group	Class	Bacteria	Phytoplankton	Zooplankton	Microphytobenthos	Macroalgae	Macrophytes	Infauna	Epifauna	Cephalopods	Fish	Birds	Marine mammals
Cultural	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	Physical and experiential interactions with natural environment	Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	M	M	M	H	H	H	M	H	H	H	H	H
		Intellectual and representative interactions with natural environment	Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	M	M	M	H	H	H	M	H	H	H	H	H
			Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	H	H	H	H	H	H	H	H	H	H	H	H
			Characteristics of living systems that enable education and training	H	H	H	H	H	H	H	H	H	H	H	H
			Characteristics of living systems that are resonant in terms of culture or heritage					H	H	H	H	H	H	H	H
			Characteristics of living systems that enable aesthetic experiences	H	H	H	H	H	H	H	H	H	H	H	H
	Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting	Spiritual, symbolic and other interactions with natural environment	Elements of living systems that have symbolic meaning			H		H	H		H	H	H	H	H
			Elements of living systems that have sacred or religious meaning			H		H	H	H	H	H	H	H	H
			Elements of living systems used for entertainment or representation	H	H	H	H	H	H	H	H	H	H	H	H
		Other biotic characteristics that have a non-use value	Characteristics or features of living systems that have an existence value	H	H	H	H	H	H	H	H	H	H	H	H
			Characteristics or features of living systems that have an option or bequest value	H	H	H		H	H	H	H	H	H	H	H

(Table 1) were applied in the estimation of the overall North Sea SSP showing that the different weighting options resulted in markedly different relative contributions of the biotic groups (Fig. 3).

3.4. Threats to the capacity to supply ecosystem services

The application of the SCAIRM method in the North Sea context showed which ecosystem components were most threatened and what the main stressors were (Fig. 4). 'Fish' and 'Cephalopods' emerged as the most threatened biotic groups, each with an Impact Risk of 94 %, followed by the 'Mammals' and 'Birds' with 61 % and 54 % respectively. Other biotic groups associated with seabed habitats showed Impact Risks in the range of 30–50 % and the phyto- and zooplankton associated with the water column habitat showed Impact Risk of approximately 10 %. Fishing was the main threat across all biotic groups, contributing 51 % to the overall threat. Of the remaining 18 sectoral activities another 23 % was contributed by mining, non-renewable energy, tourism, and agriculture. As the cumulative impact risk consists of a total of 228 different and mostly negligible stressors that also differ between biotic groups (between 147 and 203 depending on the biotic group), the least important stressors were aggregated into "Other" such that they always represent <30 % per biotic group. "Other" is further specified in SM5.

Combining the SSP per biotic group depending on the weighting options (Fig. 3) with the Impact Risk estimates per ecosystem component (Fig. 4) provided the Impact Risk to the CtSES and how this was determined by the applied in the estimation of the SSP (Fig. 5). Overall, the CtS Cultural ecosystem services section was the most threatened with an average Impact Risk of 50 % (varying between 45 and 56 % across ecosystem services classes), followed by the Provisioning ecosystem services with 46 % (varying between 14 and 94 %), and finally the Regulation & Maintenance ecosystem services with 38 % (with huge variation between 8 and 94 %) (Fig. 5). The variation within each section of ecosystem services is generally large, partly because of the wide range of class-level services covered by each section (see Table 3).

The ultimate assessment of anthropogenic threats on the CtSES was based on what was considered the most elaborate weighting option S4 (Table 1) showing how Impact Risk passes through the full linkage framework (Fig. 6). The main threats to the CtSES overall came from marine food production: primarily fishing but also aquaculture. While there were minor differences between the three major ecosystem services sections, i.e. Provisioning, Regulation & Maintenance, and Cultural, fishing always contributed more than half of the Impact Risk. The main difference between the major ecosystem services sections can be seen in the ranking of activities, where the third most significant impact (contributing 5–6 % to Impact Risk) was agriculture for Provisioning ecosystem services (i.e. through nutrients and contaminants), mining for Regulation & Maintenance ecosystem services (i.e. through physical disturbance of the seafloor) and coastal infrastructure for Cultural ecosystem services (i.e. through habitat loss and disturbance).

4. Discussion

This North Sea proof of concept confirmed that the proposed CIA-based method can accomplish a (semi-)quantitative assessment of the cumulative impacts on the CtSES. Its application in other marine ecosystems may require alternative, less data-heavy, information sources for each of the methodological steps. Despite the North Sea being one of the most information-rich marine regions, it still relied on several, often strong, assumptions and/or simplifications. These assumptions are discussed below with suggestions on how to advance towards better future assessments of the CtSES in the North Sea as well as other (and often less

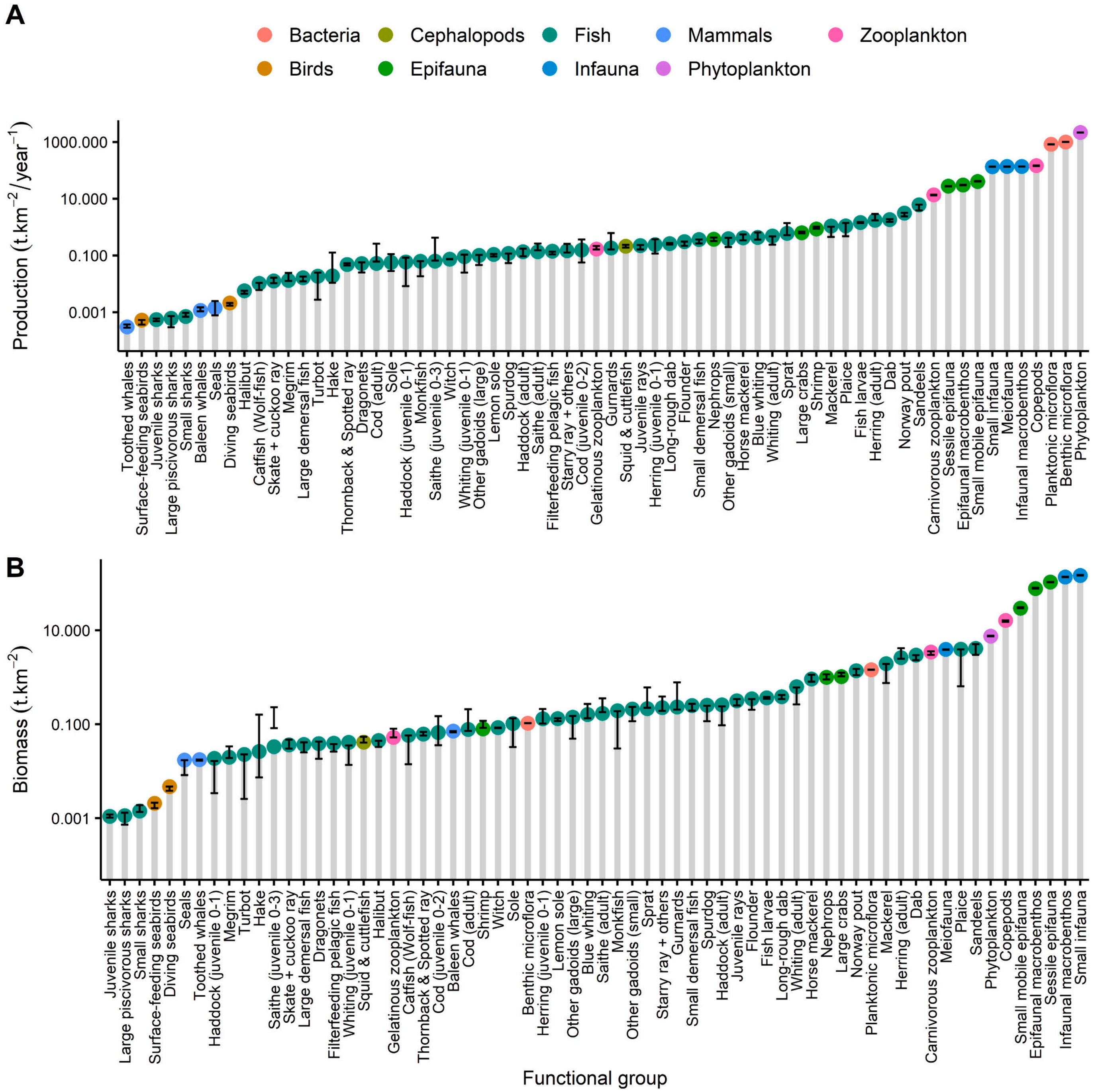

Fig. 2. Production (t.km-2.year-1) and biomass (t.km-2) for all functional groups in the North Sea Ecopath with Ecosim model. Points represent estimates of (A) production and (B) biomass in 2020 while the error bars provide the 95th percentile range based on estimates from 1991 to 2020.

data-rich) marine regions.

4.1. Cumulative impact assessment

For the CIA of the North Sea ecosystem and its relevant components, we applied the SCAIRM method (Piet et al., 2023) which has the advantage that it is comprehensive and can also be applied in data-poor situations entirely based on expert judgement while allowing the use of available quantitative information (Piet et al., 2021) in more data-rich situations. To extend this North Sea assessment to also cover the cumulative impacts on the CtSES, we matched the CIA assessment endpoints, i.e. ecosystem components, to biotic groups weighted with their estimated SSP depending on their functioning in the environmental system and the goods and benefits the ecosystem services are expected to supply in the socio-economic system (Potschin and Haines-Young, 2011). For simplicity we only considered the functioning of the biotic groups without any consideration of the habitats in which they occurred as did Culhane et al. (2018a, 2018b). While this would be feasible in the North Sea, it comes with considerable additional requirements for information on different habitat-specific vulnerabilities and functioning to achieve its full potential. The use of biotic groups without habitat specification was deemed to be adequate for the purposes of this study to provide 1) a framework of the assessment of CtSES and 2) a first (semi-) quantitative assessment of the main threats to the North Sea CtSES. These main threats are identified in terms of their contribution to the Impact Risk as calculated by SCAIRM. These Impact Risk estimates

Table 4

Selected Services Supply Potential metrics per biotic group in the North Sea. For production and biomass the estimated averages as well as their 5th and 95th percentiles are given. When not available from EwE (highlighted rows) they were derived from estimates of other biotic groups comparable in terms of their functioning, i.e. phytoplankton.

	Production (t.km^{-2}.year^{-1})			Biomass (t.km^{-2})		
Biotic group	AVG	5th	95th	AVG	5th	95th
Bacteria	1826.2083	1811.2551	1845.4337	1.5518	1.5409	1.5657
Phytoplankton	2156.9977	2144.0576	2173.1074	7.5486	7.4702	7.6629
Zooplankton	159.4789	155.5328	162.4323	19.0738	18.3835	19.7269
Microphytobenthos	21.5699	1% of phytoplankton		0.7549	10% of phytoplankton	
Macroalgae	21.5699	1% of phytoplankton		0.7549	10% of phytoplankton	
Macrophytes	2.1569	0.1% of phytoplankton		0.0755	1% of phytoplankton	
Infauna	407.4324	404.5934	410.7528	289.1771	287.2789	290.4050
Epifauna	100.9244	99.6506	102.5886	216.6299	214.4915	219.4563
Cephalopods	0.2110	0.1893	0.2366	0.0462	0.0407	0.0544
Fish	20.5346	19.1965	22.2360	20.6165	17.7225	23.8122
Birds	0.0023	0.0021	0.0026	0.0061	0.0055	0.0068
Mammals	0.0032	0.0025	0.0043	0.0996	0.0923	0.1063

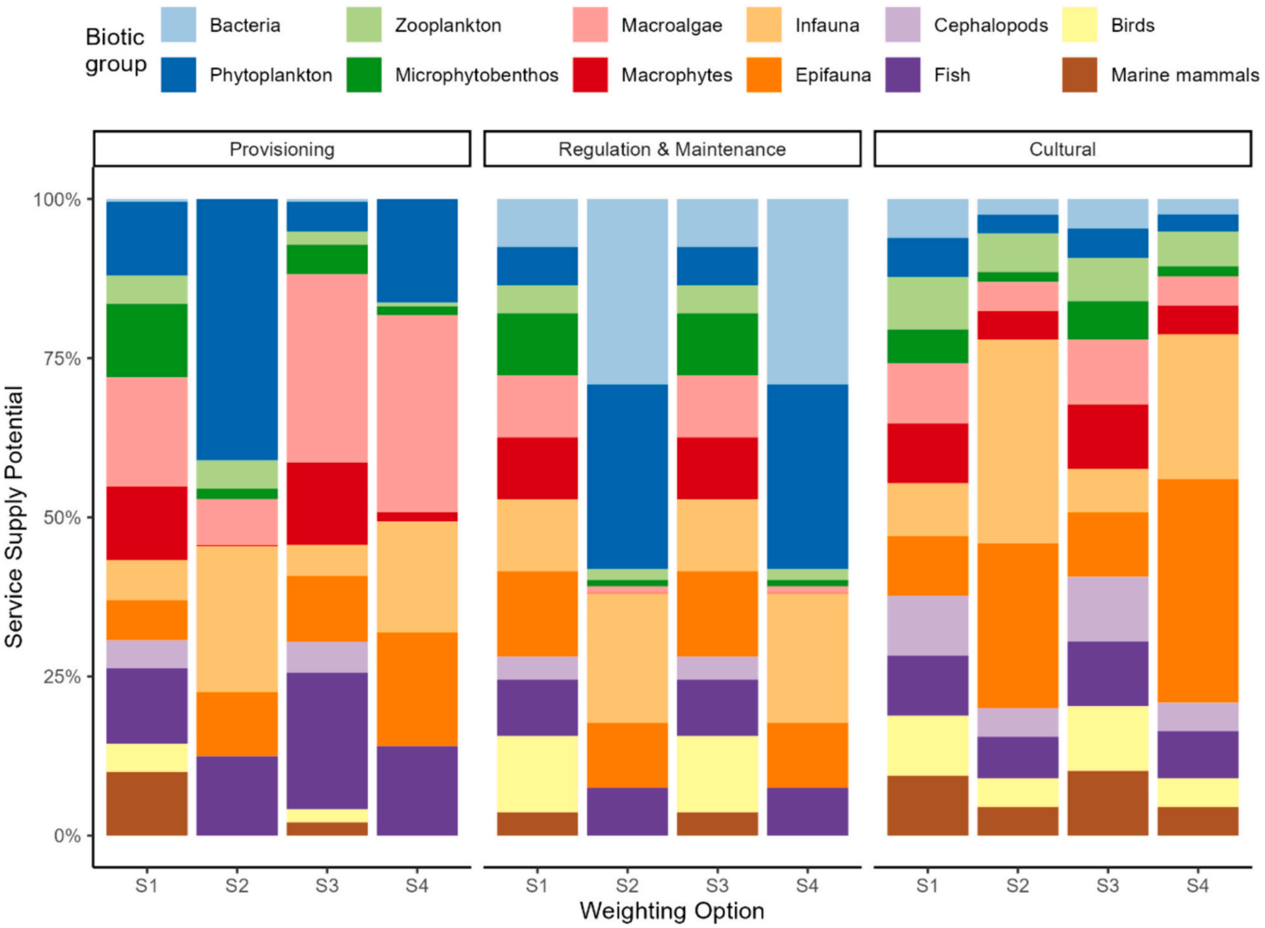

Fig. 3. Contribution of the functional biotic groups to the overall North Sea Service Supply Potential of the three main sections of Ecosystem Services, i.e. Provisioning, Regulation & Maintenance and Cultural, depending on the various options in Table 1.

should be considered an upper limit of the potential impact which, in order to be precautionary can be assumed to reflect a worst-case situation.

While the SCAIRM method was applied in this North Sea proof of concept, similar but less elaborate CIA exist for many other marine ecosystems (see e.g. https://www.ices.dk/advice/ESD/Pages/Ecosyst

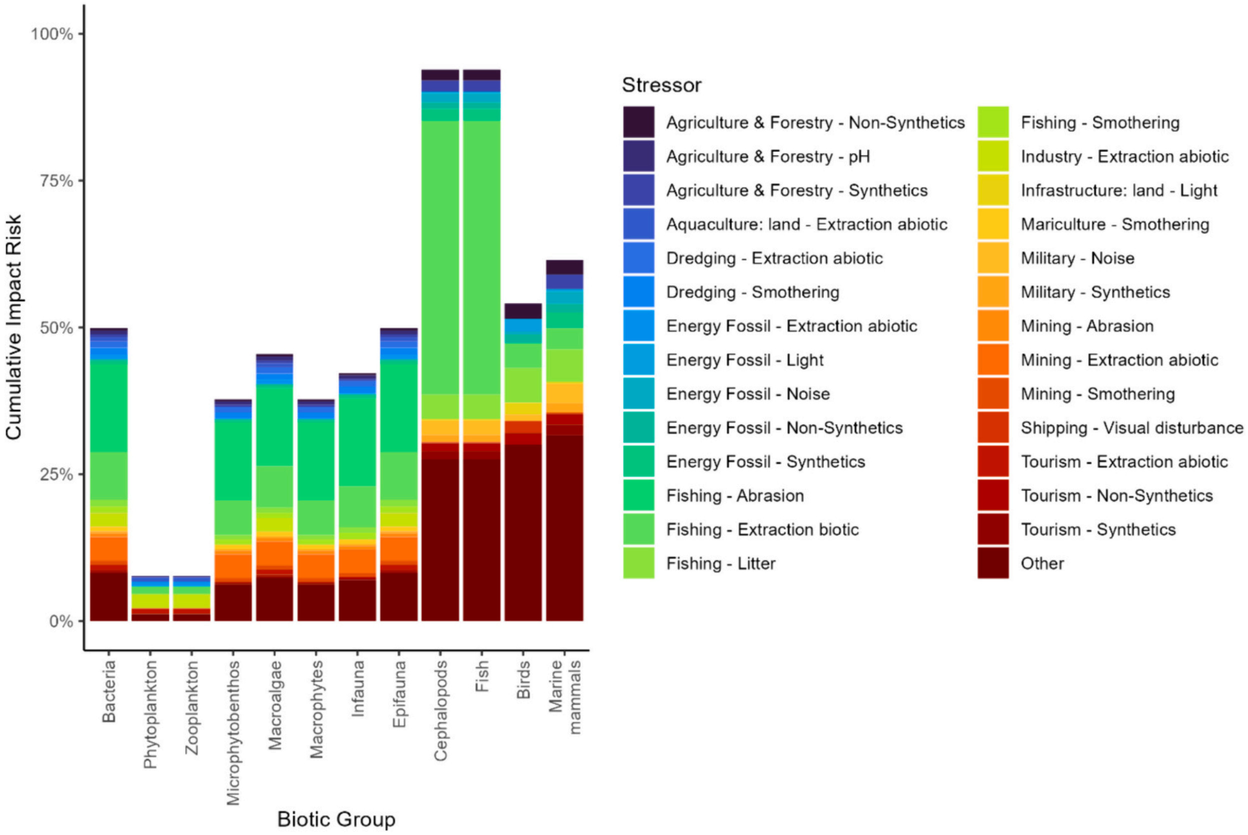

Fig. 4. Cumulative Impact Risk per biotic group in the North Sea showing the relative contributions of the main stressors (i.e. Activities and their pressures).

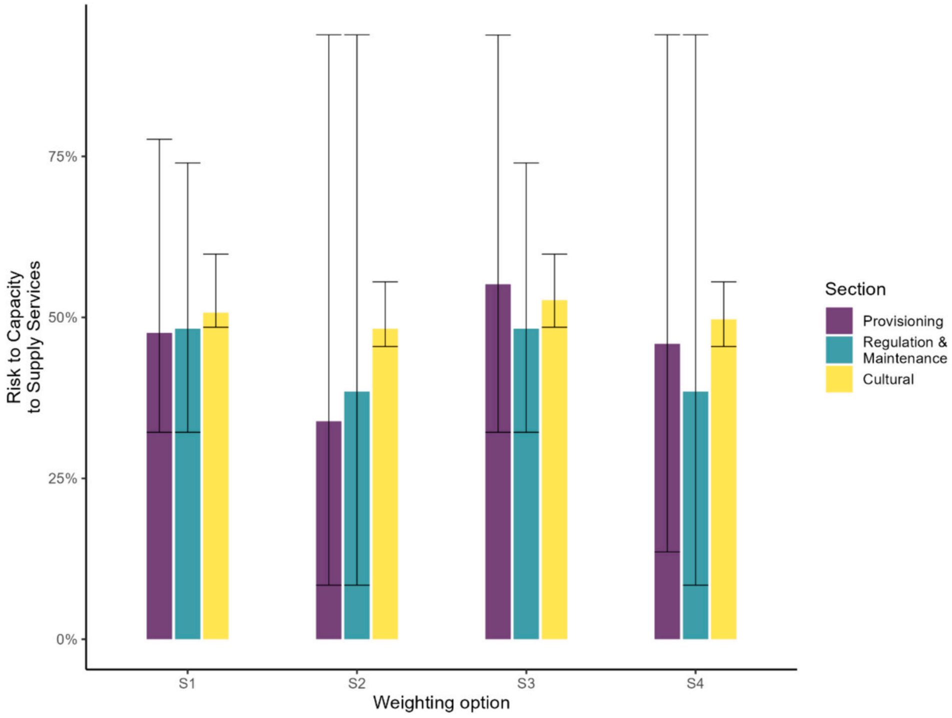

Fig. 5. Cumulative Impact Risk on the capacity to Supply each of the three main ecosystem services sections depending on the different weighting options (Table 1) to estimate the Service Supply Potential per biotic group in the North Sea. The error bars indicate the range (minimum-maximum) of the ecosystem services classes within the ecosystem services sections (see Table 2).

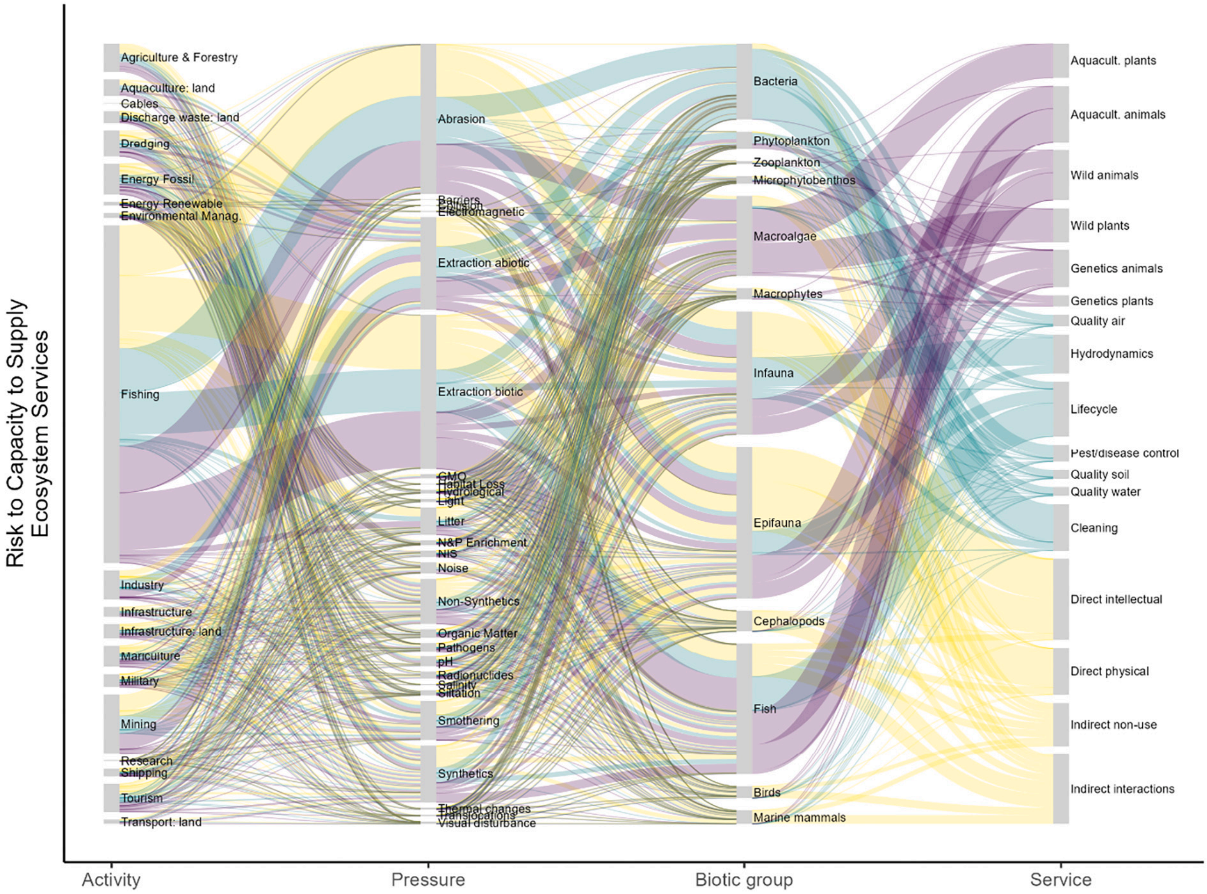

Fig. 6. Sankey diagram based on the most elaborate estimation of SSP (option S4 in Table 1) showing how the human activities and their pressures impact the functional biotic groups in the North Sea and subsequently the capacity to supply ecosystem services (represented at class level, see Table 2). The flows represent Impact Risk, in case of the stressors their contribution to it and in case of the receptors the degree to which they suffer from it. The colours correspond to the ecosystem service sections as in Table 2 and Fig. 5.

em-overviews.aspx).

4.2. Service supply potential

The SSP adopted from Teixeira et al. (2019) and Culhane et al. (2019a, 2019b) represents the functioning of each of the biotic groups together with their likelihood to contribute to the CtS of each of the specific ecosystem services. In developing an improved estimation of SSP, we distinguished different options that can be applied depending on the availability of information and expertise. The default (Option S1) is based on Culhane et al. (2019a, 2019b) and assumes that SSP is equal across all possible linkages. A first and probably biggest improvement can be achieved through the key proxy metrics representing the functioning that determines the SSP (Option S2). This was based on a review of indicators for ecosystem services assessments by von Thenen et al. (2020). It is striking that most of the indicators in the review cover the least Informative type of metric (i.e. presence/absence), but not surprising as this also comes with the least demands on the availability of information. It appears that, in general, the selection of indicators has been rather haphazard, with indicators often included that do not necessarily represent the biotic group or its functioning, but rather other characteristics such as specific management actions to protect the biotic groups (e.g. “Extent of MPAs/no-take zones”) or specific environmental variables (e.g. “pH”, “Oxygen concentration” or “Nutrients concentration”) which are at best crude substitutes of the SSP. The appropriate proxy metrics identified in this study, along with the selected key proxy metrics, should help to resolve this. For the selection of the key proxy metrics, we interpreted the ecosystem processes and functions in terms of their contribution to services and ultimately goods and benefits (see Table 1) which implied that this could be represented both by the amount (i.e. biomass and/or extent of habitat) as well as a rate (i.e. productivity, e.g. tonnes.year^{-1}). For estimation of the SSP this implied that, for all the Provisioning services and most of the Regulation & Maintenance services, the production of the biotic group was considered the best key proxy metric to represent SSP. For the Provisioning services, this follows from the fact that harvesting of biomass is also a rate and productivity was confirmed to be a key metric in a study of indicators for seafood Provisioning services which identified surplus production as the best indicator (Piet et al., 2017b). Harvesting (i.e. fisheries catches) more than the surplus production causes an impact on the asset (i.e. fish spawning stock biomass), thus interfering with future harvests and hence compromising sustainability. The Impact Risk calculated in this study essentially reflects the risk that this occurs. For the Regulation & Maintenance services, production was also assumed appropriate because much of the functioning that drives the supply of these services are linked to production rates of specific biotic groups. One exception is the “Regulation of baseline flows and extreme events” group, as processes like sediment stabilisation, accumulation, and/or wave attenuation are determined by the amount of biomass of notably biotic groups such as macroalgae, microphytobenthos, macrophytes and epifauna and infauna (Hu et al., 2014; Spalding et al., 2014; Yallop et al., 1994). Part of the Cultural services, i.e. the “Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting” which is about the standing stock of the relevant biotic groups was thought to be best represented by abundance or biomass. For the other Cultural ecosystem services, i.e. “Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting", we assumed presence would suffice despite that the title suggests that the service is entirely decoupled from its current state and (associated) presence in the environment. This should adequately reflect that a depleted natural resource, such as the extinction of a species, would negatively impact this ecosystem services. Composition, such as in terms of species richness, could be an alternative or complementary key proxy metric (see Table 2) but not applied in this study as it could not be calculated by the available foodweb model.

Food webs play a central role in our understanding of ecosystem dynamics, with associated studies providing key information on the linkages and interactions between biotic groups and how these can be impacted by human activities (Belgrano, 2019). Foodweb models such as EwE have been used previously to calculate the type of metrics that can be used to represent the SSP (Horn et al., 2021; Liquete et al., 2016). However, when estimating the SSP for each of the biotic groups we need to acknowledge that their actual contribution may not always be proportional to the selected key proxy metric because their roles, distributions, or other characteristics differ, or simply because not all species or species groups within those biotic groups contribute proportional to what the metric suggests. Moreover, as ecosystem services ultimately lead to goods and benefits that contribute to human well-being (Potschin and Haines-Young, 2011), societal preferences may affect the contribution of biotic groups. We attempted to capture this issue with the expert judgement-based estimation of the likelihood that the biotic group contributes to the SSP. These likelihood estimates capture different factors, all assumed to be relevant, but for which there is little evidence to quantify them, or combine them, into weighting factors specific to each biotic group-ecosystem services linkage such that they allow an improved estimation of the Impact Risk on the CtSES. The default likelihood of 1 indicates that all production can potentially contribute to the supply of that service. If there is evidence or good reason to assume otherwise, as when only part of the biotic group contributes, a likelihood <1 was applied. Fish and benthos are examples where only the production of commercial fish species and benthic crabs, shrimps and Nephrops was included with a likelihood of 1. For seabirds and mammals, the potential to contribute to the provisioning services was assumed to be limited to specific species and mostly local (e.g., whaling in Norway or Faroe Islands) and hence it received an arbitrary low weighting of 0.1 %. Because SCAIRM only assesses the direct cumulative impacts on the biotic groups (Piet et al., 2023), the extension to ecosystem services only considered direct links as well. For example, the link between marine mammal biomass and cultural benefits was included but not indirect links such as importance of zooplankton or fish as mediators of marine mammal biomass and its associated cultural benefits.

4.3. Estimating the capacity to supply ecosystem services

Despite the advancements made in this study, estimating the CtSES is still reliant on several assumptions. In this study we attempted to make those explicit through the application of different weighting options in the estimation of SSP. These were by no means intended to be fully comprehensive but they serve to illustrate how assumptions may affect the outcome of the assessment and were therefore primarily intended to initiate a process to further elaborate the underlying issues and drive future developments. One of those issues is conceptual in that from the perspective of a social-ecological system, this exercise would sit exclusively in the ecological system but for the estimation of the SSP we need to make inferences from the types of social and economic goods and benefits obtained and how or where these are acquired, all of which belonging to the social system if strictly interpreted. Instead of considering this contradictory assert this confirms the role of ecosystem services in linking biophysical structure, processes, and functions with the derived social and economic values and benefits (Quintessence, 2016) and hence only confirms their importance as a shared concept in both the ecological and the social systems (Biggs et al., 2012; Maes et al., 2012; Liquete et al., 2013; Mee et al., 2015). It also underlines the observation by Schirpke et al. (2022) that the assessment of Cultural ecosystem services poses various conceptual and methodological difficulties, including unclear definitions and the challenge of separating services, values, and benefits, which are often strongly interwoven (Bieling et al., 2014; Hausmann et al., 2016). Moreover, the choice of weighting options based on a perception of how biotic groups are linked to ecosystem services (S1) or the goods and benefits obtained from those services (S3) could be considered exemplary of the point made by Díaz et al. (2018) that societal preference mediates the relationship between people and the CtSES. The plea is therefore to make such societal preferences explicit when assessing the CtSES.

4.4. Threats to the North Sea capacity to supply ecosystem services

This assessment of the cumulative impacts on the North Sea CtSES has shown that at least in this marine ecosystem the CtSES is severely threatened by the current human activities and their pressures, with about half of the CtSES potentially at risk, varying between 50 % of the Cultural ecosystem services, 46 % of the Provisioning ecosystem services, and 38 % of the Regulation & Maintenance ecosystem services but with often huge variation within these broad ecosystem services sections, partly because of the diverse nature of the services included in those sections. Because the SCAIRM method at the basis of this assessment is intended to be precautionary, the actual decrease in the CtSES compared to an undisturbed situation is probably lower. The estimation is also dependent on many assumptions including how the SCAIRM output can be matched to the EwE biotic groups, the choice of appropriate key proxy metrics for each of the ecosystem services, and other considerations captured in the likelihood estimates and ultimately in the weighting options. Notably the considerations now captured by the likelihood estimates are usually ignored or implicit but were shown to considerably affect the outcome of the assessment and should probably be the first to be further developed to improve the assessment of cumulative impacts on the CtSES.

4.5. Relevance to the wider context

Ecosystem services play a key role in extending the relevance of CIAs beyond biodiversity and the ecological system. The results from this study help in understanding how the anthropogenic threats may impact the natural capital and the societal goods and benefits it provides (Maes et al., 2012; Mee et al., 2015). As such it is relevant in the context of social-ecological systems thinking and ecosystem-based management aimed not only at the conservation of biodiversity and its intrinsic value but also preserve its capacity to supply goods and benefits, which may represent monetary value. These ecocentric and anthropocentric perspectives should therefore be considered complementary when providing science advice for management. Because ecosystem services are supposed to cross the production boundary and occur both in the marine ecosystem as well as the socio-economic system (Culhane et al., 2019b) it justifies a consideration of societal preferences when assessing the cumulative impacts on the CtSES despite that the cascade model puts it exclusively in the environmental system (Potschin and Haines-Young, 2011). This is illustrated by the assessment of the CtS provisioning services in this study showing that without considering societal preferences the results are based on the assumption that half of our seafood comes from plankton (see Option S2 in Table 1 and Fig. 3) which is known not to be the case and would thus prevent any uptake of the scientific advice. Moreover, these societal preferences and specific characteristics of the biotic groups (e.g. size of individuals as in Option S3) determine the potential interaction of the CtSES with additional built, human, and social capital (Burdon et al., 2022; Elliott, 2023) and hence will determine how natural capital contributes to the supply of goods and benefits.

For assessments aimed at identifying the main anthropogenic threats impacting the supply of goods and benefits it makes little difference if the 17 ES groups according to CICES are applied as opposed to the 18 NCP reporting categories used by IPBES within the generalizing perspective proposed by Díaz et al. (2018). In both cases the CtS Regulation & Maintenance ecosystem services or Regulating NCP can be expected to be least affected by societal preferences (Fig. 5). In addition to the more tangible goods and benefits that natural capital may supply, nature's contributions to people (Díaz et al., 2018) also consider the cultural, spiritual, and inspirational values. The assumptions represented in the weighting options (i.e. S3 versus S2) can be considered to reflect the central and pervasive role that societal preferences play in these types of assessments, whether based on ecosystem services or nature's contributions to people.

This assessment method can also be aligned to the concepts used in an ecosystem accounting context (EEA, 2018) where the assets are represented by the biotic groups that make up biodiversity (UN, 2021) with characteristics captured in the condition account and the flows are represented by the selected key proxy metrics assumed to characterize how the ecosystem processes and functioning turn into services (Maes et al., 2013; Burdon et al., 2022). This method thus shows how cumulative impacts of anthropogenic stressors (as captured in a pressure account) on the (condition of the) ecosystem assets converted into a change of the ecosystem account.

4.6. Conclusion

This North Sea proof of concept shows that an existing CIA can be extended into an assessment of the cumulative impacts on the CtSES based on a (semi-) quantitative estimation of the functioning of biotic groups. The results show the extent to which this CtSES is threatened by specific stressors which is relevant to guide ecosystem-based management towards a (more) sustainable exploitation of the marine ecosystems. While showcased for the North Sea ecosystem, it can similarly be applied to other marine ecosystems and could even inform such assessments in the terrestrial domain. By improving the integration across scientific domains it allows ecosystem-based management to include all dimensions of sustainability (i.e. environmental, social and economic) and should ultimately improve informed decision making to conserve natural ecosystems and the benefits they provide for human societies.

CRediT authorship contribution statement

Gerjan Piet: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Jacob Bentley:** Writing – original draft, Formal analysis. **Ruud Jongbloed:** Validation, Formal analysis. **Anne Grundlehner:** Writing – original draft, Visualization, Formal analysis. **Jacqueline Tamis:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Pepijn de Vries:** Writing – original draft, Visualization, Software, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.174149.

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