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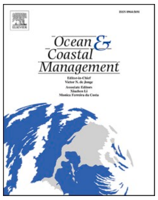

Establishing the links between marine ecosystem components, functions and services: An ecosystem service assessment tool

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ABSTRACT

Although the concept of ecosystem services has been in use for many decades, its application for policy support is limited, particularly with respect to marine ecosystems. Gaps in the assessments of ecosystem services supply prevent its empirical application. We advance these assessments by providing an assessment tool, which links marine ecosystem components, functions and services, and graphically represents the assessment process and its results. The tool consists of two parts: (i) a matrix following the ecosystem services cascade structure for quantifying the contribution of ecosystem components in the provision of ecosystem services; (ii) and a linkage diagram for visualising the interactions between the elements. With the aid of the Common International Classification of Ecosystem Services (CICES), the tool was used to assess the relative contribution of a wide range of marine ecosystem components in the supply of ecosystem services in the Latvian marine waters. Results indicate that the tool can be used to assess the impacts of environmental degradation in terms of ecosystem service supply. These impacts could further be valued in socioeconomic terms, as change in the socioeconomic values derived from the use of ecosystem services. The tool provides an opportunity for conducting a holistic assessment of the ecosystem service supply and communicating the results to marine spatial planning practitioners, and increasing their understanding and use of the ecosystem service concept.

1. Introduction

The concept of ecosystem services (ES) has been in use since the 1960's, in order to increase awareness of human dependence on ecosystems for their well-being and bring together issues of sustainability of the environment and economic growth (Millennium Ecosystem Assessment, 2005). Since then, benefiting from cross-disciplinary academic effort, the ES concept has been substantially developed (e.g., Fisher and Turner, 2008; Potschin-Young et al., 2017; Lillebø et al., 2017). It unveils the values of the natural environment to society through ES assessments (Ivarsson et al., 2017, O'Higgins et al., 2019a, Boyd and Banzhaf., 2007; Barton and Harrison, 2017) and has been used to raise awareness of the relationship between humans and nature, and to communicate scientific findings to policy makers (Ainscough et al., 2019).

Although the debate over conceptual frameworks, assessment and valuation methodologies is ongoing (e.g., Costanza et al., 2017; Diaz et al., 2018; Braat, 2018), the ES concept is embodied in regulations and policies (e.g., United Nations Convention on Biodiversity; EU Marine Strategy Framework Directive (MSFD, 2008/56/EC); EU Biodiversity strategy for 2020; EU Regulation on invasive alien species (IAS Regulation 1143/2014), and Maritime Spatial Planning Directive (MSPD, 2014/89/EU)) and a sizable effort to operationalise it has been undertaken for more than a decade. In the EU, maritime spatial planning (MSP) has been introduced as an instrument to provide support in achieving integrated maritime governance, ensuring sustainable development and Blue Growth, whilst also attaining good marine environmental status as set out by the MSFD (European Commission, 2008a; Directive 2014/89/EU; European Commission, 2008b; Hassler et al., 2019). One of the fundamental requirements to achieving these goals is the adoption of the Ecosystem-based approach (Directive, 2014/89/EU) and the use of the ES perspective (O'Higgins et al., 2019a;

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Bohnke-Henrichs et al., 2013). Integration of ES in MSP would help balance the need to protect ecosystems, whilst encouraging Blue Growth, sustainable resource use and potentially solve conflicts between marine users, perceived to be largely a result of single sector centred planning processes (Bohnke-Henrichs et al., 2013). However, despite methodological developments, the results of ES assessments rarely play an instrumental role in directly influencing maritime policy (Ainscough et al., 2019). It has been argued that this is largely because to this day, marine ES assessments are only conducted at a conceptual level, estimating the supply of theoretical rather than actual services (Hummel et al., 2019).

The most widely recognised framework for linking ecosystems and human well-being is the ES cascade framework (Potchin-Young et al., 2018). It represents the "production chain" of ES, starting from the biophysical structures and processes of an ecosystem and ending with the societal benefits (Liquete et al., 2013). However, to this day, quantitative relationships between biodiversity, ecosystem functioning and ES, are still poorly understood (Balvadera et al., 2016). This is particularly the case for deep sea and benthic habitats (Galparsoro et al., 2014). Lack of sound biophysical knowledge increases the risk of overexploitation or mismanagement of natural resources and degradation of the ecosystems (Bateman et al., 2011). ES assessment can prevent this by providing rendition of ecological knowledge into terms and concepts employed in ES, thus making the link between ecosystems and human well-being more explicit (Mangi et al., 2010; Ainscough et al., 2019; von Thenen et al., 2020).

A range of classification systems are available to aid identification of ES and should be selected depending on the aims and the objective of the assessment (La Notte et al., 2017; Hummel et al., 2019). Currently, the most popular is the Common International Classification of Ecosystem Services (CICES). It provides a nested, four tier hierarchical structure, categorising ES into three main categories (Provisioning, Regulation & maintenance, Cultural), enabling standardised assessments at various geographical scales (Haines-Young and Potschin., 2017).

Matrix-based ES assessments have been used to link different ecosystem components to a broad array of ES, using scientific literature and expert opinion (see Cabral et al., 2015; Turner et al., 2014; Ahtiainen et al., 2018 based on Kraufvelin et al., 2018; von Thenen et al., 2020).

However, the majority of matrices employed in expert elicitation based marine ES supply assessments, use semi-qualitative scoring techniques (Campagne and Roche, 2018) and often lack comprehensive and detailed description of all ecosystem components (Townsend et al., 2018).

The linkage diagram (e.g., Culhane et al., 2018) is very useful in the establishment of links between habitats and the ES they provide. The application of linkage diagrams varies from purely illustrative (e.g., O'Higgins et al., 2019b) to semi-quantitative, where a number of links per ecosystem component (e.g., Culhane et al., 2018) or the weighted importance of link (e.g., Texeira et al., 2019) are used to stress the importance of ecosystem components. The weighted linkage approach utilises output from expert filled habitat-services matrices (e.g., Jacobs et al., 2015; Geange et al., 2019), that can be used also separately from linkage diagrams to semi-quantitatively characterise the relative importance of each link.

The aim of this study is to develop an assessment tool to quantitatively describe the contribution of marine habitats and species in the supply of ES and to improve the way complex interrelations are communicated to MSP practitioners.

To achieve this aim, the following research questions were answered:

a. In which ways do the CICES V5.1 typology and the cascade framework need to be adapted to be useful in marine ecosystem service assessments?
b. How can expert elicitation matrices be developed to reflect the cascade framework to make the process of marine ecosystem service assessments more transparent and systematically gather knowledge on the interrelations between different parts of the cascade?
c. How can the expert judgement be translated into linkage diagrams which add further transparency to the process and clearly inform the audience of the results of marine ES assessments?

The Latvian marine context was used to demonstrate the two-part assessment tool, with a particular focus on benthic marine habitats.

2. Methods

Work was organized into 10 consecutive steps as illustrated in the workflow diagram (Fig. 1). The following sections (2.1 to 2.6) elaborate on the steps summarized in the figure.

2.1. Study site description

Latvian marine waters are located in the South Eastern Baltic Sea. The Baltic is a brackish, enclosed sea shared by nine countries and a multitude of sectors.

A significant part of the Latvian population lives near the coast, where coastal fishing has been a historically important part of the lives of coastal communities; shaping culture and providing livelihoods (CBD/EBSA/WS/2018/1/4). Nowadays, traditional fishing practices have declined and fishing villages are increasingly popular tourism and recreation spots (see CHERISH EU, 2019 project).

The type and abundance of marine organisms found in the study area varies depending on the availability of sunlight and substrate type.

The euphotic zone (approx. up to 10 m depth in the Gulf of Riga and 20 m in the open Baltic Sea) host mosaics of hard substrate (stones, pebbles), sand and mixed-substrate habitats (see Fig. 2). Hard substrate habitats are the most prominent and ecologically significant habitat types. They are hot-spots of biodiversity, hosting macroalgal communities, mussels, mobile invertebrates and fish (Norling and Kautski, 2008).

In the deeper waters, large areas of the seabed are formed of muddy sediments hosting many infaunal invertebrate species. In the open Baltic Sea, muddy sediment is largely found in the anoxic zone under permanent halocline, where mostly microbial activity can be expected.

Overtime, the Baltic has been significantly impacted by large-scale fisheries and nutrient release (HELCOM, 2018).

2.2. Expert elicitation

A panel of five scientists was assembled for a semi-structured, interdisciplinary group discussion to identify regionally relevant ES and quantitatively describe the importance of ecosystem components and functions in their supply.

A snowball sampling technique (Henry, 1990; Palinkas et al., 2013) was employed to source participants based on recommendation by researchers in Latvia. Expert competence was ensured by years of work or study of the South Eastern Baltic Sea marine environmental and social systems. Regional knowledge (Singh et al., 2017), understanding of the ES concept, as well as specialized technical knowledge (Jacobs et al., 2015) were also seen as very important criteria for the selection of the participants, to ensure that they are well informed and that all responses are reliable. Individuals with a range of backgrounds were selected, including knowledge of marine biology, ecology, biogeochemistry, sociology, geography and economics. A group setting was chosen to promote discussion and challenge the experts' overconfidence and biases (Singh et al., 2017).

The group size was limited by the availability and response rate of experts fulfilling the sampling criteria. Although some (Champagne and Roche, 2018) have argued that the number of experts in panels should range from 10 to 15, others (Jacobs et al., 2015) have also recognised that when gathering expert knowledge on topics such as ecosystem

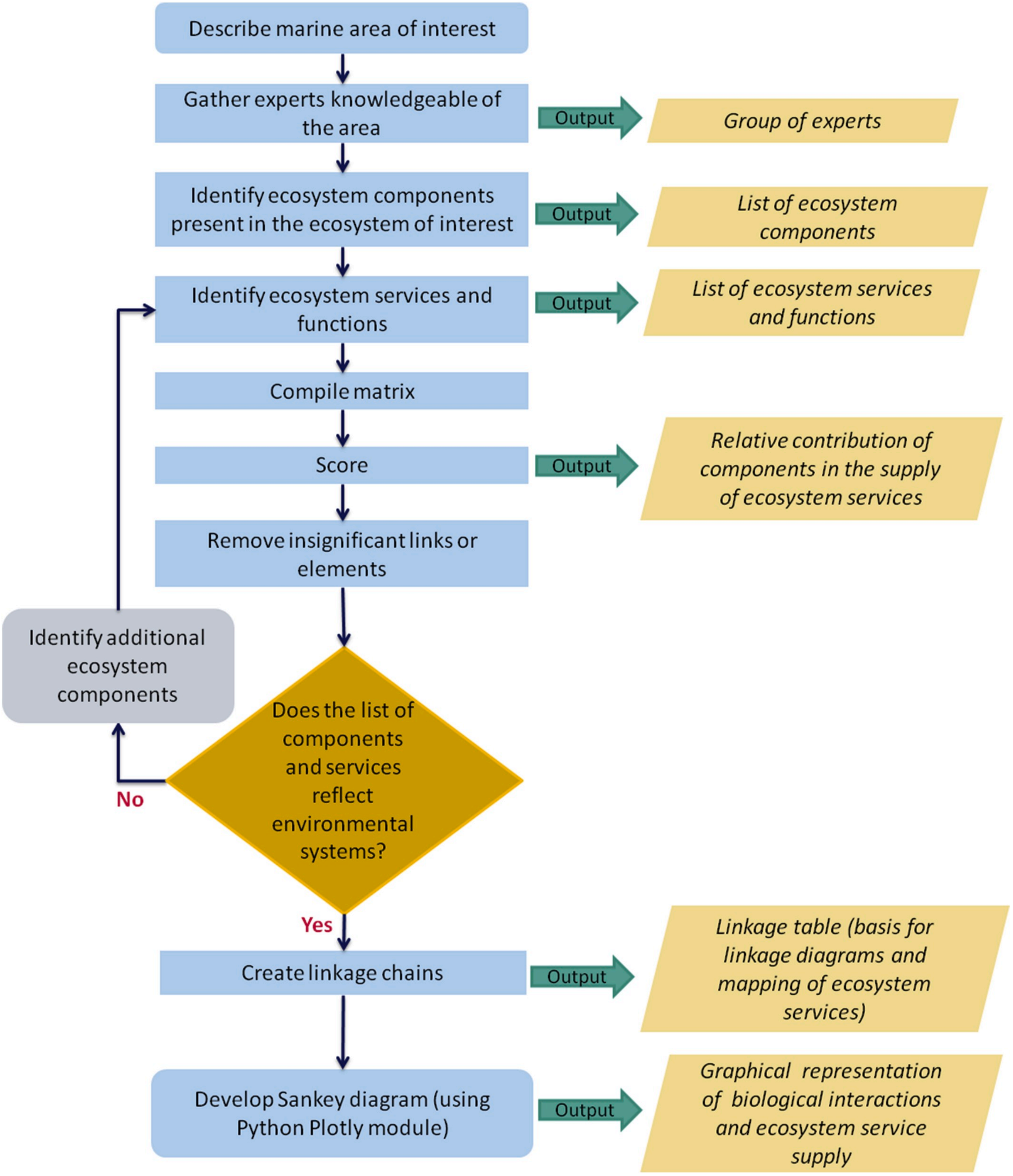

Fig. 1. Steps taken to arrive at a quantitative description and graphical representation of the relative importance of ecosystem components in the supply of ecosystem services.

capacity to supply ES, the number of respondents is insignificant and the focus should remain on generation of data with high confidence levels which depends on experts' backgrounds. What's more, experience from Sweden shows that the number of experts used to assess the impacts on the ecosystem from various human pressures is on average about 5.3 (Pålsson, 2020, personal communication). After careful consideration, it was concluded that a panel of five participants with the necessary knowledge was sufficient.

The exercise was completed in three sessions: component & habitat identification, ecosystem service identification, and the scoring activity.

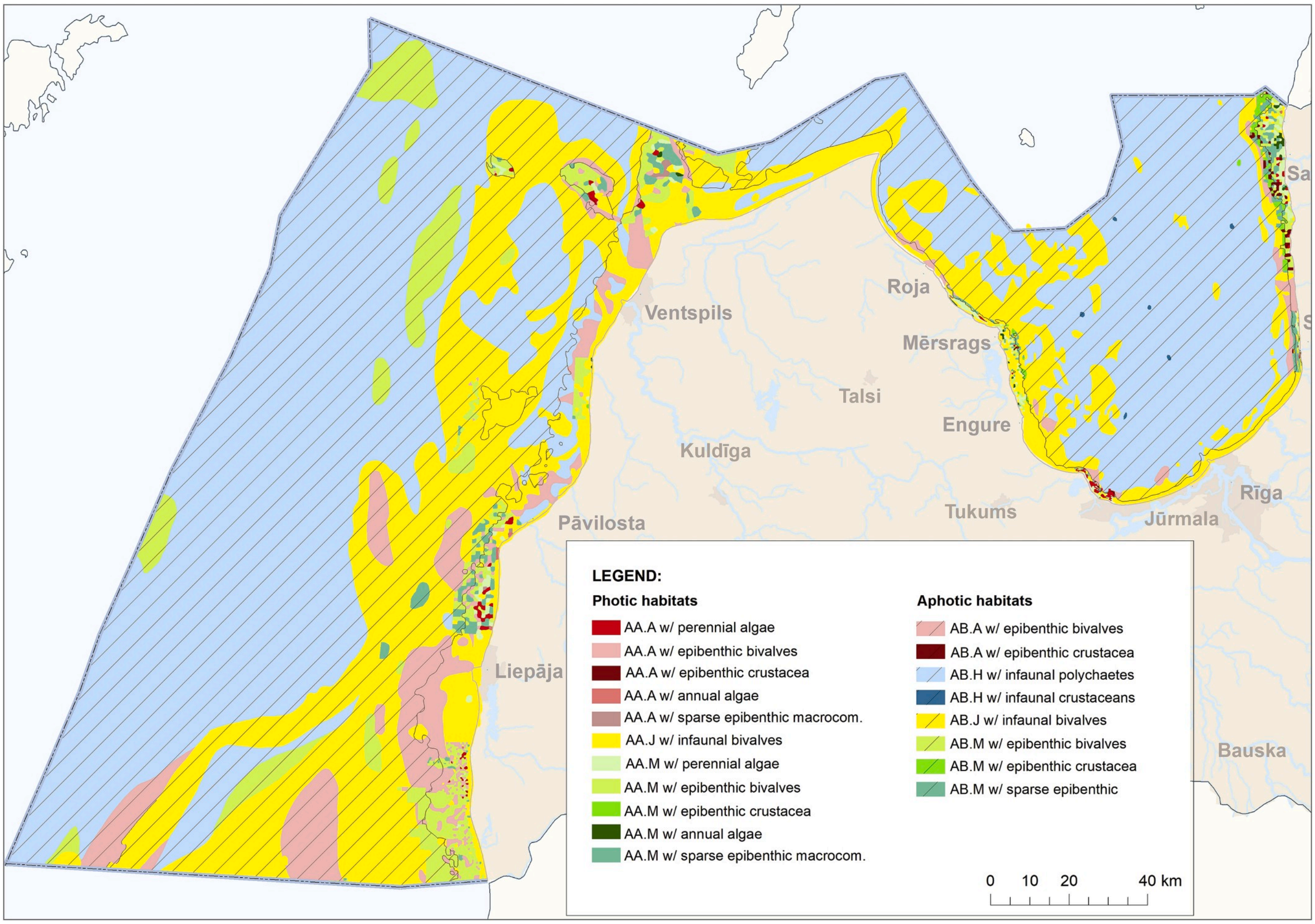

Fig. 2. Map showing the distribution of marine habitats in the case study area categorised according to the HELCOM HUB (2013) classification system. AA.A- Baltic photic rocks and boulders, AB.A-Baltic aphotic rocks and boulders, AA.M- Baltic photic mixed substrate, AB.M- Baltic aphotic mixed substrate, AA.J- Baltic photic sand, AB.J- Baltic aphotic sand, AB.H-Baltic aphotic mud, AD.N- Baltic photic pelagic, above halocline, AE.N- Baltic aphotic pelagic, above halocline (HELCOM, 2013).

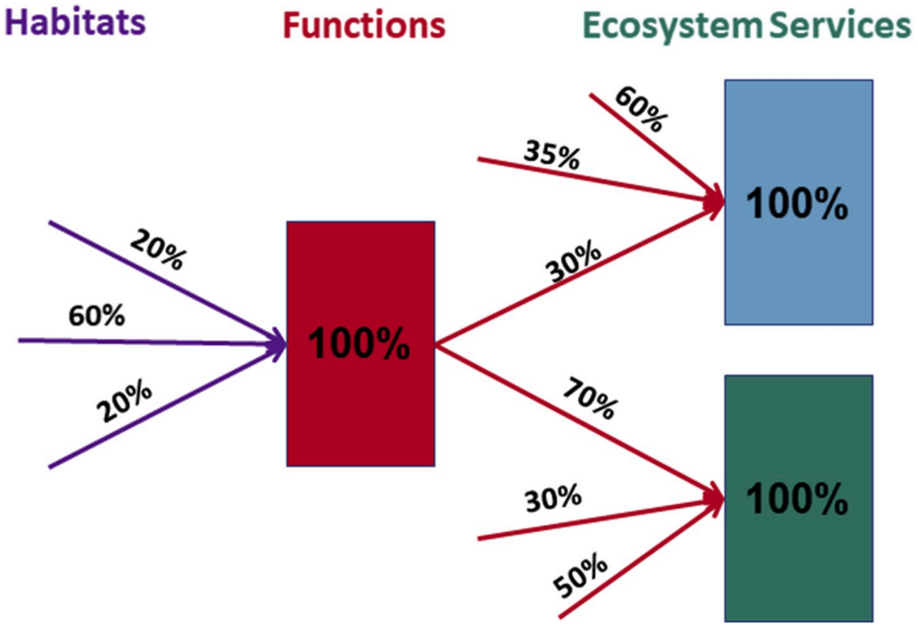

Fig. 3. A conceptual framework for the quantification of ecosystem service supply.

The discussion broadly followed the IDEA (“Investigate,” “Discuss,” “Estimate” and “Aggregate) protocol for structuring expert elicitation in science (Hemming et al., 2017).

2.3. Identification of ecosystem components

To begin with, marine scientists catalogued species and habitats found in the case study area. Underwater habitat maps of the Latvian territorial waters were analysed following the HELCOM HUB (HELCOM, 2013) classification system. Habitats were described down to Level 5 resolution, which defines the dominance of certain species or species complexes in the habitats. The identified habitats were classified against three main factors – substrate type, dominant species and whether or not the habitat in question is photic or aphotic.

The habitat classification system used in this study often displays already aggregated information, with a level of resolution insufficient for the purpose of this study. Therefore, the group of experts identified a list of dominant ecosystem components or species complexes performing similar ecological roles, like perennial algae, annual algae, mussels, epibenthic crustacea etc., that form or are associated with the corresponding habitat. To ensure that all species identified in the case study area were included in the assessment (with the exception of birds and mammals), they were organized into species complexes according to their functions.

In addition to benthic habitats, pelagic habitats and species that are interlinked with benthic habitats were also included in the assessment.

The list of ecosystem components was employed in a group discussion, in order to identify the functions performed by the species and habitats.

2.4. Adaptation of CICES v5.1 and the cascade framework

ES were identified using CICES v5.1, on the basis of relevance for the South Eastern Baltic Sea marine environment and the Latvian sociocultural context. The experts listed all CICES v.5.1 Group and Class level ES supplied by the habitat and the species previously selected. Thereafter, the selected ES were further revised to facilitate a marine ES assessment embedded in the case study context. Particularly, *Regulation & Maintenance services* were scrutinized, since a number of ES listed in CICES were found to correspond with the Potschin et al. (2016) definition of function (see La Notte et al., 2017), where function is a role of the ecosystem or its components in delivering ecosystem services.

The list of Cultural ES (CES) was borrowed from a study on the Latvian citizens’ interaction with the marine environment and the significance they attach to various marine cultural ES conducted by Ahtiainen et al. (2019). Revisions were made to the list by the natural scientists of the expert panel, which involved clustering of the closely conceptually related CES originating from the same set of ecosystem functions.

2.5. Matrix compilation and scoring

The same group of experts were asked to quantitatively describe the links between the different ecosystem components, functions and services in terms of percentages, estimating the proportions of the service that are supplied by each one of its contributing parts. The scoring process begun with a description of the species’ importance in the maintenance of the habitats. Highest scores were assigned to dominant species playing the most important roles and the remainder distributed among the rest, according to their relative importance. The habitats were then studied in terms of their contribution towards the performance of ecosystem functions, which were then rated for their contribution towards the supply of ecosystem services (see Fig. 3).

The assessment was seen as an iterative process. Scoring was done in several rounds, allowing the experts to ensure the relevance of the ES and to identify gaps in the list of ecosystem components. After the initial scoring round, some ES were found to be insignificant (relative contribution of <1%) and were removed from the list. A second round of scoring was carried out with the revised list of ES and ecosystem components. Experts discussed each score and worked out final consensus scores, describing all links featured in the matrices. It was assumed that the state of habitat is in good condition and the proportion amongst the habitat constituents is in balance.

Confidence reporting, describing the group’s collective degree of confidence, took place in parallel to the scoring process. As suggested by Jacobs et al. (2015) and Bradley (2017), the participants were asked to rate their confidence for each set of values entered into the matrix based on two criteria: level of evidence (limited, medium or robust) and degree of agreement on the matter in the group (low, medium or high). Confidence was presented on a 5 level scale - “very low” (1), “low” (2), “medium” (3), “high” (4), and “very high” (5), where low agreement and limited evidence resulted in very low confidence and robust evidence and high agreement in very high confidence.

2.6. Construction of the linkage chains and diagram

Sankey diagrams depict a flow of links between a multitude of nodes and the magnitude of each of the connections (Cuba, 2015). They have been widely used in industrial ecology and engineering to depict material flows in order to communicate issues of resource management and energy conservation (Schmidt, 2008). In recent years, they have been employed as visualisation instruments in land use planning (as seen in Cuba, 2015), but largely for illustrative purposes only (O’Higgins, 2019b; Curmi, 2013). Limited adoption of the diagram in planning can be seen as a missed opportunity, as only few instances have been found where Sankey diagrams have been employed as a tool aiding the planning process (as seen in the AQUACROSS project). The Sankey diagrams were seen as a suitable instrument for working with and visualising the ES assessment in this study, as they share their intrinsic structure with that of the cascade framework - both organise information in levels, in hierarchical order and in a flow from left to right.

To get an understanding of the overall contribution of each ecosystem component in the provision of ecosystem services, the experts’ ascribed scores were used to work out the relative value of each element with respect to its outgoing and incoming links. The collected data from the matrix were translated into a list of quantitatively defined connections, linking all elements one by one, from ecosystems services to ecosystem components through ecosystem function, and in turn creating a chain of links.

Inverse scores and inverse relative contribution values were calculated to describe the relative importance of the defined links in a flow starting with ecosystem components.

The diagram was built using the Python programming language and the *Plotly* module (Plotly Technologies Inc, 2015) in a *Jupyter* notebook web-based interactive environment.

To demonstrate the full functionality and uses of the tool, a single ES (*Nutrient regulation (by incorporation in biomass)*) was isolated for an assessment of change in the supply of ES due to environmental degradation. The input data describing the relative importance of each ecosystem components in the system was altered to imitate change in the ecosystem conditions.

3. Results

3.1. Ecosystem components and habitats

Twenty-one benthic and two pelagic habitats were identified by the experts (see Table 1) and linked to species, or species complexes (ecosystem components) forming a corresponding habitat or were associated with one.

Fish species were separated into groups of benthic and pelagic fish, as they relate to benthic habitats at different life-stages. The scores given

Table 1

Relative importance of species in the maintenance of habitats (in percentages, %). Confidence rated 1 (very low) to 5 (very high). AA.A- Baltic photic rocks and boulders, AB.A-Baltic aphotic rocks and boulders, AA.M- Baltic photic mixed substrate, AB.M- Baltic aphotic mixed substrate, AA.J- Baltic photic sand, AB.J- Baltic aphotic sand, AB.H-Baltic aphotic mud, AD.N- Baltic photic pelagic, above halocline, AE.N- Baltic aphotic pelagic, above halocline (HELCOM, 2013).

Habitats	**Ecosystem components**								
	Perennial algae	Annual algae	Mussels (*Mytilus trossulus*)	Epibenthic crustacea (*Balanus*)	Other macro-invertebrates	Infaunal bivales (*Macoma, Mya*)	Infaunal crustacea (*Monoporeia*)	Infaunal polychaetes (*Marenzellaria*)	Microbes
Photic hard substrate benthic habitats									
AA.A w/perennial algae	55	15	20	1	1				
AA.A w/annual algae	20	50	20	4	1				
AA.A w/epibenthic bivalves			70	12	5				
AA.A w/epibenthic crustacea			5	85	3				
AA.A w/sparse epib. macrocomunn.			33	33	33				
Aphotic hard substrate benthic habitats									
AB.A w/epibenthic bivalves			50	10	0,1				
AB.A w/epibenthic crustacea			10	70	10				
Photic mixed substrate benthic habitats									
AA.M w/perennial algae	54	20	20	0,1	0,1				0,1
AA.M w/annual algae	20	55	20	3	0,1				0,1
AA.M w/epibenthic bivalves			49	0,1	10	0,1	0,1	0,1	0,1
AA.M w/epibenthic crustacea			20	69	0,1	0,1	0,1	0,1	0,1
AA.M w/sparse epib. macrocommun.			0,1	20	50	20	10	0,1	0,1
Aphotic mixed substrate benthic habitats									
AB.M w/epibenthic bivalves			49	10	20	20	0,1	0,1	0,1
AB.M w/epibenthic crustacea			0,1	49	20	20	10	0,1	0,1
AB.M w/sparse epib. macrocommun.			0,1	33	0,1	33	33	0,1	0,1
Photic soft substrate benthic habitats									
AA.J w/infaunal bivalves					0,1	50	20	10	0,1
Aphotic soft substrate benthic habitats									
AB.J w/infaunal bivalves					0,1	50	20	10	0,1
AB.J w/infaunal polychaetes					1	20	10	49	0,1
AB.J w/infaunal crustacea					1	20	49	20	0,1
AB.H w/infaunal polychaetes					10		20	50	20
AB.H w/infaunal crustaceans					10		50	20	20
Photic pelagic habitats									
AD.N									0,1
Aphotic pelagic habitats									
AE.N									10

to fish species reflect whether the respective species uses the habitat for spawning, e.g., herring, or for feeding, e.g., cod and flounder.

Relatively high scores were assigned to microbes found in both pelagic and benthic habitats, as they perform important transformation processes. Similarly, high scores were assigned to phytoplankton and zooplankton in pelagic habitats as their main constituents.

3.2. *Relative importance of ecosystem components in the functioning of ecosystems*

All in all, ten ecosystem functions were identified (See Table 2).

Group level CICES ES *Lifecycle maintenance, habitat and gene pool protection* significantly contributes toward human well-being; however, it has been argued that the contribution is largely indirect and that this ES should be considered as an ecosystem function (Lamothe and Sutherland, 2018). Consequently, the *ES Lifecycle maintenance, habitat and gene pool protection* was split into three separate functions: *Spawning/nursery habitats, Refuge/shelter habitats, Fish feeding grounds*.

Within an ecosystem, macroalgae assimilating nutrients with the help of solar energy play the role of primary producers. Although annual algae have higher photosynthesis rates and higher growth rates, storage of carbon is more efficient in perennial algae (Pedersen et al., 2010), making them almost equally important in the functioning of the ecosystem. At the same time, algal stands also provide *spawning and nursery habitats* for different fish species and *refuge/shelter habitats* for different life stages of fish.

The functions *Primary production* and *Spawning and nursery habitats* were further divided into benthic and pelagic. The division of *Primary production* was done to account for benthic habitats in primary production, as benthic macroalgae compose the high primary production on

Ecosystem components									
Phytoplankton	Zooplankton	Cod	Flounder	Round goby	Salmon	Herring	Sprat	%	Confidence
Photic hard substrate benthic habitats									
		0,1	1,0	0,1		7		100	5
		0,1	0,1	0,1		5		100	5
		1	10	1		1		100	5
		1	5	1		0,1		100	4
		0,1	0,1	0,1		0,1		100	3
Aphotic hard substrate benthic habitats									
		20	20	0,1				100	5
		10	0,1	0,1				100	4
Photic mixed substrate benthic habitats									
		0,1	0,1	0,1		5		100	5
		0,1	0,1	0,1		1		100	5
		20	20	0,1				100	4
		10	0,1	0,1				100	4
		0,1	0,1	0,1				100	3
Aphotic mixed substrate benthic habitats									
		0,1	0,1	0,1				100	5
		0,1	0,1	0,1				100	5
		0,1	0,1	0,1				100	4
Photic soft substrate benthic habitats									
		0,1	20	0,1				100	5
Aphotic soft substrate benthic habitats									
		0,1	20	0,1				100	5
		0,1	20	0,1				100	3
		0,1	10	0,1				100	4
								100	4
								100	4
Photic pelagic habitats									
49	40				1	5	5	100	4
Aphotic pelagic habitats									
	64	5			1	10	10	100	4

small units of area as opposed to planktonic communities, where small primary production is produced over large territories, altogether composing the highest primary production in water bodies (Miller, 2004). The division of function *Spawning and nursery habitats* was done to account for different spawning strategies, e.g., benthic feeder cod is using pelagic habitat for spawning while pelagic feeder herring is using benthic habitat.

In the case of *Spawning and nursery habitats, benthic* the species composition of macroalgae is crucial for the survival of fish larvae, as the rigid structures of the perennial algae ensure the best oxygen conditions for the development of fish eggs, while the dominance of annual algae in the spawning grounds leads to higher mortality of fish eggs.

The presence of macroalgae also adds an additional three-dimensional structure to the hard-bottom benthic habitats necessary for the *Refuge and shelter habitats* function, where the presence of rocks and boulders determines the function of the habitats. For this function, aphotic hard bottom habitats play an important role, explaining the rather homogeneous distribution of scores among the benthic habitats.

Finally, two-dimensional flat sandy habitats with rich infauna receive the highest scores as *Fish feeding grounds* of the demersal fish (like flatfish).

The function *Accumulation of materials* is very important for large muddy areas of Latvian territorial waters, where organic materials tend to accumulate permanently and undergo biological transformations (*Microbial transformations*) or burial. Further ecosystem functions *Filtration of suspended matter, Microbial transformations* and *Transport of materials and dispersal* were included in the analysis, in order to cover the whole spectrum of functions provided by marine habitats.

Overall, the identified functions can be separated into two distinct groups:

Table 2
Role of habitats in ecosystem Functions (in percentages, %). Confidence rated 1 (very low) to 5 (very high). AA.A- Baltic photic rocks and boulders, AB.A-Baltic aphotic rocks and boulders, AA.M- Baltic photic mixed substrate, AB.M- Baltic aphotic mixed substrate, AA.J- Baltic photic sand, AB.J- Baltic aphotic sand, AB.H-Baltic aphotic mud, AD.N- Baltic photic pelagic, above halocline, AE.N- Baltic aphotic pelagic, above halocline (HELCOM, 2013).

Habitats	Ecosystem Functions									
	Spawning and nursery habitats, benthic	Spawning, nursery and feeding habitats, pelagic	Refuge and shelter habitats	Primary production, benthic	Primary production, pelagic	Fish feeding grounds	Filtration of suspended matter	Transport of materials and dispersal	Accumulation of materials	Microbial transformations
Photic hard substrate benthic habitats										
AA.A w/perennial algae	30		15	30			2			
AA.A w/annual algae	25		12	25						
AA.A w/epibenthic bivalves			7			3	20			
AA.A w/epibenthic crustacea			5				1			
AA.A w/sparse epibenthic macrocommunity			5							
Aphotic hard substrate benthic habitats										
AB.A w/epibenthic bivalves			6				35			
AB.A w/epibenthic crustacea			5							
Photic mixed substrate benthic habitats										
AA.M w/perennial algae	25		10	25			2			1
AA.M w/annual algae	20		8	20						1
AA.M w/epibenthic bivalves			5			3	20			1
AA.M w/epibenthic crustacea			4							1
AA.M w/sparse epibenthic macrocommunity			4							1
Aphotic mixed substrate benthic habitats										
AB.M w/epibenthic bivalves			5			4	15			1
AB.M w/epibenthic crustacea			5				1			1
AB.M w/sparse epibenthic macrocommunity			4							1
Photic soft substrate benthic habitats										
AA.J w/infaunal bivalves						30	2			9
Aphotic soft substrate benthic habitats										
AB.J w/infaunal bivalves						40	2			9
AB.J w/infaunal polychaetes						10				9
AB.J w/infaunal crustacea						10				9
AB.H w/infaunal polychaetes									50	25
AB.H w/infaunal crustaceans									50	25
Photic pelagic habitats										
AD.N		70			100			60		1
Aphotic pelagic habitats										
AE.N		30						40		1
%	100	100	100	100	100	100	100	100	100	100
Confidence	4	4	3	5	5	4	4	5	5	3

Table 3

Relative importance of ecosystem functions in the supply of Cultural ecosystem services (in percentages, %). Confidence rated 1 (very low) to 5 (very high).

Ecosystem Functions	Cultural Ecosystem services					
	Water environment for recreation	Water environment for science & education	Water environment for cultural & historical heritage	Water environment for spiritual experience	Existence of habitats & species	Water environment for enjoyment of seascape
Spawning and nursery habitats, benthic		10				
Spawning, nursery and feeding habitats, pelagic	25	15	35	30	20	50
Refuge/shelter habitats		8			15	
Primary production, benthic		10			15	
Primary production, pelagic		12	15		20	
Fish feeding grounds		10	35		15	
Filtration of suspended matter	55	12	4	30	15	25
Transport of materials and dispersal	20	3	10	20		
Accumulation of materials		10	1	20		15
Microbial transformations		10				10
%	100	100	100	100	100	100
Confidence	4	3	3	2	4	3

Table 4

Relative importance of ecosystem Functions in the supply of Provisioning ecosystem services (in percentages, %). Confidence rated 1 (very low) to 5 (very high).

Ecosystem Functions	Provisioning Ecosystem services								
	Wild algae	Plant energy	Materials from algae	Wild fish, pelagic- herring	Wild fish, pelagic- sprat	Wild fish, benthic- flounder	Wild fish, benthic- cod	Wild fish, benthic- round goby, eelpout	Fishmeal
Spawning and nursery habitats, benthic				35		35		40	21
Spawning, nursery and feeding habitats, pelagic				15	55		40		30
Refuge/shelter habitats						10	15	20	10
Primary production, benthic	100	100	100						0
Primary production, pelagic				30	30		10		4
Fish feeding grounds						35	35	25	20
Filtration of suspended matter				5	5	20		15	5
Transport of materials and dispersal				15	10				10
Accumulation of materials									
Microbial transformations									
%	100	100	100	100	100	100	100	100	100
Confidence	5	5	5	4	4	3	4	3	3

- those which depend on the presence of species forming distinct biotopes, including *Filtration of suspended matter*, *Microbial transformations*,
- and those which are determined by the abiotic properties or the three-dimensional structure of habitats, including *Accumulation of materials, Transport of materials and dispersal.*

The importance of species is most pronounced in the function *Filtration of suspended matter,* depending almost exclusively on the hard substrate habitats dominated by the single mussel species *Mytilus trossulus,* with minor contribution of epibenthic crustaceans (*Balanus sp.*). Likewise, the function *Microbial transformations* depends solely on the presence of microbes performing nutrient transformation processes, like nitrification, ammonification or denitrification.

The function *Accumulation of materials,* on the other hand, is fully dependant on the storage capacity of the aphotic muddy sediments, where both muddy habitats (AB.H) receive equal scores, irrespective of species dominance (see Table 2).

Similarly, the function *Transport of materials and dispersal* depends solely on the physical properties of the water column. Since in the Baltic Sea the wind induced water currents are stronger in the photic layer than the currents in the aphotic, the photic pelagic habitats have received higher scoring.

3.3. Relative importance of ecosystem functions in the supply of ecosystem services

3.3.1. Cultural services and the relative importance of functions in their supply

The CES can be divided into two broad groups (see Table 3). Firstly, ES such as *Science & Education, Existence of habitats & Species* and *Cultural & Historical heritage,* which depend on the existence of species and habitats. Secondly, ES such as *Water environment for recreation, spiritual experience* and *enjoyment of seascape,* whose supply is associated with the

Table 5
Relative importance of ecosystem Functions in the supply of Regulation and Maintenance ecosystem services (in percentages, %). Confidence rated 1 (very low) to 5 (very high).

Ecosystem Functions	Regulation and Maintenance Ecosystem services						
	Nutrient regulation (by denitrification)	Nutrient regulation (by N, P burial)	Nutrient regulation (by nutrient incorporation in biomass)	Nutrient regulation (by N_2 assimilation)	Hazardous substances accumulation and transformation	Physicochemical retention of pollutants	Carbon sequestration
Spawning and nursery habitats, benthic							
Spawning, nursery and feeding habitats, pelagic			10				
Refuge/shelter habitats							
Primary production, benthic			15		5		10
Primary production, pelagic				100			
Fish feeding grounds			5				
Filtration of suspended matter			70		55		30
Transport of materials and dispersal							
Accumulation of materials		100			30	100	50
Microbial transformations	100				10		10
%	100	100	100	100	100	100	100
Confidence	3	3	4	3	4	3	3

physical properties of water, including cleanliness and transparency. As a whole, the latter group is maintained by ecosystem functions, such as *Filtration of suspended matter*, *Spawning and nursery habitats, pelagic* as well as *Transport of material and dispersal.* Meanwhile, the former depends on the whole range of ecosystem functions which ensure the sustainability of the ecosystems.

3.3.2. *Provisioning services and the relative importance of functions in their supply*

To reflect the fact, that whilst morphologically and ecologically similar, pelagic fish can have very different spawning strategies, *CICES v.51 Class Wild animals (terrestrial and aquatic)* used for nutritional purposes was divided into five Class types according to fish species (see Table 4). In the case of the Baltic Sea, sprat (a pelagic fish) is a pelagic spawner (Parmanne et al., 1994), while herring (also a pelagic fish) uses benthic spawning grounds, in particular dense perennial macroalgae beds (Aneer, 1989). Similarly, Baltic cod (a demersal fish) feeds on benthic organisms and small pelagic fish, however though, it uses a pelagic spawning strategy (Nissling and Westin, 1997). In order to accommodate future market price based monetary valuation, an ES *Fishmeal* was introduced in addition to fish species. The ES *Fishmeal* consists of most of the mentioned fish species, so it is based on most of the functions maintaining these species.

On one hand, some links between ecosystem functions and the Provisioning ES are fairly obvious, such as the link between ES *Wild algae or Plant energy* and the ecosystem function *Primary production, benthic.* On the other, the links between fish species and ecosystem functions are much more complex and less obvious. The primary example of such a case is the supply of the ES *Wild fish, pelagic-herring,* where at least five different functions are at play, including *Primary production, pelagic,* as phytoplankton serves as a food source for zooplankton which, in turn, is a food source for pelagic fish.

The quality of fish depends also on *Transport of materials and dispersal* as well as on *Filtration of suspended matter*, as they provide clean, oxygen rich water suitable for living and spawning. Similar considerations are used also for other Provisioning ES.

3.3.3. *Regulation and maintenance services and the relative importance of functions in their supply*

The group level *ES Mediation of wastes or toxic substances of anthropogenic origin by living processes* was split into Classes *Regulation of nutrients* and *Hazardous substances accumulation and transformation*. It was argued that, although nutrients and hazardous substances can be considered as wastes, completely different biological mechanisms are involved in the transformation processes (Watson et al., 2016). While nutrients are essential for the growth of organisms and only excess of nutrients (eutrophication) leads to unwanted growth (Gustafsson et al., 2012), the presence of hazardous substances is incompatible with growth of any organism (Ioannides, 2002) and different mechanisms of detoxification and transformation are used in order to cope with them or to survive (Ioannides, 2002; Nokolaivits et al., 2019).

It was observed during the study that the supply of the service *Nutrient regulation* varies greatly among different marine habitats and the functions they perform (Hasler et al., 2016). To reflect this, the introduced ES *Nutrient regulation* was further subdivided into four types (e.g., *Nutrient regulation: by denitrification; by phosphorus (P) and (N) burial; by nutrient incorporation in the biomass; by atmospheric* N_2 *assimilation*).

It was further found that the services *Nutrient regulation by denitrification, by P burial, by N assimilation* and also *Physicochemical retention of pollutants,* are each supplied by a single ecosystem function (see Table 5) and are 100% dependent on that one link.

While other ES are based on multiple functions, like *Nutrient regulation by nutrient incorporation in the biomass,* the highest score is attributed to the *Filtration of suspended matter*, but *Primary production, benthic* receives only a minor score. In this study, *Primary production,*

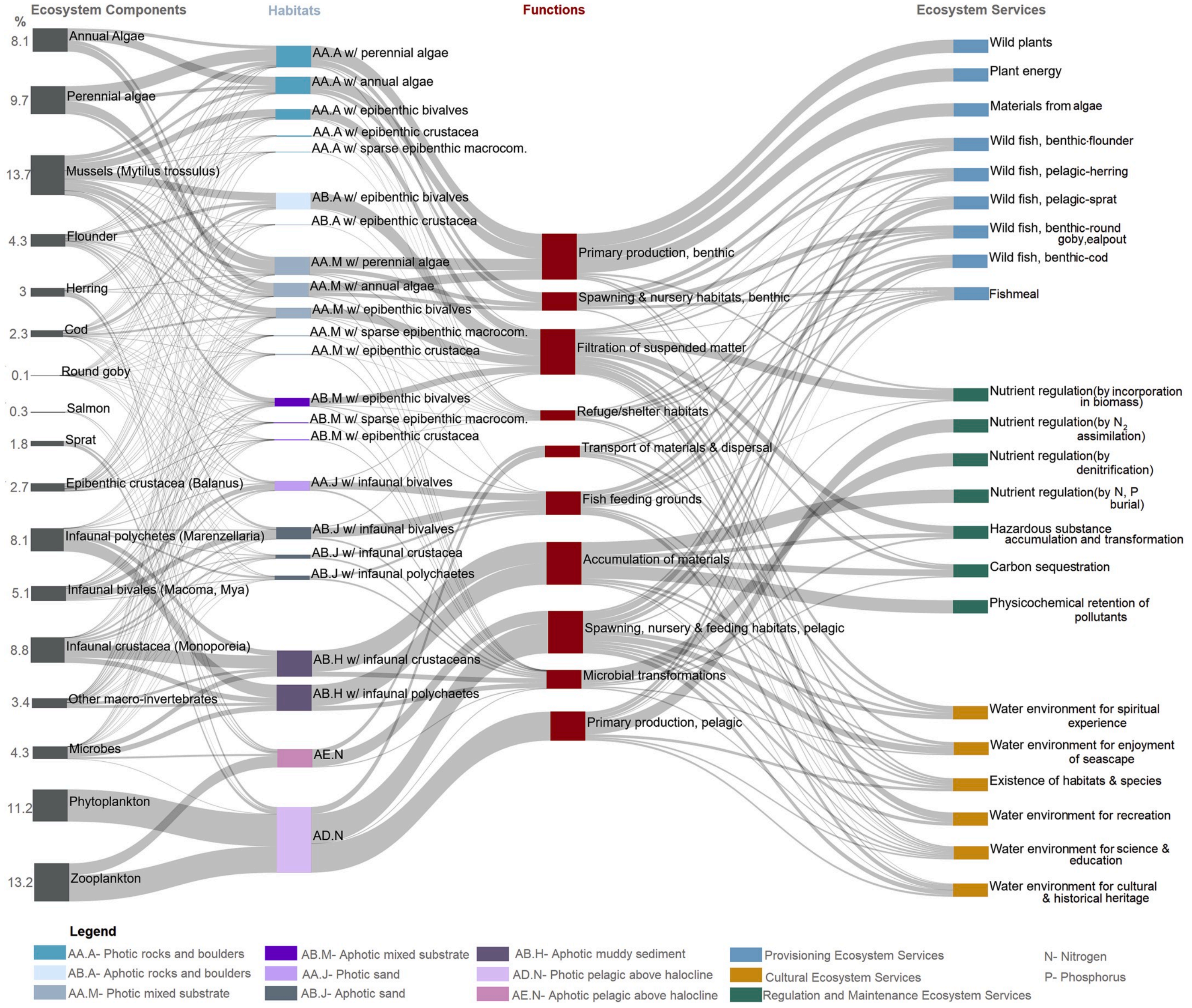

Fig. 4. Linkage diagram depicting the relative importance of species (left-hand side) in the supply of ecosystem services (right-hand side). Contribution of species is quantitatively described as parts of a whole, where the whole is the sum of all ecosystem services (100%). Width of connecting lines reflects strength of links, while weight of bars conveys the importance of elements in the system.

pelagic was not considered as a significant component in nutrient incorporation in biomass, as the turnover rate of phytoplankton is high and the nutrients are continuously recycled in the ecosystem. Furthermore, the accumulation of nutrients in phytoplankton biomass is a seasonal phenomenon in the Baltic Sea.

Ecosystem functions *Filtration of suspended matter*, *Primary production, benthic*, *Accumulation of materials* and *Microbial transformations* play a significant role in the fate of hazardous substances, as well as *Carbon sequestration.*

In the case of *Hazardous substance accumulation and transformation*, *Filtration of suspended matter* was identified as the key ecosystem function ensuring the supply of the service. For ES *Carbon sequestration,* however, the highest importance was attributed to the function *Accumulation of materials.*

Filtration of suspended matter is considered as a significant sink of carbon, since filtrating mussels are forming a large biomass on the hard substrate habitats, incorporating carbon in the biomass and storing it for several years.

3.4. Linkage diagram

It is made evident by the diagram depicting the supply of the full range of ES, that few of the ES are supplied by a single ecosystem function, and none are supplied by a single species (see Fig. 4).

Regardless, Mussels (*Mytilus trossulus* 13.7%) was identified as the most important ecosystem component, contributing to a variety of hard substrate habitats which are core to ecosystem functions *Filtration of suspended matter, Primary production and Spawning and nursery habitats, benthic* (see Fig. 4).

Relatively small contribution to Nutrient regulation (by incorporation in biomass) can be ascribed to macroalgae and fish feeding on the benthic invertebrates.

As it may be expected in marine ecosystems, the photic pelagic habitat dominated by phytoplankton (11.2%) and zooplankton (13.2%) is at its entirety responsible for pelagic *Primary production* and the supply of ES *Nutrient regulation by Nitrogen assimilation*.

The results of the assessment of the supply of a single Regulating ES

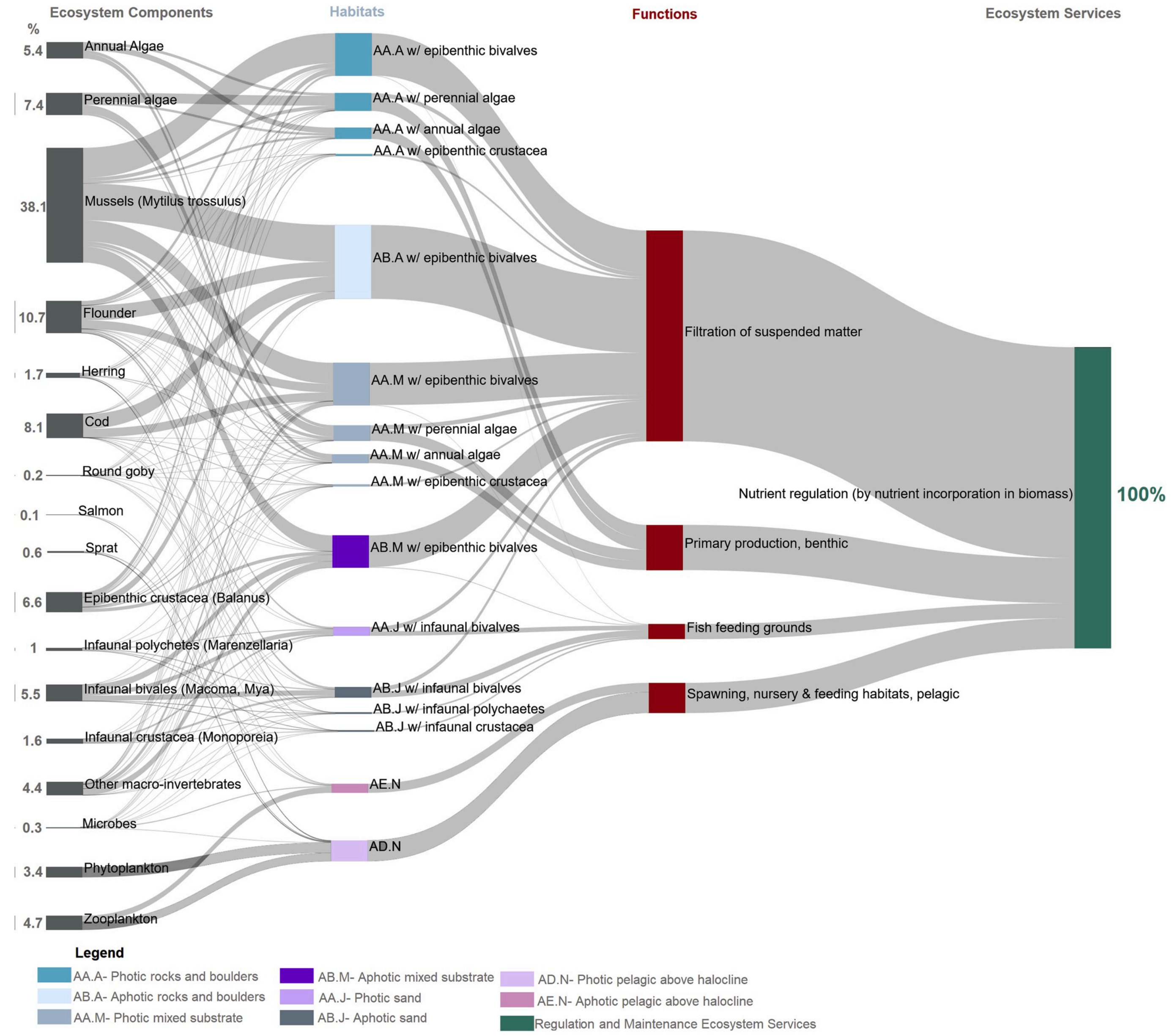

Fig. 5. Linkage diagram depicting the supply of the ecosystem service *Nutrient regulation by incorporation in biomass* in a state of good environmental status.

Nutrient regulation (by incorporation in biomass) suggest that by decreasing the size of mussel population by 90% would decrease the supply of the ES to 65.7% (see Figs. 5 and 6). The change in importance is reflected in the decrease of the relative importance of the function *Filtration of suspended matter* as well as of other functions.

4. Discussion

The outputs of the matrix-based ecosystem service assessment tool presented in this paper provide a holistic overview of the ecosystem structure and links ecosystem components with the corresponding ES, estimating their relative contribution in the supply of the ES. The generated diagram graphically represents connectivity between the ecosystem and the services it supplies, as well as the strength of the connections.

Meanwhile, the results of this assessment show that the supply of ecosystem services relies on a wide range of species, as it is also seen in Teixeira et al. (2019) and Culhane et al. (2018). They also suggest that the species within the analysed ecosystem can be ordered hierarchically according to their overall significance in the supply of ecosystems services.

The assessment outcomes highlight the importance of keystone species, such as mussels and annual and perennial algae. The relatively high importance of benthic habitats and species is not surprising, as they serve as areas of refuge and feeding, as well as spawning grounds for a wide range of marine species during some part of their life cycle. Keeping this in mind and referring back to the habitat distribution map (Fig. 1) presented in this paper, it becomes apparent that these highly valuable habitats occupy a relatively small area.

Although our understanding of the functioning of marine benthic communities is still limited, it is known that various anthropogenic and natural pressures have severe impacts on marine communities and ecosystem structures (Halpern et al., 2007).

In the case study area, the density of mussel beds has significantly

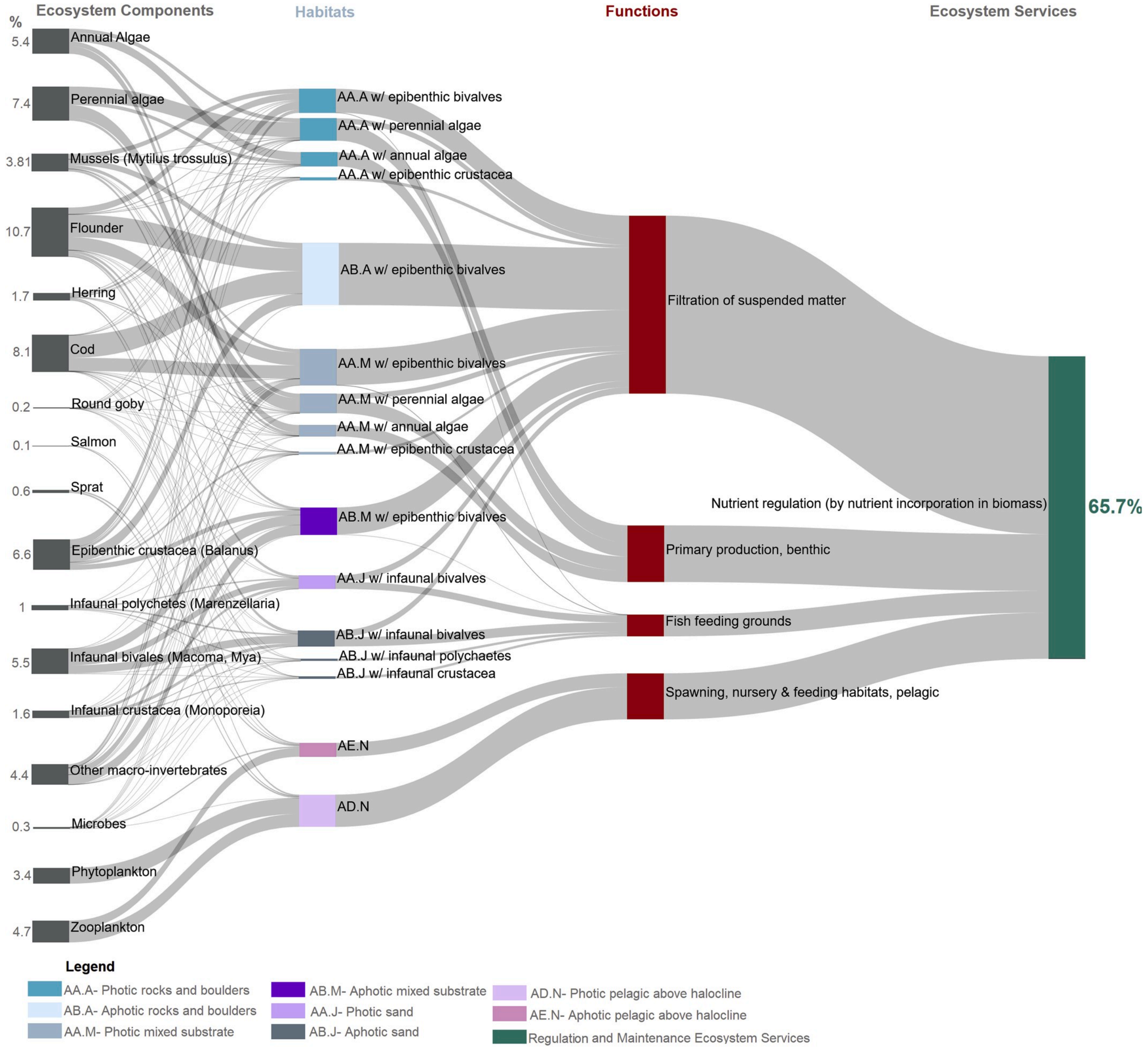

Fig. 6. Linkage diagram depicting the supply of the ecosystem service *Nutrient regulation by incorporation in biomass* in a state where the mussel (*Mytilus trossulus*) population has decreased by 90%.

decreased due to the invasion of the alien species *Neogobius melanostomus*, intensively feeding on mussels (Ustups et al., 2016). Mussels are important ecosystem components in hard substrate habitats - filtering large volumes of seawater, increasing sedimentation rates and increasing the transparency of water, and accumulating nutrients and hazardous substances in the biomass (Kautsky and Wallentinus, 1980). As illustrated by the diagram (Fig. 4), the decrease of mussel population may have devastating effects on the supply of *Nutrient regulation (by incorporation in biomass)*. However, the decrease in ES *Nutrient regulation (by incorporation in biomass)* supply is not as big as it would have been expected, given that mussels are a keystone species in the ecosystem in question. This highlights limitations of the assessment method.

One limitation is that despite the disappearance of one or several links, the next level, e.g., habitat, function or ecosystem service, is still present. This is not always true, as some links may be more critical than others. For example, it is well known that if ecosystem degradation results in complete disappearance of the habitat forming species, the whole habitat along with its functions and ecosystem services disappears as well, and the spatial changes can be clearly demonstrated on a map (e. g. Geange et al., 2019). It is well documented that some changes in dominant species like the disappearance of perennial algae, used by the Baltic herring as spawning grounds (Šaškov et al., 2014), can have profound effect on the availability of suitable spawning grounds (Kanstinger et al., 2018). Change in spawning success, if for example annual algae are used as substitute, is less well explored. Consequently, the uncertainty associated with knowledge gaps on the capacity of species to adapt to changes in the marine ecosystem caused by external forces, presently has not permitted us to implement the critical component or function principle. Therefore, the results of different scenarios should be interpreted with a certain level of caution.

Further, the sorting process of links according to their significance and dismissal of some of them as insignificant, may result in loss of some important connections which may have been undervalued by the experts and inflation of the importance of others. This step is, however, necessary to ensure that the diagram is not overcrowded with information and only depicts the most important services and links (Teixeira et al., 2019).

Despite its limitations, the approach described in this paper substantially improves the assessment of habitat degradation, as it provides the opportunity not only to estimate the loss of habitat area as demonstrated by Geange et al. (2019), but also to assess the impacts of gradual habitat degradation on the availability of corresponding ecosystem services.

Furthermore, single pressure-impact scenarios, such as the one presented above, demonstrate change in the system as whole and can assess the full extent of impact.

The option to deconstruct the ecosystem and analyse the effects of ecosystem change on the service supply on a step by step basis, could be useful during discussions among experts and MSP practitioners on a wide spectrum of issues, ranging from the designation of new marine protected areas to the establishment of marine aquaculture or wind farms. Arguably and more importantly, it could increase MSP practitioners' level of understanding of the ecosystem services assessments process, the relative biophysical value of ecosystem components and the connection between ecosystems and human well-being. The custom-built diagram has extended the functionalities, allowing import of field data, interactive features such as pop-up labels and ability to move elements around increasing the amount of information the diagram carries, as well as widening the range of its uses.

We recognize that the MSP practitioners would greatly benefit from a value mapping function, even more if such a tool was able to perform socio-economic ES valuation (Pandeya et al., 2016). While the tool does not yet provide the possibility of mapping, data on spatial distribution of habitats types could be used in conjunction with the assessment results to indicate areas of relatively high contribution towards the supply of ES.

Also, an integrated ES valuation process and the reliability of its results, relies heavily on a comprehensive quantitative biophysical assessment of the natural assets and a clear description of the service flow (Laurila-Pant et al., 2015; Pandeya et al., 2016). To ensure that the results of the study can be easily employed for economic valuation, adherence to the cascade model was seen as essential. We believe that the approach utilized in this paper to adapt CICES to marine context, can help reduce the risk of double counting in socio-economic valuation studies discussed by Bateman et al. (2011).

It should also be noted that the numerically quantifiable carrying capacity of habitats in respect to species, is assessed based on expert opinion that might be biased. In essence, the acceptance that changes to the environment can be irreversible (e.g., Duarte et al., 2009), has a potential to alter the perception of the demands placed on habitat area and quality. Furthermore, as discussed by Jacobs et al. (2015), expert consensus does not necessarily ensure a good decision, nor does the method eliminate the need for data and evidence. This is illustrated by decreasing confidence levels as experts move along the linkage chain, largely due to the scarcity of evidence to support their responses. For application on a bigger scale, larger numbers of experts and a survey-based method would be recommended in order to ensure the validity and reliability of results.

5. Conclusion

The tailor-made tool presented in this study enables the quantification of the relative importance of marine habitats in the supply of ecosystem services. As the discussion suggests, the tool can be used to assess the impacts of environmental degradation in the supply of multiple or an isolated ecosystem service. What's more, the graphical representation of the assessment process and results, provide an opportunity for communicating to non-experts the complexity of the ecological systems, ensuring ecosystem service flow.

The inclusion of habitats as components within the assessment provides the opportunity for spatial assessment of ES for use in maritime spatial planning. To further develop this functionality, and ensure its applicability in MSP, the tool should be tested out by planners.

Notably, the study demonstrates that there is still room for improvement when it comes to the operationalisation of CICES v5.1. It introduces several new ecosystems services, that are highly relevant in the marine context but overlooked in the classification system. However, to ensure their validity they will need to be applied in studies on a greater scale and involving more experts.

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