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Review Paper

Linking natural capital stocks with ecosystem services in the Northern Baltic Sea

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A B S T R A C T

The Baltic Sea is a heavily used marine area in Northern Europe delivering valuable services to the inhabitants of its surrounding countries. Understanding how the structure and functioning of marine ecosystems deliver ecosystem services is still limited. However, this information is increasingly needed for ecosystem accounting, marine spatial planning and managing natural resources sustainably. In this study we reviewed ecosystem services provided by marine natural capital, i.e. the elements in the environment that are essential for providing the services. Altogether 48 habitats belonging to 8 habitat groups, and 11 mobile species (i.e. fish and pinnipeds) were assessed using literature and expert knowledge in the Northern Baltic Sea. To our knowledge, this is the first time when all habitats are included in an ecosystem services assessment in the area. The results show that of all possible service linkages, 31–56% were identified for habitats (depending on the habitat group in question) and 28–51% of linkages could not be assessed because of the limited knowledge. For mobile species, 53% of all possible services linkages were recognized and 15% of linkages could not be assessed because of limited knowledge. The results demonstrate the importance of the marine habitats for delivering regulating services, particularly those mitigating harmful effects of human activities such as carbon and nutrient storages, and their importance to services that are yet to be discovered. The results also show that mobile species are particularly important for provisioning and cultural services. The current study supports on-going policies such as the Baltic Sea Action Plan and marine spatial planning by providing knowledge on ecosystem services that can be adopted into decision-making in the areas where the distribution and location of habitats and species are known. It also acts as a starting point for a more in-depth trade-offs analysis of different ecosystem services.

1. Introduction

Anthropogenic pressures are affecting the ocean worldwide by threatening the biodiversity, habitats and functioning of ecosystems, and hence the provision of ecosystem services (here on ESs) which provide benefits for society (Cardinale et al., 2012; Costanza et al., 2014; Halpern et al., 2015; IPBES, 2019). The increasing awareness of the ESs underpinning our well-being has created a need for further quantitative and qualitative data on the services, their location; (Burdon et al., 2019; Liquete et al., 2013), and their economic, ecological and socio-cultural values (Burdon et al., 2018).

Marine ecosystems are dynamic and complex, and identifying the

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pathways from ecosystem structures and functions to ESs is a challenge. However, information about ESs is increasingly required for management and decision-making as we need to ensure that the capacity of the ecosystems to supply services can be sustained and even improved (Scharin et al., 2016). Marine policies such as the Marine Strategy Framework Directive (Directive 2008/56/EU) and the Maritime Spatial Planning Directive (Directive 2014/89/EU) require EU member states to apply ecosystem-based management for the sustainable development of their sea areas, aiming to ensure that the pressures and use of marine ecosystem goods and services are kept in sustainable level. This requires identifying the natural stocks contributing to the services supply. Also, the renewed Baltic Sea Action Plan by the Baltic Marine Protection Commission – Helsinki Commission (HELCOM) raises the importance of ESs in the governance of the Baltic Sea (HELCOM, 2021). Furthermore, the EU biodiversity strategy 2020 (COM/2011/0244) called the member states for Mapping and Assessing the Ecosystems and their Services (MAES) and valuing them for accounting purposes by 2020. However, the complete assessment is yet to be performed in the marine areas given the paucity of data and current data gaps, particularly when it comes to regulating and cultural services (Maes et al., 2020). The updated biodiversity strategy (COM/2020/380) encourages that research on the ESs is continued.

In addition, there are increasing efforts to include natural capital accounting to the national accounting systems. Natural capital refers to all elements in the environment that are providing the services, such as habitats important for carbon sequestration. Ecosystem accounting which is part of the system of environmental economic accounting, is a new statistical framework by the United Nations (United nations et al., 2021) that aims to measure the natural capital stocks and their condition in a standardized way. Ecosystem accounts, including ecosystem extent, condition and services supplied, will be compiled for specific geographical areas (United nations et al., 2021). The European Union has a requirement that national natural capital accounts are reported (Vallecillo et al., 2022). To be able to compile the accounts, understanding the condition of natural capital stocks and their links to ESs is crucial.

The Baltic Sea is important for the delivery of ESs and the societal benefits for the surrounding Baltic states. Human activities, such as commercial fisheries, recreation, and tourism, are directly dependent on the provision of ESs given their reliance on the supply of fish stock and supply of clear water and clean beaches. Such ESs are intensively utilized and highly valued (Hasler et al., 2016). The Baltic Sea is a relatively young and shallow low salinity brackish water basin with less biodiversity compared to other sea areas in Europe. It is facing a range of human induced pressures, such as high levels of eutrophication and excessive amount of coastal seabed disturbance (HELCOM, 2018) which affect the potential of the Baltic Sea to provide ESs. Algal blooms, for example, negatively impact the experience of recreational users of the sea every year thus reducing the cultural ESs associated with leisure and recreation (Atkins and Burdon, 2006; Gren et al., 2000). Nieminen et al. (2019) found that people are willing to pay for a better state of the Baltic Sea ecosystem, if that results in reduced algal blooms during the summer months when recreation activities most frequently occur.

Many marine habitats such as seagrass and mussel beds are inherent structures of marine ecosystems that enable the existence of species communities and provide food, shelter and nursery grounds for various species (Liquete et al., 2016). Many ESs such as carbon storage and flood protection are directly dependent on the habitat area and the extent of the community (Harrison et al., 2014). Thus, habitats form valuable natural capital stocks and are essential units in understanding the ability of an ecosystem to provide services (Culhane et al., 2018).

Studies across Europe have linked marine habitats to the provisioning of ESs (Burdon et al., 2017; Culhane et al., 2020; Potts et al., 2014; Salomidi et al., 2012; Teixeira et al., 2019; Turner and Schaafsma, 2015). In the Baltic Sea, however, the studies have concentrated mainly on a few habitats (Heckwolf et al., 2021; Rönnbäck et al., 2007) or the assessments are based on expert knowledge (Armoškaitė et al., 2020; Schumacher et al., 2021), and data and literature based, comprehensive assessment is lacking. In particular, the Northern Baltic Sea habitats are poorly covered by previous studies. The habitats in the area form unique combination of marine and freshwater habitats. As climate change and other human pressures may cause changes in the distribution of both freshwater and marine habitats, understanding the role of habitats in the provision of ESs would be crucial for accounting and protecting these valuable natural capital stocks and guaranteeing the flow of ESs also for future generations.

In this paper, we review ESs provided by the Northern Baltic Sea natural capital. We assess all known habitat types in the Northern Baltic Sea listed in the assessment of Threatened Habitat Types in Finland (Kotilainen et al., 2018). The classification is compatible with the HELCOM Underwater Biotope and Habitat Classification System (HELCOM HUB) and the European Nature Information System (EUNIS) classification of habitats. We follow the Common International Classification of Ecosystem Services (CICES) as the ES classification framework and 1) identify the links between habitats / species and their related services using existing literature and expert knowledge, 2) identify habitats and species that are particularly important for providing multiple services, and identify the services that are provided only by a few habitats or species, 3) compare the vulnerability status of habitats to the number of delivered services 4) identify knowledge gaps, i.e., which habitats are not covered in the literature and 5) summarize the results so that they can be used in further studies and to support decision-making.

2. Methods

2.1. Study area

The current study area covers the Northern parts of the Baltic Sea including the Gulf of Bothnia, the Gulf of Finland and the Northern Baltic proper (Fig. 1). The Baltic Sea is located in the Northern hemisphere stretching from 53°N to 66°N latitude and from 10°E to 30°E longitude and is one of the largest brackish water basins in the world. It is very shallow with an average depth of 54 m with a maximum depth of only 459 m (Kullenberg and Jacobsen, 1981). The Baltic Sea is connected to the North Sea through the narrow Danish straits that only allows a small volume of saline water to flow into the Baltic Sea. There is a strong salinity gradient across the sea, the Northern parts being the most oligohaline (0.5 to 5.0 ppt) (Kullenberg and Jacobsen, 1981). It is also a young sea: the last shift from fully freshwater phase to saline was 8,000 years ago when the last ice age was ending and the surface of marine areas rose globally (Kullenberg and Jacobsen, 1981). These features together with regular ice cover during the winter have resulted in relatively low numbers of species living in the sea (HELCOM, 2010). The species composition varies from marine and brackish water species in the Southern Baltic Sea to an increased dominance of freshwater species in the Northern and Eastern Baltic Sea. Particularly the coastal areas of the Eastern Gulf of Finland and Northern parts of Gulf of Bothnia provide a habitat for many freshwater species. The resulting underwater habitats differ from the marine habitats but can resemble them functionally which may lead to similar ES production.

2.2. Ecosystem services

This study follows the approach developed by Potts et al. (2014) where the results are presented in a matrix format with habitats and species listed in rows and ESs listed in columns. We use the Common International Classification of Ecosystem Services (CICES) v. 5.1 (Haines-Young and Potschin, 2018) for the selection of ES, as this classification has been adopted widely in many assessments and policies in the EU, including the MAES process that aimed to achieve the goals of EU's Biodiversity Strategy 2020 (Maes et al., 2014) and within the UK by

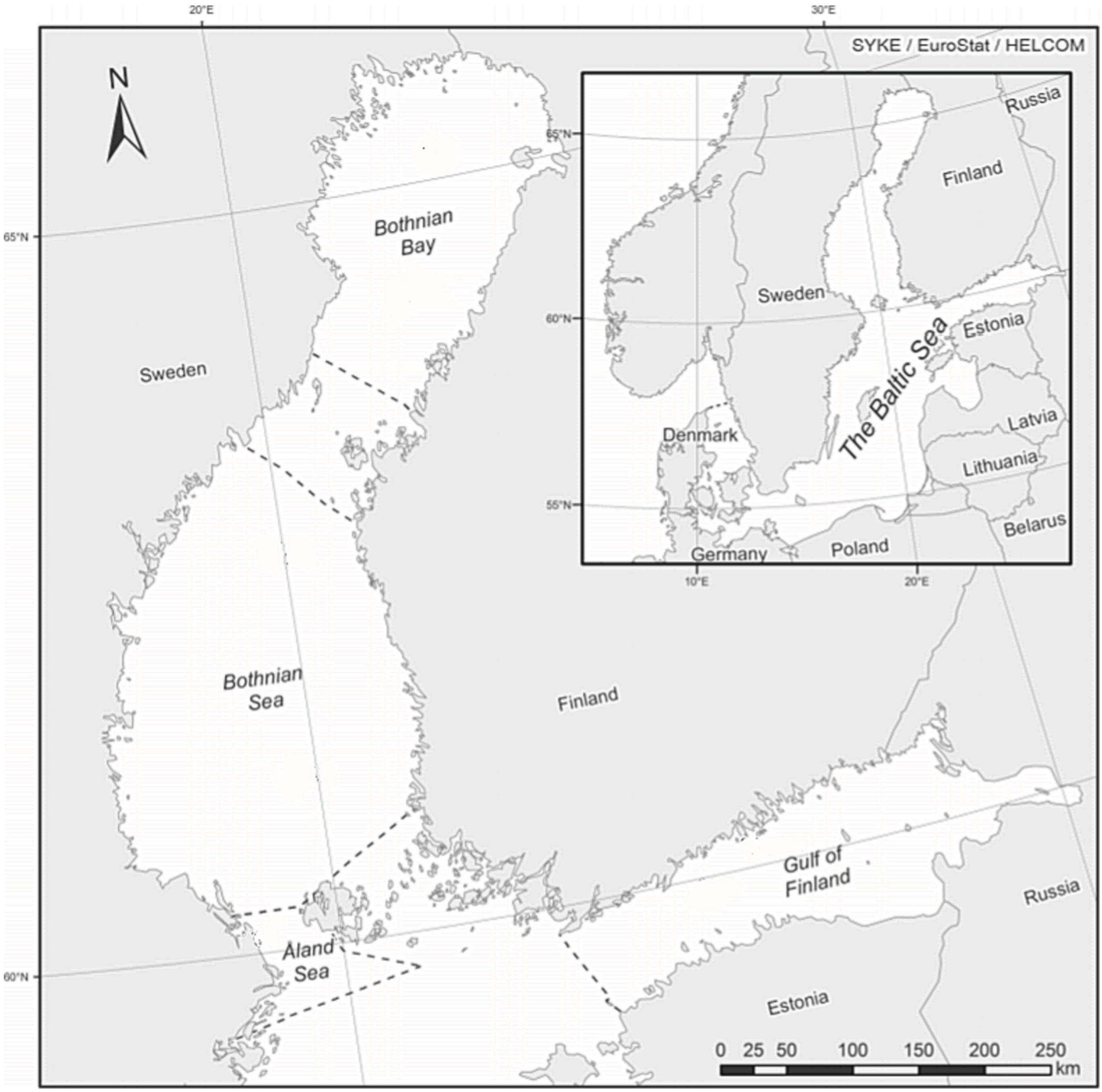

Fig. 1. Map of the study area covering the Northern Baltic Sea.

the Joint Nature Conservation Committee (JNCC) who developed an online universal asset-service matrix tool (JNCC, 2023). The CICES framework was adapted to the Baltic Sea context and some modifications were made for example: some services were split e.g., CICES service "2.1.1.2 Filtration / sequestration / storage / accumulation by micro-organisms, algae, plants, and animals" was divided to two: accumulation / storage etc. of toxins and harmful substances, and accumulation / storage etc. of nutrients. This helped the assessment of these services, as the accumulation of harmful substances may cause harm to certain species whereas accumulation of nutrients mainly does not. Also, some services were merged, e.g. CICES services "3.1.1.1 Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions" and "3.1.1.2 Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through observational interactions" were merged together; and some services such as "2.1.2.1 Smell reduction", "2.1.2.2 Noise attenuation", "2.1.2.3 Visual screening", and "2.2.1.2 Buffering and attenuation of mass movement" were not seen as relevant in the Baltic Sea context and they were left out of the assessment.

We decided to focus mainly on final services that lead directly to societal benefits as this would allow mapping and valuation of the benefits in forthcoming studies. By following the interpretations of Culhane et al. (2019), we left services such as "2.2.2.1 Gamete dispersal", "2.2.2.2 Seed dispersal", and "2.2.4.2 Decomposition and fixing processes and their effect on soil quality (sediment nutrient cycling in marine context)" out of our assessment as these are mainly considered as intermediate services and are contributing to a balanced biodiversity and ecosystems. However, the service "2.2.2.3 Maintaining nursery populations and habitats" was included in the study despite that the service is often considered as an intermediate service. We wanted to emphasize the importance of habitats to services such as fisheries and thus assessed the contribution of habitats to commercially important fish species. A total of 21 services were assessed and the complete list of selected services, their short names and descriptions are presented in the Table 1.

2.3. Habitat classification and selection of mobile species

HELCOM has classified the habitats in the Baltic Sea in the Underwater Biotope and Habitat Classification System (HELCOM HUB) which is compatible with the European Nature Information System (EUNIS). Finland has used a habitat classification system adopted from HELCOM HUB in the assessment of Threatened Habitat Types in Finland (Kotilainen et al., 2018). The Finnish national system was applied here as it includes seven broader habitat groups that are further divided based on the characterizing species, it covers all known habitats in the Northern Baltic Sea, and it contains information on their IUCN Red list classification. However, as the pelagic group of Finnish national classification system includes only "Pelagic habitats in the Northern Baltic Proper and the Gulf of Finland", "Pelagic habitats in the Bothnian Sea and the Åland Sea", "Pelagic habitats in the Bothnian Bay" and "Baltic Sea seasonal ice", the information about ice, salinity and halocline were added. In our study, we assess HELCOM HUB and Finnish national classification system habitats side-by-side with the main focus on the habitat characterizing species.

Some highly mobile species, such as fish and marine mammals, cannot be placed in only one habitat. Following the approach by Potts et al. (2014) we included eight fish species that have importance for commercial and/or recreational fishery, into the assessment. The fish species included: Baltic herring (*Clupea harengus membras*), sprat (*Sprattus sprattus*), European smelt (*Osmerus eperlanus*), perch (*Perca fluviatilis*), pikeperch (*Sander lucioperca*), pike (*Esox lucius*), European whitefish (*Coregonus lavaretus*) and salmon (*Salmo salar*). In addition, cod (*Gadus morhua*) that currently has no commercial value in Finland due to poor stock status, was included into the assessment. In addition, two pinniped species; grey seal (*Halichoerus grypus*) and ringed seal (*Pusa hispida botnica*) inhabiting the area were included into the assessment. A total of 48 different habitats and 11 mobile species were assessed (see Table 2 & Appendix A).

2.4. Data collection

A team of experts (N = 14) with different backgrounds were invited to participate in the review. The aim was to achieve as broad an understanding of different habitats and species as possible and to guarantee a solid knowledge base on ESs to aid reviewing and searching the literature and assessing the links from habitats and species to services. Thus, Baltic Sea researchers with backgrounds on for example algae, vegetation and mussel communities as well as pelagic, fish and seals were invited to participate. The lead of the expert team had expertise on marine ecosystem services.

All possible combinations of habitats or species and services were assessed by the experts. Each expert assessed a habitat group from which they had most expertise and knowledge. If the link from the habitat or species to the services was established by an expert a confidence score was given to the link based on the following criteria:

blank = not enough information to assess the link
D = disservice (e.g. accumulation of toxins to commercially important fish)
0 = no link exists
P = link exists but service is not used by society (potential use is under investigation)
1 = link exists by expert assessment
2 = link exists by scientific literature outside the study area but considered applicable to the study area, or by grey literature or website
3 = link exists by definition (e.g. oxygen produced through primary production by all autotrophic organisms)
4 = link exists by scientific literature from the study area

Each link between habitats and ES was first assessed by one of the experts and then reviewed by the leading author and other experts in several meetings. Thus, the work flow of the expert group consisted of 1) two workshops where the selection of ESs and their definitions were discussed, 2) a literature review and expert assessment where each expert gathered literature on specific habitats or species and gave a confidence score to the link, and 3) several review rounds and meetings of the results among the expert team and leading author where the gathered literature and expert confidence scores were harmonized and discussed until there was a common agreement on the scores. Most of the links did not require harmonization among the expert team as they were based on literature but some scores that were purely based on expert judgement required more discussions.

2.5. Vulnerability analysis

As the loss of biodiversity has been named as one of the greatest threats to the provisioning of ecosystem services and benefits to the human societies (Cardinale et al., 2012), we wanted to investigate the potential threat caused by degraded and lost habitats to the service delivery in the Baltic Sea based on the vulnerability status of the habitats. Following on from the assessment of IUCN Red List status of the habitats (Kotilainen et al., 2018), we compared the IUCN Red List status and the number of ESs supplied by each habitat using Levene's test (1960). The test compares the equality of variances between groups, and the statistical analysis was performed using R software (R Core Team, 2021).

3. Results

3.1. Provision of services by the natural capital stocks

All assessed natural capital stocks i.e. habitats and species are supplying ESs in the Northern Baltic Sea (Table 2). Depending on the habitat group, 31 – 56 % of all possible habitat-service combinations were identified (Table 3a). The role of habitats is highlighted particularly on the supply of regulating services as they covered 37–69 % of all identified services (Table 3b). For mobile species, most of the linkages are related to cultural services (Table 3b). There are differences in the number of services provided by the habitats; the number of services identified for many of the intensely studied habitats such as benthic habitats characterized by *Fucus vesiculosus* is generally higher than for many other habitats (Table 2). In general, around 28–51 % of the linkages could not be assessed for the habitats but there was some variation between groups; for example, the unassessed linkages of the group "other benthic habitats" cover 51 % because of the limited availability of knowledge on these habitats (Table 2). Most of the linkages could be assessed for mobile species and only 15 % of the links remained unassessed.

The complete data table with associated literature references and comments related to their links can be found in the Appendix A and text reviewing the links by each habitat group can be found in Appendix B.

3.2. Vulnerability status compared to the number of supplied services

We investigated if the service supply of some of the habitats can be considered threatened based on the IUCN Red List classification of habitats and species. We compared the habitats and species and their

Table 1
Ecosystem services according to the CICES framework, their adopted descriptions and the names used in this study.

	CICES code	CICES class name	Name in this study	Description (mostly adapted from CICES classification)
Regulation & Maintenance	2.2.2.3	Maintaining nursery populations and habitats	Habitats	Providing habitats, nursery habitats or food for wild plants and animals that can be useful to us.
	2.1.1.1	Bio-remediation of wastes by micro-organisms, algae, plants, and animals	Bio-remediation	Bio-remediation (breaking down) of wastes, toxicants (including toxins from algal sources), harmful substances and other contaminants from human sources
	2.1.1.2	Filtration/sequestration/storage/accumulation micro-organisms, algae, plants, and animals	Toxins	Filtration / sequestration / storage / accumulation of toxicants (including toxins from algal sources) and harmful substances from human sources.
			Nutrients	Filtration / Sequestration / storage / accumulation of nutrients from human sources.
	2.2.1.1	Control of erosion rates	Erosion	Stabilisation and retention of sediments, attenuation of wave energy in coastal areas (Culhane et al., 2019). This is a final service as it provides benefits and safety for people and protects man-made structures through the prevention of erosion in coastal areas (Culhane et al., 2019).
	2.2.1.3	Hydrological cycle and water flow regulation- flood control	Flood	Attenuation of wave energy through ecosystem structures, breaking the energy of waves before they reach the shore (Culhane et al., 2019)
	2.2.3.1	Pest control (including invasive species)	Pests	Providing a habitat for native pest control agents or predation on invasive species. Also, native species that competes effectively with an invasive species, etc.
	2.2.5.2	Regulation of the chemical condition of salt waters by living processes – oxygen	Oxygen	Net production of atmospheric oxygen by the photosynthesising components of the marine ecosystem.
	2.2.6.1	Regulation of chemical composition of atmosphere and oceans	Carbon	Sequestration and storage of carbon (or climate gases such as methane). Carbon buried in the sediment and carbon in living (or dead) biomass.
Provisioning	1.1.5.1 1.1.6.1	Wild plants or animals (terrestrial and aquatic, including fungi, algae) used for nutrition	Food	Wild harvested plants or animals used for nutrition.
	1.3.1.1	Other	Feed	Wild harvested plants or animals that are used for as feed for farmed animals or as fertilisers in agriculture.
	1.1.5.2 1.1.6.2	Fibres and other materials from wild plants or animals for direct use or processing (excluding genetic materials)	Materials	Wild harvested plants or animals used as materials such as harvestable surplus of seaweed biomass that can be used for example as an insulating material.
	1.1.5.3 1.1.6.3	Wild plants or animals (aquatic, including fungi, algae) used as a source of energy	Energy	Wild harvested plants or animals used as an energy source. Seaweed used as a source of energy, biogas from aquaculture waste.
	1.1.2.1 1.1.2.2 1.1.2.3 1.1.4.1 1.1.4.2 1.1.4.3	Plants cultivated or animals reared by in- situ aquaculture grown for nutritional purposes, fibres and other materials or as an energy source	Cultivation	Organisms that are in situ cultivated for use as food, feed, fertilizers, other materials or energy (excluding genetic materials)
	1.2.1.1 1.2.1.2 1.2.1.3 1.2.2.1 1.2.2.2 1.2.2.3	Seeds, spores and other plant or animal materials collected for maintaining or establishing a population, Higher and lower plants (whole organisms) or wild animals used to breed new strains or varieties, Individual genes extracted from higher and lower plants or animals for the design and construction of new biological entities	Genetic	Resources (DNA, genes, cells, tissues, and entire organisms) that are removed and then cultured, grown artificially, for use in biotechnology, bioengineering, bioprospecting, etc. such as in the food industry, or for the production of pharmaceuticals, cosmetics and food supplements. This service can also include wild seed/spat for fish farms and shellfish farms where they are taken from the wild and cultured in an artificial environment, before being moved out into farms for growth (Culhane et al., 2019).
Cultural	3.1.1.1 3.1.1.2	Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions or observational interactions	Recreation	Physical /mental activities and experiences, leisure / relaxation time that depend on the ecosystems and their biota.
	3.1.2.1 3.1.2.2	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge, Characteristics of living systems that enable education and training	Research	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge or that enable education and training.
	3.1.2.3	Characteristics of living systems that are resonant in terms of culture or heritage	Heritage	The things in nature that help people identify with, the history or culture of where they live or come from / sense of place.
	3.1.2.4	Characteristics of living systems that enable aesthetic experiences	Aesthetic	Characteristics of living systems that enable aesthetic experiences. The beauty of nature.
	3.2.1.2	Elements of living systems that have sacred or religious meaning	Symbolic	Using nature to as a national or local emblem. The things in nature that have spiritual importance for people.
	3.2.1.3	Elements of living systems used for entertainment or representation	Enter-tainment	Marine biota/ecosystems supply this service when marine wild species, wilderness, ecosystems and sea-scapes are subject to ex-situ viewing/experiencing through different forms of media, e.g., documentaries, aquariums, films, books, etc.

Table 2
Summary table of the review results. Services provided by the natural capital stocks i.e. habitats and mobile species. The number and colour indicate the confidence of the link: **blank** = not assessed (not enough information to assess the link), **D = disservice**,**P = link exists but service is not used, 0 = no link**, **1 = link exists** (expert assessment), **2 = link exists** (scientific literature outside from study area, grey literature or website, **3 = link exists** (self-evident link), **4 = link exists** (scientific literature from the study area).

	Ecosystem services																				
	Regulating and maintenance									Provisioning						Cultural					
Habitats groups and mobile species (service providers)	Habitat	Bio-remediation	Toxins	Nutrients	Erosion	Flood	Pests	Oxygen	Carbon	Food	Feed	Materials	Energy	Cultivation	Genetic	Recreation	Research	Aesthetic	Heritage	Symbolic	Entertainment
Hard benthic habitats characterized by perennial algae or aquatic moss	4																				
Fucus spp		2	4	4			4	4	4	2	P	2 / P	P	2 / P	2 / P	4	4	4	4		2
red algae			4	4		0		3	3	0		4 / P	0	4	4	1	4	1			2
perennial filamentous algae		2	4	3		0		3	3	0		0	0	P	P	1	4				2
aquatic moss		2	4	3	0	0		3	3	0	0	0	0				4				2
Soft benthic habitats characterized by vegetation	4																				
Hippuris spp		4	1	3	3	0		3	3	0	0		0				4				2
Potamogeton spp and/or Stuckenia pectinata		4	1	4	4			3	4	0	0		0				4				2
Ranunculus spp		4	1	4	4			3	3	0	0		0				4				2
Zannichellia spp		4	1	4	3			3	3	0	0		0				4				2
watermilfoil (Myriophyllum spicatum and/or Myriophyllum sibiricum)		4	1	4	4	1		3	3	0	0		0				4				2
Exposed by Charales		4	1	3	3			3	3	0	0	0	0				4				2
Sheltered by Charales		4	1	3	3			3	3	0	0	0	0				4				2
Najas marina		4	1	3	3			3	3	0	0		0				4				2
Zostera marina		4	4	4	4			4	4	0	0		0			1	4	1			2
Eleocharis		4	1	3	3			3	3	0			0				4				2
floating-leaved plans		4	1	3	3	1		3	3	0						1	4				2
Phragmites australis		4	1	4	4	1		3	4	0	4	2	P			1 / D	4	1	1		2
Benthic habitats characterized by unattached vegetation	4																				
unattached Fucus spp		2	4	4	1			3	3		0	2	P	2	2	1	4				2
unattached rigid hornwort (Ceratophyllum demersum)		2	1	4	1	1		3	3	0	0	0	0			1	4				2
unattached aggregations of lake ball (Aegagropila linnaei)		2	2	3		0		3	3	0	0	0	0				4				2
Hard benthic habitats characterized by invertebrates																					
Mytilus spp		4	4	4		0	1	0	4	0	0		P	P	P	1	4	2	1	1	2
zebra mussel (Dreissena polymorpha)		4	4	4		0		0	3	0	0		P	P	P	1	4		1	1	2
Amphibalanus improvisus				3	0	0		0	3	0	0	0	0			1	4				2
hydroids (Hydrozoa)				3	0	0		0	3	0	0	0	0				4				2
Benthic habitats characterized by annual algae	4																				
Vaucheria spp		4		3	1	0		3	3	0	0	0	0			1	4				2
Chorda filum and/or Halosiphon tomentosus				3		0		3	3	0	0	0	0			1	4				2
filamentous annual algae		2	4	4		0		3	3	0		0	P	P	P	1	4		1		2

(continued on next page)

Table 2 (*continued*)

Soft benthic habitats characterized by invertebrates	4																				
Mya arenaria		4	4	4		0		0	4	0	0	0	0			1	4	1		1	2
Macoma balthica		4	4	4		0		0	4	0	0	0	0			1	4	2		1	2
Cerastoderma spp		4	4	4		0		0	4	0	0	0	0			1	4	2		1	2
Unionidae		4	4	3		0		0	4	0	0	0	0				4			1	2
infaunal polychaetes		4	4	4		0		0	4	0	0	0	0				4				2
Monoporeia affinis and/or Pontoporeia femorata		4	4 / D	4		0		0	4	0	0	0	0				4				2
Bathyporeia pilosa		4	3	3		0		0	4	0	0		0				4				2
by midge larvae (Chironomidae)		4	4	4		0		0	4	0	0	0	0				4				2
Other benthic habitats	4																				
microphytobenthic organisms and grazing snails				3		0		4	3	0	0					1	4				2
anaerobic organisms		4		3		0		0	3	0	0						4				2
globular colonies of cyanobacteria or ciliates				3		0		3	3	0	0						4				2
Benthic shell gravel habitats				3	1	0		0	1	0	0						4				2
with ferromanganese concretion		4	4	4	1	0		0	1	0	0	P		P	P		4				2
Pelagic habitats and sea ice	4																				
Photic pelagic under 4 ‰ fully mixed		1	1	3	0	0	1 / D	3	4	0	P	P	P	1		1	3	1			2
Aphotic pelagic under 4 ‰ fully mixed		1	1	3	0	0	1 / D	0	4	0	0	0					3				2
Photic pelagic over 4 ‰ fully mixed		1	1	3	0	0	1 / D	3	4	0	P	P	P	1		4	4	1			2
Aphotic pelagic over 4 ‰ fully mixed		1	1	3	0	0	1 / D	0	4	0	0	0					3				2
Photic pelagic over 4 ‰ above halocline		1	1	3	0	0	1 / D	3	4	0	P	P	P	1		1	3	1			2
Aphotic pelagic over 4 ‰ above halocline		1	1	3	0	0	1 / D	0	4	0	0						3				2
Aphotic pelagic over 4 ‰ below halocline)			1	3	0	0	1 / D	0	4	0	0						3				2
Seasonal ice: ice season over 60 days					1 / D				3	0	0	0	0			1	3	1	1		2
Seasonal ice: ice season under 60 days					1 / D				3	0	0	0	0			1	3	1	1		2
Mobile species																					
Clupea harengus	4	0	4 / D	4	0	0		0	4	4	4	P	0			4	4	2	4		2
Sprattus sprattus	4	0	4 / D	4	0	0		0	4	4	4	P	0			4	4		2		2
Osmerus eperlanus	4	0	4 / D	3	0	0		0	3	4	0	P	0			4	4		2	2	2
Gadus morhua	4	0	4 / D	3	0	0		0	3	4	0	0	0			4	4	2	1		2
Perca fluviatilis	4	0	4 / D	3	0	0		0	3	4	0	0	0			4	4	2	2	2	2
Sander lucioperca	4	0	4 / D	3	0	0		0	3	4	0	0	0	4	4	4	4	2	2	2	2
Coregonus lavaretus	4	0	4 / D	3	0	0		0	3	4	0	0	0	4	4	4	4	2	2	2	2
Salmo salar	4	0	4 / D	3	0	0		0	3	4	0	0	0	4	4	4	4	2	4	2	2
Esox lucius	0	0	4 / D	3	0	0		0	3	4	0	0	0			4	4	2	2	2	2
Halichoerus grypus	0	0	4	4	0	0		0	4	2	0	2	0			1	4	2	1		2
Pusa hispida botnica	0	0	4	4	0	0		0	4	2	0	2	0			1	4	2	1		2

IUCN classes to the services they are producing. We found no difference in the number of recognized ESs among the habitats with different IUCN status (Levene's statistical test, $p = 0.07$) (Fig. 2). Although, the results are close to significant and the situation could change in the future.

4. Discussion and conclusions

4.1. Marine habitats provide a strong basis for regulating services

Our study demonstrates the importance of the natural capital stocks of the Northern Baltic Sea to the provision of the ESs. The marine habitats and species provide a broad range of ESs, and their role is highlighted particularly in the supply of regulating services. Although the services produced by marine habitats and species have been assessed in previous studies (e.g. Armoškaitė et al., 2020; Culhane et al., 2018; Potts et al., 2014; Salomidi et al., 2012; Schumacher et al. 2021), our study is the first literature-based assessment in the Northern Baltic Sea covering all marine underwater habitats (based on classification by Kotilainen et al. (2018)) and some mobile species. Thus, even the importance of less well studied habitats could be assessed in the study. The results apply largely to the Baltic Sea area, although to cover better also the Southern parts of the sea, more habitats should be included in the assessment due to more saline conditions.

Most of the services are produced by several habitats (Table 2) which creates a more stable basis for the delivery of ESs. Generally, the habitats that have been most studied such as habitats characterized by *Fucus*, *Phragmites* and *Mytilus* were also linked to most of the services. These are usually habitats with large extents or that act as key species in the ecosystem, and their role for ecosystem functioning is well known. Some habitats such as those belonging to the group "other benthic habitats" are less well studied, and this is reflected in the lack of understanding of the ESs they are providing; the blank cells in the Table 2 indicate knowledge gaps. One prominent finding of the current study is that the role of habitats in producing certain ESs including pest control, genetic services and many cultural services is generally unclear. This means that we do not have a clear picture of the underpinning functions behind these services and the lack of understanding makes them difficult to manage.

The role of habitats in delivering regulating services is emphasized and it can be concluded that all habitats contribute to these services. For example, carbon storage is linked to all assessed habitats and species as all living organisms contain carbon and thus contribute to the standing carbon stock to some extent. We did not assess the relative role of habitats in producing the services, as undertaken by Potts et al. (2014), but it is worth noting that there can be considerable difference in the amount or volume of services that the habitats can supply. For example, the most important carbon stocks are long-lived e.g., those with over 50 years of time (IPCC, 2007) and thus some of the habitats and species are clearly more important for storing carbon than others. These include long storages such as soft sediments and roots of long-living vascular plants (Burrows et al., 2014). Also short-lived species may have an important role for the stock if the community biomass does not change or only increases in the long term.

According to the newly reviewed United Nations accounting system, accounting for all carbon stocks and their potential losses is recommended (United nations et al., 2021). Species and habitats with longevity less than a year, annual algae or phytoplankton for example, will probably not comprise an important carbon stock from this point of view but plankton can act as a transporter of carbon to the benthic sediments that may act as carbon sinks and provide a long-term storage for carbon (Richardson and Jackson, 2007; Snelgrove, 1999). Although there is an initial understanding regarding the stock of carbon in different marine habitats, we still lack knowledge regarding their role for turnover and long-term sequestration, and their potential feedback to the atmosphere (through greenhouse gas & aerosol production).

Similar to carbon, nutrients are stored in all living organisms, but the longevity of the storage is relevant for the service efficiency. Also, the volume matters; the larger the extent of the habitat, the more important it can be considered for mitigating the climate and eutrophication effects. For example, soft sediments characterized by clam *Macoma baltica* have great extent in the study area (VELMU map service: https://paikkatieto.ymparisto.fi/velmu/index_eng.html) and thus potentially encompass an important stock of carbon compared to more traditionally considered species (Scheffold and Hense, 2020; Mäkelin and Villnäs, 2022). On the other hand, although the seagrass *Zostera marina* can bind a substantial amount of carbon, it has very limited extent due to low salinity concentrations in the area.

4.2. New provisioning services may be discovered and utilized in the future

Fish are traditionally the most prominent resource for provisioning services, and this is the case also for the Baltic Sea. Apart from fish, the harvesting or cultivation of other species and habitats is very small scale, despite the long traditions of cultivation in Europe and the growing interest towards the cultivation of macroalgae and mussels globally. However, there are many potential future uses identified for certain habitats, or more precisely, to certain species such as *Fucus* (company: https://originbyocean.com/) and *Mytilus* (Haemers et al., 2002). This potential is related to service "raw materials" as new uses of many chemical compounds and proteins found in those species and would be based on either *in-situ* cultivated organisms or artificial growth of organisms or their tissues in laboratories. These services are also dependent on natural habitats and their environmental status as the cultivated individuals rely on natural stocks and recruits. Thus, natural habitats are needed for this kind of innovation to be possible in the future as there are still many species that are not well-studied but might hold potential for future uses.

4.3. Cultural services are difficult to assess using matrix approach

The generic matrix approach works well for assessing the provisioning and regulating services but may not be the most suitable method for assessing cultural services. Few studies have accounted for the full range of cultural services, and apart from recreational services, they are usually underrepresented in the ESs assessments (Liquete et al., 2013). Most of the knowledge gaps also in our study relate to cultural services. Cultural values are more challenging to study because they are generated through more complex pathways and are more bound to specific locations than many other services (Geange et al., 2019). Charismatic and clearly visible species are usually important for cultural services (Potts et al., 2014), and also in the current study, mobile species played a key role in delivering these services. There is still further research needed to achieve a more complete understanding of the cultural services. For policies such as maritime spatial planning this means that current knowledge of cultural services should be complemented with case specific knowledge, preferably engaging local stakeholders to input local knowledge (Burdon et al., 2019). Also, many times the ESs studies seem to be conducted either by economists or natural scientists and are consequently lacking a social science perspective (McKinley et al., 2020). This is also a challenge in our study as our expert team consisted mainly of natural scientists which may cause a potential bias towards assessing regulating services more thoroughly as they more directly relate to ecosystem functions.

4.4. Ecosystem functions are underpinning ecosystem services

Our work concentrated on the final services provided by the habitats and selected species which enables conducting economic analysis and valuation of benefits in the following steps. Final services lead to human benefits and using clear and relevant units along the cascade helps to avoid double-counting (Boyd and Banzhaf, 2007). But it is worth noting

Table 3
a. Summary of the results per habitat group: percentage of identified services produced by habitats compared to all possible habitat-service combinations and the percentage of linkages that were not identified or could not be assessed. **b.** The share of regulating, provisioning, cultural services, and services that are not currently used but obtain potential future uses from the identified services.

a.

Habitat group	Identified services	No services identified	Could not be assessed
Hard benthic habitats characterized by perennial algae or aquatic moss	56 %	16 %	28 %
Soft benthic habitats characterized by vegetation	45 %	14 %	41 %
Benthic habitats characterized by unattached vegetation	50 %	17 %	33 %
Hard benthic habitats characterized by invertebrates	44 %	28 %	29 %
Benthic habitats characterized by annual algae	43 %	22 %	35 %
Soft benthic habitats characterized by invertebrates	36 %	29 %	34 %
Other benthic habitats	31 %	18 %	51 %
Pelagic habitats and sea ice	46 %	22 %	32 %
Mobile species	53 %	32 %	15 %

b.

Habitat group	Regulating	Provisioning	Cultural	Potential
Hard benthic habitats characterized by perennial algae or aquatic moss	44%	16%	31%	9%
Soft benthic habitats characterized by vegetation	69%	2%	28%	1%
Benthic habitats characterized by unattached vegetation	60%	10%	27%	3%
Hard benthic habitats characterized by invertebrates	37%	0%	46%	17%
Benthic habitats characterized by annual algae	50%	0%	38%	12%
Soft benthic habitats characterized by invertebrates	55%	0%	45%	0%
Other benthic habitats	55%	0%	35%	10%
Pelagic habitats and sea ice	49%	4%	36%	11%
Mobile species	28%	18%	51%	3%

that habitats have a fundamental role in maintaining life and biodiversity in the marine environment. The habitats with a less central role in service production may have a key role in ecology and thus in supporting the final services (Geange et al., 2019). By including the "maintaining habitats and providing food" service in our assessment we were able to highlight the role of habitats in supporting the fish species and seals that are highly mobile. This service is usually interpreted as an intermediate or supporting service (Culhane et al., 2019; Potts et al., 2014). Listing and analysing all the functions and interactions behind each service would be very challenging to complete given current gaps in knowledge and evidence. Instead, we recommend appreciating the complexity of ecosystems and conserving the habitats and species to an extent that preserves their functioning and thus guarantees the flow of ESs in the future.

The human well-being is being threatened by the degrading ecosystems and the loss of biodiversity (Cardinale et al., 2012), and the condition of the ecosystems is closely linked to the capacity of an ecosystem to produce services (United nations et al., 2021). In this study, the IUCN Red List threat status of habitats was used as an indication of habitat vulnerability and the potential threat to the service delivery. The threat status was not statistically linked to the number of services the habitats are providing, although the p-value was very close to significant (Fig. 2), and the result might change in the future. Particularly, when the habitats that play a key role in the ecosystem and provide many services such as *Fucus* are threatened, the ability of an ecosystem to provide services may be compromised. Services can also be reliant on each other and therefore loss in delivery of one service (e.g., fish nursery function) can have a knock-on effect on other services (e.g., food provision).

4.5. Comparison with other studies

The low number of species existing in the Northern Baltic Sea enabled us to include all identified habitats in the area which may not be possible in many other marine areas due to higher number of species and habitats. Thus, our study may act as an interesting case study where all the habitats and their ESs can be mapped and assessed. Although, it could be further complemented with assessment of large-scale habitats as many cultural services and for example nursery areas are usually generated by wider environmental features and habitat complexes such as shallow bays. Also, services provided by birds could be included in the future (see for example Burdon et al., 2017).

The matrix approach has increasingly been used to analyse ecosystem services during the past decade (Campagne et al., 2020) but most of its applications cover only terrestrial environments. However, some examples from the marine environment exists; for example, Müller et al. (2020) assessed 18 marine compartments in the Southern parts of the Baltic Sea using the matrix approach. They included some key community, sediment and water body types in their study which were assessed using expert judgment. In the follow-up study, Schumacher et al. (2021) updated the study to better fit the habitat classification with the EU's habitat directive (Directive 92/43/EEC) and HELCOM HUB. Our approach differs from the studies by Müller et al. (2020) and Schumacher et al. (2021) as these two studies use more rough habitat classification compared to our study, as we have focused on the characterizing species of the habitats and included total of 48 different habitats. Also, they have scored the links from habitats to services using ecosystem service potential values whereas our scores demonstrate the confidence of each link and do not consider the strength or importance of the linkages. We used literature as the first source of information in our study and expert assessment to supplement the data if no literature was available. It could be argued that this diminishes the potential subjectivity of the expert-based assessment.

In those parts where the studies can be compared, the results seem rather consistent. For example, both our study and the study by Müller et al., 2020 demonstrate that the marine habitats are important for global climate regulation i.e. storage and sequestration of carbon. Our study complements the previous studies by adding the Northern Baltic Sea perspective to the assessment as the area has much lower salinity conditions than the Southern parts. Also, Schumacher et al., 2021 call for better differentiation of marine waters based on HELCOM HUB for Baltic Sea wide ES assessment. Our study fills this gap as it is compatible with HELCOM HUB and it adds detail to the habitat classification by taking the characterizing species of different habitats into account.

4.6. Applying results in marine management

This study supports implementation of multiple EU and global frameworks and policies by providing crucial knowledge on ESs provided by marine ecosystem. For example, implementation of both the

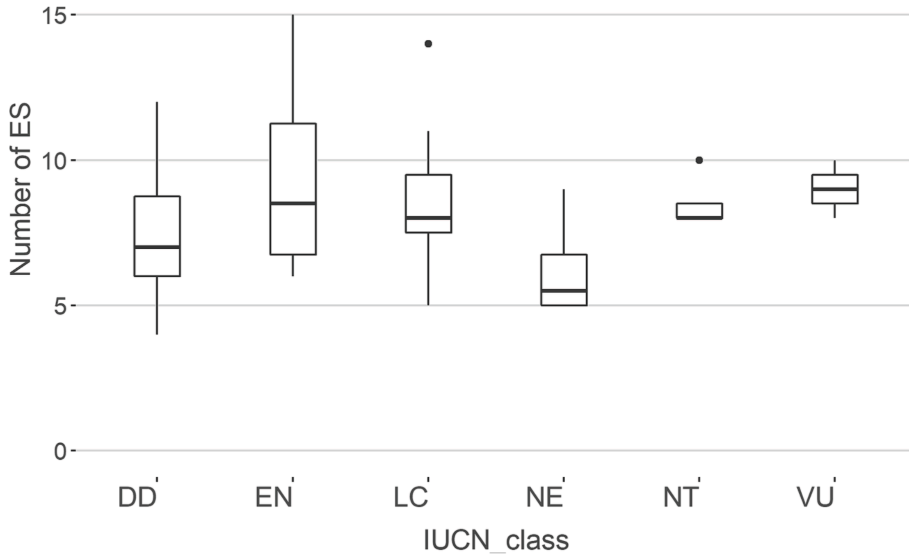

Fig. 2. Vulnerability of benthic habitats compared to number of identified services. No significant differences between groups (p = 0.07). IUCN red list classes of habitats: DD = data deficient, NE = not evaluated, LC = least concerned, NT = near threatened, EN = endangered, VU = vulnerable. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

MAES process in the EU and ecosystem accounting (United nations et al., 2021) benefit from the study as the results can be used for mapping and modelling of ESs. There are good habitat distribution maps available through the VELMU map service (https://paikkatieto.ymparisto.fi/velmu/index_eng.html) in our study area, and combining information from this study to the habitat models will offer an opportunity to evaluate the ecosystem service supply in different spatial scales. This is particularly required for ecosystem accounting. Including the natural capital stocks and their services to the national accounts is an important effort to demonstrate the value of ecosystems and species to the economy and our well-being (United nations et al., 2021), and our study contributes to fulfilling this target.

MSFD (Directive 2008/56/EU) and the newly updated version of the Baltic Sea Action Plan (HELCOM, 2021), which both are important policies in the Baltic Sea, emphasize the identification of ESs. The aim is that the human pressures are kept on a level that allows achieving good environmental status of the environment and the capacity of the ecosystem to provide services for current and future generation. Our results can be used in fulfilling this aim, particularly for identification of the ESs.

From the global perspective, the Kunming-Montreal Global Biodiversity Framework (GBF) (CBD/COP/DEC/15/4), that builds on the strategies of the Convention of the Biological Diversity and other agreements, seeks to achieve harmony between people and nature. It states that “by 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people.” Our study takes steps towards achieving its targets that include restoring, maintaining and enhancing nature’s contributions to people.

In addition, maritime spatial planning requires information on ESs. When planning human activities in any area, the potential trade-offs should be made visible throughout the process. Traditionally, the existence of habitats and species is considered as a trade-off with human activities, but the ecosystem service approach broadens this scope and highlights those trade-offs that are also harmful for human benefits. For example, if a wind farm is being planned in a certain area, the ESs and particularly the regulating services provided by habitats and species can be assessed using the information provided by the current study. The construction of the wind farm probably degrades some of the habitats (and on the other hand, creates new ones) and the services provided by the destroyed habitats are also lost. Although the examples of implementing the ES knowledge in the maritime spatial plans are scarce (Galparsoro et al., 2021), once the information on the ESs and their spatial distribution increases, the application of this information becomes easier.

To conclude, some general advice of including the ESs into marine management can be given based on the current study. First, as habitats are important for supporting the ecosystems and providing particularly regulating services, the human activities that are harming or destroying marine habitats will always have trade-offs with at least 1) the capacity of habitats providing regulating services, including carbon and nutrient storages and mitigation the effects of harmful substances; 2) the ESs that are yet to be discovered and used; and 3) ecosystem functioning that is underpinning ESs. Second, cultural services are usually specific to certain locations and often ecosystem-based matrix approaches are not enough to assess them. Cultural services require additional social science research to ensure that they are more appropriately represented in ES assessments. Finally, as marine systems are complex, instead of trying to understand every single function behind every service, we recommend conserving the habitats and species in a level that guarantees the flow of ESs and prevents any unwanted knock-out effects where for example the loss of one species suddenly affects the flow of ESs produced by other species. A good starting point could be the target of the Convention of Biological Diversity to protect 30 % of our lands and oceans by 2030. This will also guarantee the flow of ESs for future generations.

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

The review data is shared as a table format along with the article. Please see Appendix A.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2023.101585.

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