

A.5 Assessment of ecosystem services provided by protected benthic habitats

Authors: Armoskaite, A., Sprukta, S., Andersone, I., Strāķe, S., Bārda, I., 2025



Table of Contents

Summary	3
1 Introduction	5
1.1 Key concepts and research context.....	6
1.1.1 The DAPSIR butterfly	6
1.1.2 A linkage-based method for the assessment of relative ecosystem service supply.	7
1.1.3 Ecosystem functioning and service supply by marine habitats in Latvian marine waters.	10
1.1.4 Previously detected benthic habitat changes in the Latvian Marine Protected Areas	17
1.2 Report Objectives	19
2 Methods.....	20
2.1 Mapping current ecosystem functioning and service supply	21
2.2 Change analysis	21
2.3 Pairing cumulative impact and ecosystem service analysis to assess change in ecosystem service supply.....	23
3 Findings.....	24
3.1 State of ecosystem functioning.....	24
3.2 Ecosystem service supply	30
3.3 Change in ecosystem functioning and service supply since 2020.....	33
3.4 A combined method for analysis of change in multiple ecosystem services simultaneously in response to changes in cumulative impacts: a Gulf of Riga test case.	35
4 Conclusion.....	37
5 References.....	39

Summary

The status of ecosystems and human well-being and welfare are intrinsically linked. Healthy marine ecosystems can provide a wide range of ecosystem services, such as carbon sequestration and fish for food, which people benefit from. Ecosystem capacity to supply services is finite and dependent on good ecosystem functioning. At the same time, ecosystems are under great pressure from human activities; their ecosystem functioning and service supply are often compromised due to physical damage or biogeochemical conditions negatively affecting species and habitats. Marine protected areas (MPAs) are instruments for controlling direct or local pressures by regulating what activities take place within a specific area. The primary aim of MPAs is the conservation and protection of species and habitats from pressures. The positive effects of an improved ecosystem condition are also felt by society. Evidence on the benefits of MPAs to human well-being can enhance social and political acceptance by enhancing public understanding of human-sea interconnectivity and advocating for nature conservation.

An ecosystem services approach provides an analytical framework that supports the analysis of the relationship between people and ecosystems, with a focus on the ways in which people benefit from and affect the natural environment through interaction with it. Within the framework, ecosystem services are the direct contribution of the ecosystem to human well-being, underpinned by the ecosystem functioning of species communities and habitats. For instance, recovering fish spawning and feeding grounds characterised by healthy algae beds may lead to an increase in fish stocks over time, also known as the spillover effect of MPAs, and improved water conditions for recreation benefiting coastal fisher communities by securing a fish important for their livelihoods and seaside towns through improved supply of locally caught fish for food, and a more attractive water environment for tourists. Linkage chains or pathways can assess and represent the supply of services and the interaction between society and the environment. These depict the multiplicity of interconnections and dependencies between various parts of ecosystems and their impacts on human welfare.

This study assesses the ecosystem functions and services supplied by habitats in Latvian marine waters, focusing on benthic habitats and protected stony reefs. This study applies a linkage-based ecosystem service analysis method and the geospatial habitat data collected by the Latvian Institute of Aquatic Ecology during the Life REEF project and before it, to graphically and geospatially represent ecosystem functioning and service supply by benthic habitats in Latvian marine waters. It also explores the impacts of notable coastal benthic habitat composition change on ecosystem functioning and service supply in the Eastern Coast of the Gulf of Riga and the Western Coast of the Gulf of Riga MPAs. The results show a significant decrease in macroalgae cover of around 64% in the Eastern coast of the Gulf of Riga between 2009 and 2022, and around 54% in the Western coast of the Gulf of Riga MPA between 2015 and 2024. Ecosystem functions most significantly affected include benthic primary production, benthic spawning and nursery habitats. The most severely impacted were the provisioning services directly reliant on the availability of algae as a raw material.

Lastly, this study also develops and tests a method for applying a cumulative impact assessment methodology in ecosystem service supply to assess the implications of changing pressures on ecosystem services. This method supports the analysis of change in multiple ecosystem services simultaneously in response to changes in cumulative impacts. It integrates two separate methodologies and uses geospatial

data and expert knowledge. The method was tested in a scenario where fishing for herring in the Gulf of Riga was reduced by 50%. The results of the analysis can support other scenario analyses and depict the effects of pressure changes on ecosystem functioning and service supply.

1 Introduction

This report describes ecosystem services supplied by benthic habitats in Latvian marine waters, namely the protected stony reefs. Stony reefs are protected under the European Habitats Directive (Council Directive 92/43/EEC), and in the Baltic Sea consist of rocks, boulders and pebbles and sand covered in species such as mussel (e.g. *Mytilus trossulus*), red, brown, and green macroalgae and host macrofauna (e.g. crustaceans or benthic fish) making them a hotspot of biodiversity (HELCOM, 2013a, 2013b).

An ecosystem services approach provides an analytical framework that supports the analysis of the relationship between people and ecosystems, with a focus on the ways in which people benefit from and affect the natural environment through interaction with it. Within the framework, ecosystem services are the direct contribution of the ecosystem to human well-being, underpinned by the ecosystem functioning of species communities and habitats. Healthy marine ecosystems can provide a wide range of ecosystem services, such as carbon sequestration and fish for food, which people benefit from. While no ecosystem service is provided by a single species, some play a more significant role than others in some specific ecosystem functions and thus contribute more to specific ecosystem service supply (Armoskaite et al. 2020). For instance, algae beds provide the essential spawning grounds for most regionally commercially important fish species, and mussels filter water and are known to improve water transparency, which is important in supplying a whole range of cultural ecosystem services, providing social and economic benefits (Armoskaite et al. 2021; Pakalniete et al. 2021). Algae beds provide the essential spawning grounds for most regionally commercially important fish species. Mussels also filter water and are known to improve water transparency, supply a whole range of ecosystem services, and provide social and economic benefits (Armoskaite et al. 2021).

Linkage chains or web diagrams are commonly used to represent ecosystem service supply and the interactions between society and ecosystems. In the Latvian marine context, a linkage-based method was developed to assess relative ecosystem functioning and the supply of multiple services (Armoskaite et al. 2020). Experts identify key components (e.g., species, habitats), functions, and services, and assign weights to their interactions. These weights are used to calculate the relative contribution of ecosystem components to functioning and service supply. A coefficient is applied to assess change over time to reflect proportional variation in biomass or spatial distribution based on expert estimates (e.g., a 50% species decline) or empirical data (e.g., geospatial comparison across time). The contribution values provide a sense of relative importance of the different components in the ecosystem in service supply and enable analysis of how ecosystem changes impact functioning and service supply as their capacity to contribute changes over time.

This study applies a linkage-based ecosystem service analysis method and the geospatial habitat data collected by the Latvian Institute of Aquatic Ecology during and before the Life REEF project to assess and map the ecosystem services provided by protected stony reef habitats and demonstrate how changes in the ecosystem over time affect service supply based on a retrospective analysis of the Gulf of Riga stony reef composition. The results presented in this report underline the significance of ecological data collected during the LIFE REEF project in improving understanding of the spatial distribution of ecosystem functions and services, and marine species' contribution to society. Ultimately, the results presented in this report demonstrate how an ecosystem service approach can be used to create an evidence base for selecting areas for protection that explicitly highlights the impact on human welfare.

This report is divided into four main chapters. The remaining sections of the first introductory chapter provide a more detailed introduction to the research context, including an overview of key concepts, the ecosystem service assessment approach applied in this study, an overview of the relative importance of marine species and habitats in functioning and services in the Latvian marine context, and the report's objectives. The second chapter describes the methods used to assess the current service supply using the most recent Life REEF field work observations. The third chapter presents the results in a discussion format, followed by the final concluding chapter.

1.1 Key concepts and research context

A social-ecological systems (SES) approach implies explicitly that people are part of the natural environment – we affect it, and it affects us. SES and the 'systems' worldview, in general, is a way of drawing attention to the relational qualities and processes between objects as key elements of reality (Preiser et al. 2022) and attempts to disentangle the complex and dynamic interactions between people and ecosystems (Schlüter et al. 2019; Biggs et al. 2022). Since the 1990s, an SES approach has been key in understanding and tackling environmental sustainability challenges (Potchin-Young et al. 2018; Schlüter et al. 2019). Common frameworks have been developed to guide SES analysis, including the DAPSIR/ DAPSI(W)R(M) butterfly (Elliot and O'Higgins 2020).

1.1.1 The DAPSIR butterfly

DAPSIR or DAPSI(W)R(M) stands for *Drivers- Activities-Pressures-State-Impacts (on Welfare)- Responses (in Measures)*. The conceptual visualisation depicts DAPSIR/ DAPSI(W)R(M) (Henceforth: DAPSIR) elements of a social-ecological system on two interconnected sides of the butterfly. One side includes all elements in a social system (orange side in Figure 1), and the other – ecological (blue side in Figure 1).

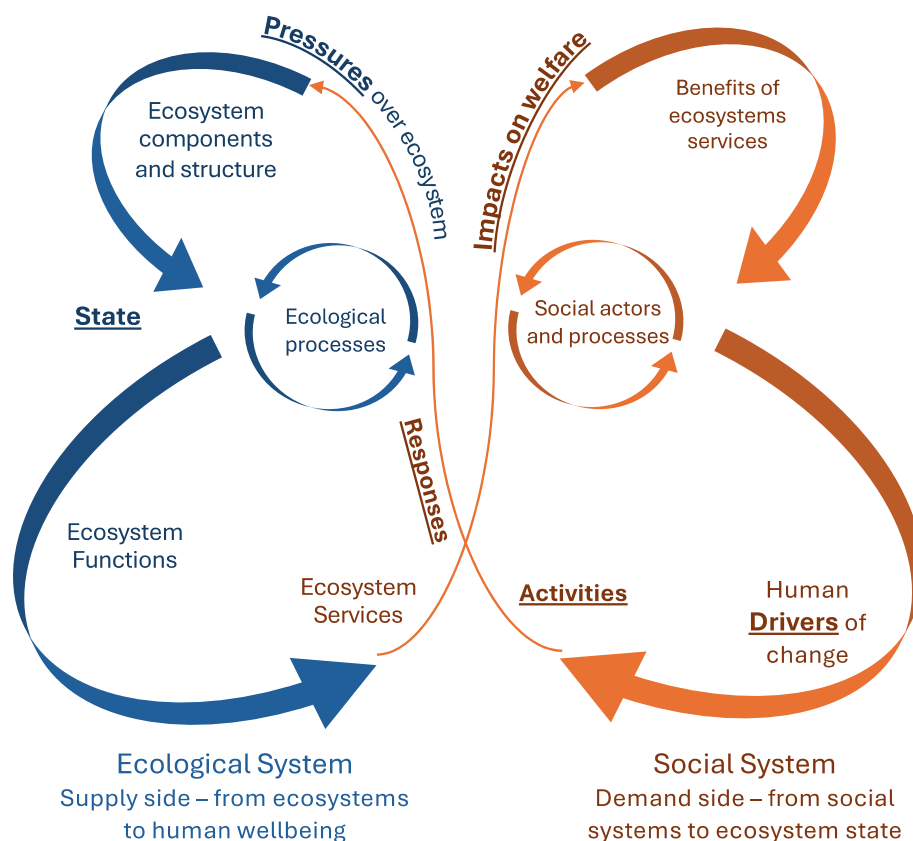


Figure 1 The DAPSIR butterfly adapted from Elliot and O'Higgins (2020) to highlight the core elements of the DAPSIR-type models explicitly.

Drivers are the essential human needs underpinning human *Activities*, which result in *Pressures* on and a change in the *State* of the ecosystem (e.g., habitat composition or species abundance) (Patrício et al. 2016; Elliot and O'Higgins 2020; Figure 1). Changes in the ecosystem *Impact human welfare* (Patrício et al. 2016). For instance, a decrease in the abundance of some fish populations may affect fish landings, directly impacting fishers' well-being and others who may depend on fish as a food source. Ecosystem service and (dis)benefits supply and distribution can be used to measure Impacts on human welfare (Frederiksen et al. 2021). Management *Responses* are often taken to mitigate or change impacts on welfare, which may be actions targeted at changing the drivers and human needs or activities and sea use (Elliott and O'Higgins 2020).

1.1.2 A linkage-based method for the assessment of relative ecosystem service supply.

A linkage framework-based ecosystem service analysis approach for relative, multiple ecosystem service supply analysis can calculate weighted, numerical descriptions of the overall relative 'contribution' of ecosystem components and structures in ecosystem functioning and service supply. It can be used to analyse changes in the ecosystem, ecosystem functioning, and service supply. It provides one way of understanding the links between the ecological system of the DAPSIR butterfly and the social side. The 'contribution' values can then be graphically represented in maps depicting several or single services mapped using marine species distribution data and complex linkage web diagrams depicting the flow of service supply.

Firstly, the importance of the ecosystem functions (*FI*) in the supply of each service, habitats (*HI*) in the performance of each ecosystem function, and species (*SI*) in the formation of every habitat were calculated:

$$isw = \left(\frac{SI}{\sum SI} \right) \times 100$$

$$ihw = \left(\frac{HI}{\sum HI} \right) \times 100$$

$$ifw = \left(\frac{FI}{\sum FI} \right) \times 100$$

(1)

fw is the expert ascribed weight defining the relationship between a single service and an ecosystem function, *hw* is the weight describing the relationship between a function and a habitat, *sw* is the weight describing the relationship between a habitat and a species. Inverse weights are calculated for each original expert assigned weight. Inverse weights describe species' (*isw*) importance in habitat formation, habitat's (*ihw*) importance in function performance and the importance of each function (*ifw*) in the supply of services:

$$isw = \left(\frac{SI}{\sum SI} \right) \times 100$$

$$ihw = \left(\frac{HI}{\sum HI} \right) \times 100$$

$$ifw = \left(\frac{FI}{\sum FI} \right) \times 100$$

(2)

The sum of the values defining the importance of each species (*SI*), habitats (*HI*) and functions (*FI*) and the inverse weights were then used to work out the relative contribution of each species (*SRC*), habitat (*HRC*) and function (*FRC*) in the ES supply:

$$SRC = \frac{\sum SI \times isw}{100}$$

$$HRC = \frac{\sum HI \times ihw}{100}$$

$$FRC = \frac{\sum FI \times ifw}{100}$$

(3)

The *FRC* value indicates the level of service supply. 100 is the contribution of species, habitats, and functions at full capacity in a good environmental state.

Change is reflected in the *FRC* value. An increase in *FRC* indicates an increase in service supply, and vice versa. Change analysis can be conducted in different ways. However, the primary step is to adjust the *SRC* or *HRC* to reflect the new ecosystem state (equation 4) that differs from the reference good environmental state using a coefficient (*C*) that reflects the relative change in species abundance or state.

$$\text{Adjusted SRC} = \text{SRC} \times C$$

(4)

Service supply then needs to be recalculated (equation 3) to get a new *FRC* for each service, and the reference ecosystem service supply scenario *FRC* values must be subtracted from the new supply scenario *FRC* values. The coefficient (*C*) can reflect the proportional variation in biomass or the spatial distribution of the species or habitat at different time frames within the studied area, based on e.g. estimated, rough change in ecosystem components, e.g. specific species reduction by 50% (as in Armoskaite et al. 2020) or empirical data, e.g. geospatial data species or habitat at different time frames, to calculate proportional change over time. This is exemplified in Armoskaite et al. (2021).

A critical aspect of change analysis is that it can only be done within the boundaries of the reference assessment, meaning that it can only include the elements already considered during weighing of importance in the system. To perform change analysis with fewer elements than initially considered in the reference assessment, the linkage chains associated with the ecosystem component or service supply of interest need to be identified and isolated from the wider system, along with the numerical descriptions.

1.1.3 Ecosystem functioning and service supply by marine habitats in Latvian marine waters.

The above-described linkage-based assessment method was applied to analyse ecosystem functioning and service supply in the Latvian marine context (Armoskaite et al. 2020). Seventeen marine species, twenty-three habitat types, ten ecosystem functions, six cultural ecosystem services, nine provisioning and seven regulating and maintenance services were identified and assessed in 2020. Microsoft Office Excel was used to calculate the contribution values and change analysis, and the Plotly module (Plotly Technologies Inc. 2015) was used in a Jupyter Notebook web-based environment to visualise the results in Sankey diagrams (Figure 2).

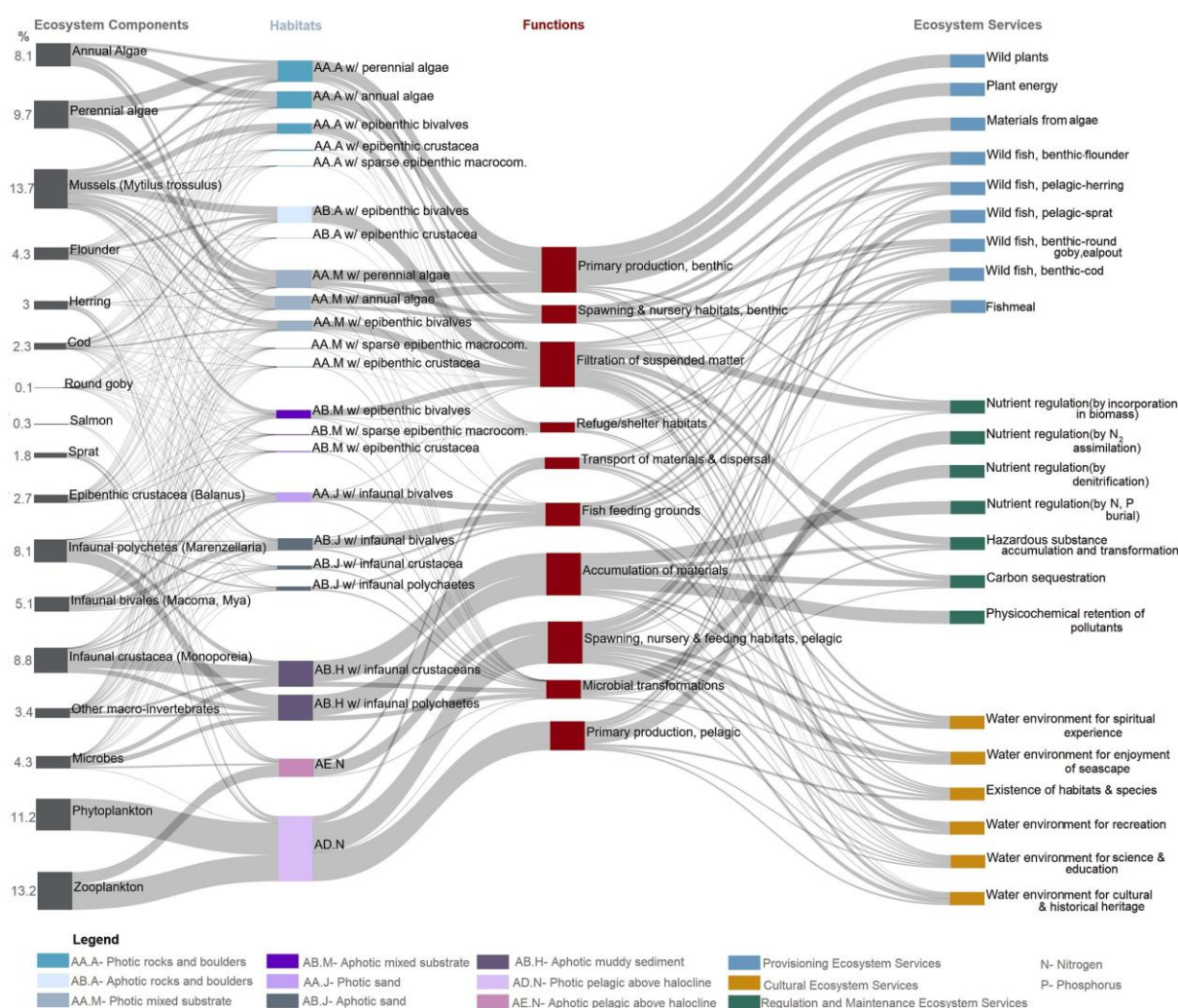


Figure 2 A linkage diagram depicting the relative importance of ecosystem species, habitats, and ecosystem functions in total ecosystem service supply based on the results of an expert elicitation workshop. Image source: Armoskaite et al. 2020.

This study conducted three expert elicitation workshops and several rounds of individual consultations to identify Latvian context-specific ecosystem components, functions, and services and describe element interactions through weights (Armoskaite et al. 2020). Firstly, the experts analysed underwater habitat maps of the Latvian territorial waters using the HELCOM HUB (HELCOM, 2013) classification system to identify marine species and habitats relevant for the assessment (Figure 3).

		SPECIES															Total (must add up to 100)	Confidence			
		Perennial algae	Annual Algae	Mussels (<i>Mytilus trossulus</i>)	Epibenthic crustacea (<i>Balanus</i>)	Other macro-invertebrates	Infaunal bivalves (<i>Macoma</i> , <i>Mya</i>)	Infaunal crustacea (Monoporeia)	Infaunal polychaetes (<i>Marenzelleria</i>)	Microbes	Phytoplankton	Zooplankton	Cod	Flounder	Round goby	Salmon			Herring	Sprat	
HABITATS (HELCOM HUB)	Photic hard substrate benthic habitats	AA.A w/ perennial algae	55,0	15,0	20,0	1,0	1,0						0,1	1,0	0,1		7,0		100	5	
		AA.A w/ annual algae	20,0	50,0	20,0	4,0	1,0						0,1	0,1	0,1		5,0		100	5	
		AA.A w/ epibenthic bivalves			70,0	12,0	5,0						1,0	10,0	1,0		1,0		100	5	
		AA.A w/ epibenthic crustacea			5,0	85,0	3,0						1,0	5,0	1,0		0,1		100	4	
		AA.A w/ sparse epibenthic macrocom.			33,0	33,0	33,0						0,1	0,1	0,1		0,1		100	3	
	Aphotic hard substrate benthic habitats	AB.A w/ epibenthic bivalves			50,0	10,0	0,1						20,0	20,0	0,1				100	5	
		AB.A w/ epibenthic crustacea			10,0	70,0	10,0						10,0	0,1	0,1				100	4	
	Photic mixed substrate benthic habitats	AA.M w/ perennial algae	54,0	20,0	20,0	0,1	0,1				0,1			0,1	0,1	0,1		5,0		100	5
		AA.M w/ annual algae	20,0	55,0	20,0	3,0	0,1				0,1			0,1	0,1	0,1		1,0		100	5
		AA.M w/ epibenthic bivalves			49,0	0,1	10,0	0,1	0,1	0,1	0,1		20,0	20,0	0,1				100	4	
		AA.M w/ epibenthic crustacea			20,0	69,0	0,1	0,1	0,1	0,1	0,1		10,0	0,1	0,1				100	4	
		AA.M w/ sparse epibenthic macrocom.			0,1	20,0	50,0	20,0	10,0	0,1	0,1		0,1	0,1	0,1				101	3	
		Aphotic mixed substrate benthic habitats	AB.M w/ epibenthic bivalves			49,0	10,0	20,0	20,0	0,1	0,1	0,1		0,1	0,1	0,1				100	5
			AB.M w/ epibenthic crustacea			0,1	49,0	20,0	20,0	10,0	0,1	0,1		0,1	0,1	0,1				100	5
			AB.M w/ sparse epibenthic macrocom.			0,1	33,0	0,1	33,0	33,0	0,1	0,1		0,1	0,1	0,1				100	4
	Photic soft substrate benthic	AA.J w/ infaunal bivalves					0,1	50,0	20,0	10,0	0,1			0,1	20,0	0,1				100	5
		AB.J w/ infaunal bivalves					0,1	50,0	20,0	10,0	0,1			0,1	20,0	0,1				100	5
Aphotic soft substrate benthic habitats		AB.J w/ infaunal polychaetes					1,0	20,0	10,0	49,0	0,1		0,1	20,0	0,1				100	3	
		AB.J w/ infaunal crustacea					1,0	20,0	49,0	20,0	0,1		0,1	10,0	0,1				100	4	
		AB.H w/ infaunal polychaetes					10,0		20,0	50,0	20,0								100	4	
		AB.H w/ infaunal crustaceans					10,0		50,0	20,0	20,0								100	4	
Photic pelagic habitats		AD.N									0,1	49,0	40,0				1,0	5,0	5,0	100	4
	Aphotic pelagic habitats	AE.N									10,0		64,0	5,0			1,0	10,0	10,0	100	4

Figure 3 Habitats and species included in the Latvian scale ecosystem functioning and service supply assessments. Adapted from Armoskaite et al. 2020.

One of the most widely used is the Common International Classification of Ecosystem Services (CICES v5.1), a predefined list of ecosystem services that was used during expert workshops to identify ecosystem functions and services relevant to the South-Eastern Baltic Sea marine environment and the Latvian socio-cultural context. Ten ecosystem functions, six cultural ecosystem services, nine provisioning and seven regulating and maintenance services were identified and assessed (Figure 4).

Ecosystem Functions	Spawning & nursery habitats, benthic	Regulation and maintenance services	Nutrient regulation (by denitrification)
	Spawning, nursery & feeding habitats, pelagic		Nutrient regulation (by N, P burial)
	Refuge/shelter habitats		Nutrient regulation (by nutrient incorporation in biomass)
	Primary production, benthic		Nutrient regulation (by N assimilation)
	Primary production, pelagic		Hazardous substances accumulation & transformation
	Fish feeding grounds		Physicochemical retention of pollutants
	Filtration of suspended matter		Carbon sequestration
	Transport of materials & dispersal	Provisioning services	Wild plants
	Accumulation of materials		Plant energy
	Microbial transformations		Materials from algae
Cultural services	Water environment for recreation		Wild fish, pelagic- herring
	Water environment for science & education		Wild fish, pelagic- sprat
	Water environment for cultural & historical heritage		Wild fish, benthic- flounder
	Water environment for spiritual experience		Wild fish, benthic- cod
	Existence of habitats & species		Wild fish, benthic- round goby, eelpout
	Water environment for enjoyment of seascape		Fishmeal

Figure 4 Ecosystem functions and services supplied by marine habitats in Latvian marine waters (Armoskaite et al. 2020)

The experts then assigned weights to describe the connection between species, habitats, ecosystem functions and ecosystem services, which were used to calculate the relative contribution values.

Figure 5 illustrates the relative contribution of habitats and species to ecosystem functioning.

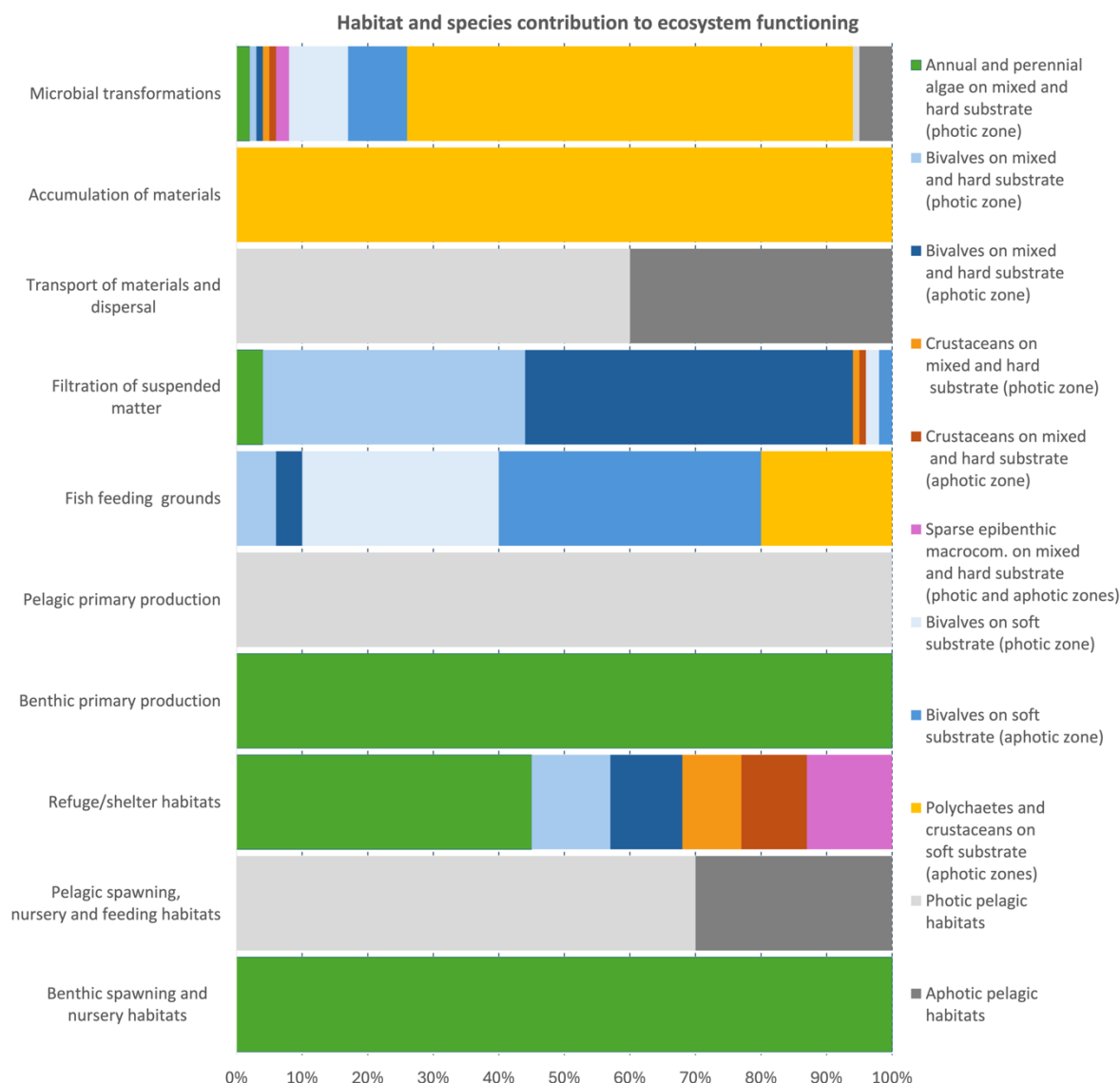


Figure 5 relative contribution of habitats and species to ecosystem functions. Adapted from Armoskaite et al.2020.

Macroalgal beds are the sole maintainers of benthic spawning and nursery grounds and perform primary production. Bivalves play a key role in the filtration of suspended matter. Most hard and mixed sediment habitats, including stony reefs covered in bivalves and crustaceans, provide refuge and shelter. Fish feeding grounds were identified as largely areas of soft substrate in the photic and aphotic zones characterised by mussels, polychaetes, and crustaceans, as well as—to a lesser extent—stony reefs covered in mussels. Aphotic and photic pelagic habitats are essential for maintenance of pelagic spawning, nursery and feeding grounds, pelagic primary production and and transport and dispersal of materials. Polychaetes and crustaceans accumulate materials in the soft substrate in the aphotic zone. They are also the main contributors to microbial transformations.

Figures 6 and 7 illustrate the relative contribution of habitats and species to ecosystem services and their contribution to three categories of ecosystem services. The results show that all habitat types provide a range of ecosystem services. Although some may have a more significant role in specific service supply than others. Several are the sole suppliers of a single service.

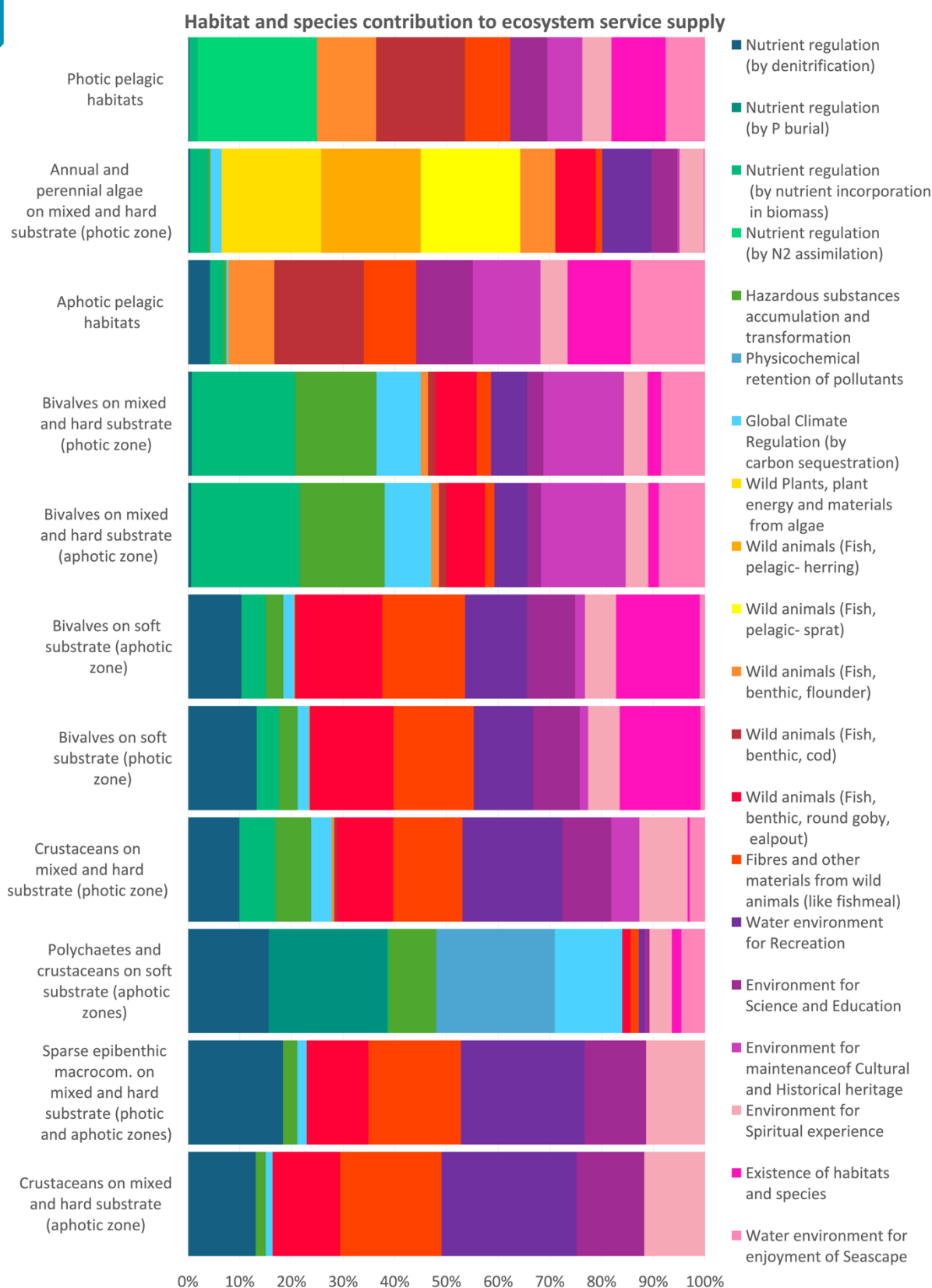


Figure 6 Habitat and species contribution to ecosystem service supply. Adapted from Armoskaite et al. 2020

For instance, perennial and annual macroalgal habitats provide 100% of the material for producing energy or algae-based fertiliser. Macroalgae beds also contribute towards Nutrient regulation by nutrient

incorporation in biomass, a water environment for recreation and the supply of wild benthic fish (e.g., flounder and round goby). Habitats characterised by bivalves on mixed and hard substrate in the photic and aphotic zone play an even greater key role in nutrient regulation by nutrient incorporation in biomass. They also support hazardous substance accumulation and transformation, global climate regulation by carbon sequestration, and the supply of some wild benthic fish. Bivalves on soft substrate, Bivalve-dominated habitats, including bivalves in soft sediment, contribute greatly to a range of cultural services by maintaining the water environment transparent and attractive for users. Polychaetas and crustaceans on soft substrate in the aphotic zone are also the sole providers of nutrient regulation by phosphorus burial. However, they also contribute to hazardous substance accumulation and transformation, physicochemical retention of pollutants, and global climate regulation by carbon sequestration. Photic pelagic habitats supply 100% of the ecosystem service's nutrient regulation by N_2 assimilation, maintain a supply of wild fish, and contribute to various cultural ecosystem services.

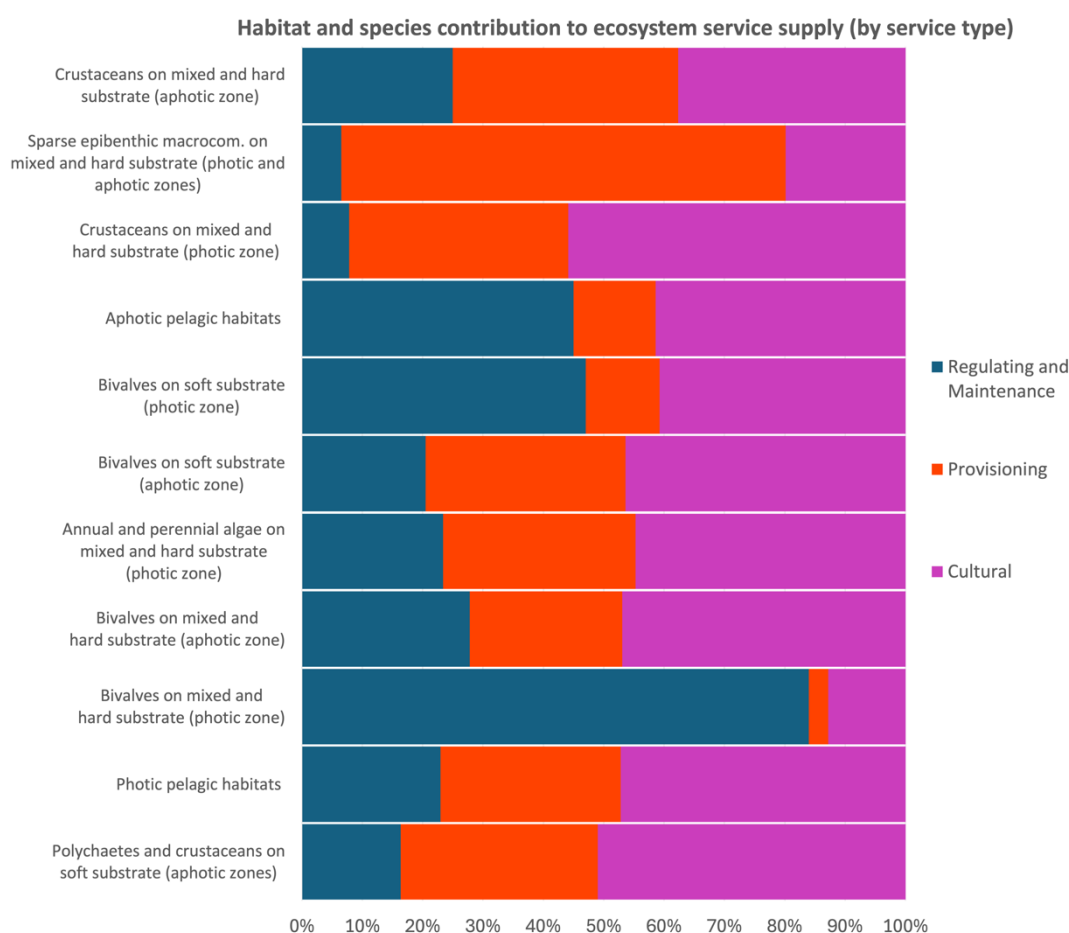


Figure 7 Habitat and species contribution to ecosystem service supply by service type. Adapted from Armoskaite et al. 2020.

1.1.4 Previously detected benthic habitat changes in the Latvian Marine Protected Areas

A retrospective study of three Latvian MPA sites revealed major shifts in habitat composition and the cover of key habitat-engineering species between 2006–2019 and 2016–2019 (Armoskaite et al. 2021; Figure 8). Three case study sites representative of the stony reef habitats made up of hard substrate – Jūrmalciems (92 %) and Pape (78 %) in the protected area ‘Nida-Pērkone’, and Ragaciems (98 %) in the protected area ‘Western coast of the Gulf of Riga’.

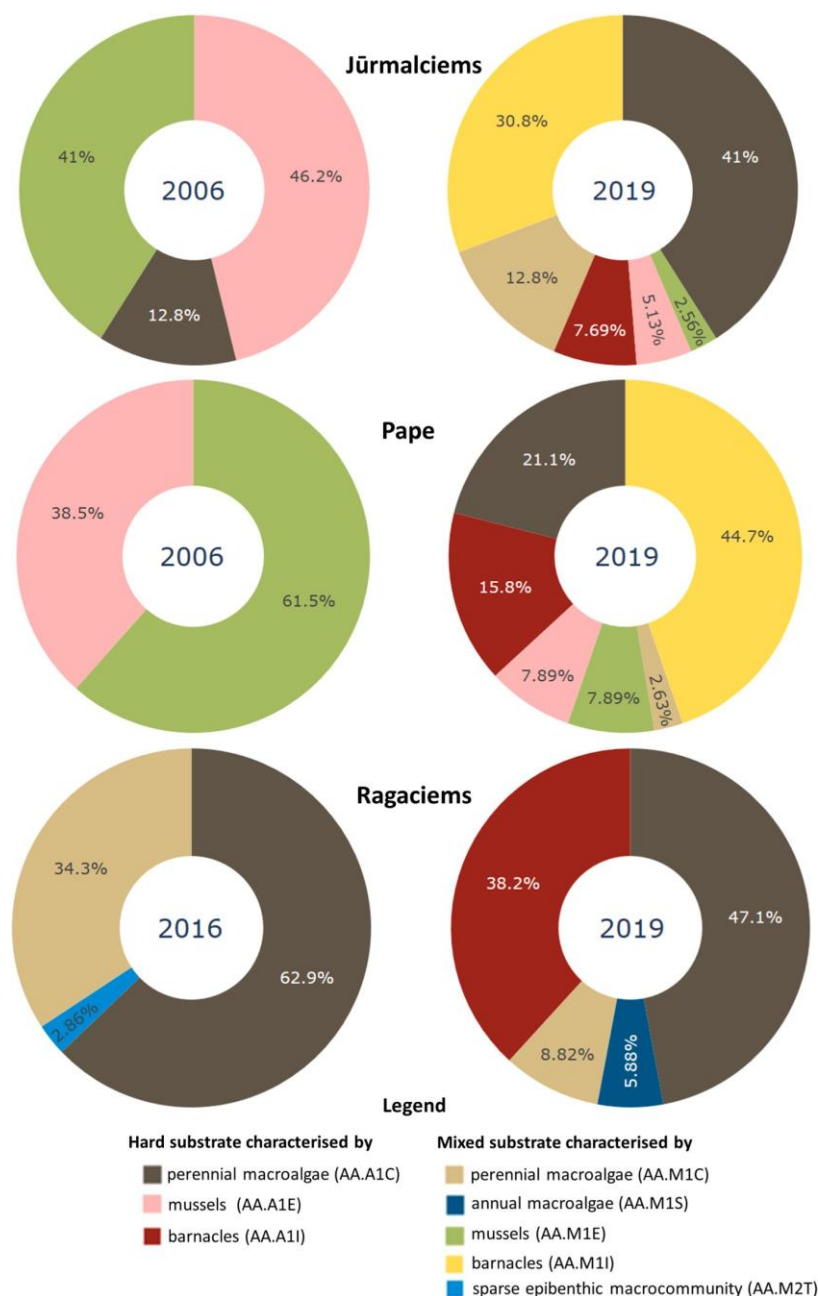


Figure 8 Changes in habitat composition in the three studied sites. Image source: Armoskaite et al. 2021.

Observations made from underwater video recordings captured on a 500 m-to-500 m grid and analysed and categorised into habitat types according to the dominance of species or species complexes (Level 5) following the HELCOM Underwater Biotope and Habitat Classification System based on the substrate type and benthic

community type based on coverage of all visually identifiable species. Jūrmalciems was visited in 2016 and Pape and Ragaciems were visited in 2006. All sites were then revisited in 2019.

Geospatial benthic habitat cover maps and relative ecosystem service supply change analyses were used to develop maps depicting changes in ecosystem functions and services due to habitat composition changes in Latvia (Armoskaite et al. 2021).

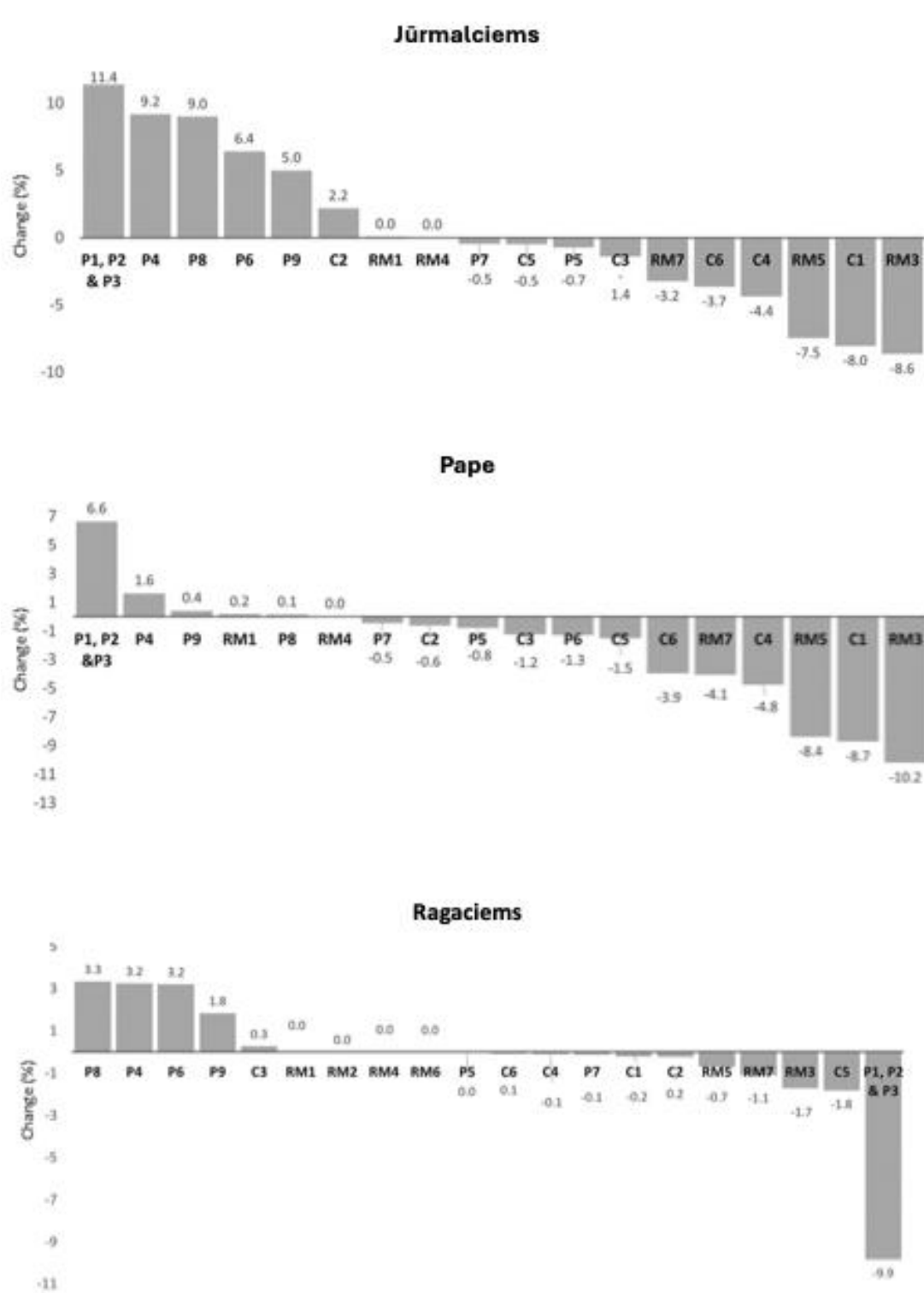


Figure 9 Changes in relative ecosystem service supply in the three studied sites. Image source: Armoskaite et al. 2021.

Notable changes were observed in the relative cover of *Mytilus trossulus*, perennial algae, barnacles, and, to a lesser extent, annual algae and sparse epibenthic macro communities. These successional shifts were closely linked to changes in ecosystem functions and service supply and were primarily driven by pressures such as the spread of invasive species beyond MPA boundaries (Armoskaite et al. 2021).

1.2 Report Objectives

This report aims to assess ecosystem functions and services supplied by habitats in Latvian marine waters, focusing on benthic habitats and protected stony reefs. It sets out to fulfil the following three objectives:

1. Use the most recent geospatial knowledge of coastal benthic habitat composition to graphically, geospatially represent ecosystem functioning and service supply by benthic habitats in Latvian marine waters.
2. Explore the impacts of notable coastal benthic habitat composition change on ecosystem functioning and service supply.
3. Develop and test a method for applying a cumulative impact assessment methodology in ecosystem service supply to assess the implications of changing pressures on ecosystem services.

2 Methods

In this study, the focal elements of analysis are the ecosystem state, specifically the state of benthic habitats including stony reefs, the pressures inflicting stress and changing the ecosystem state and the impacts on welfare through the analysis of ecosystem service supply (Figure 10).

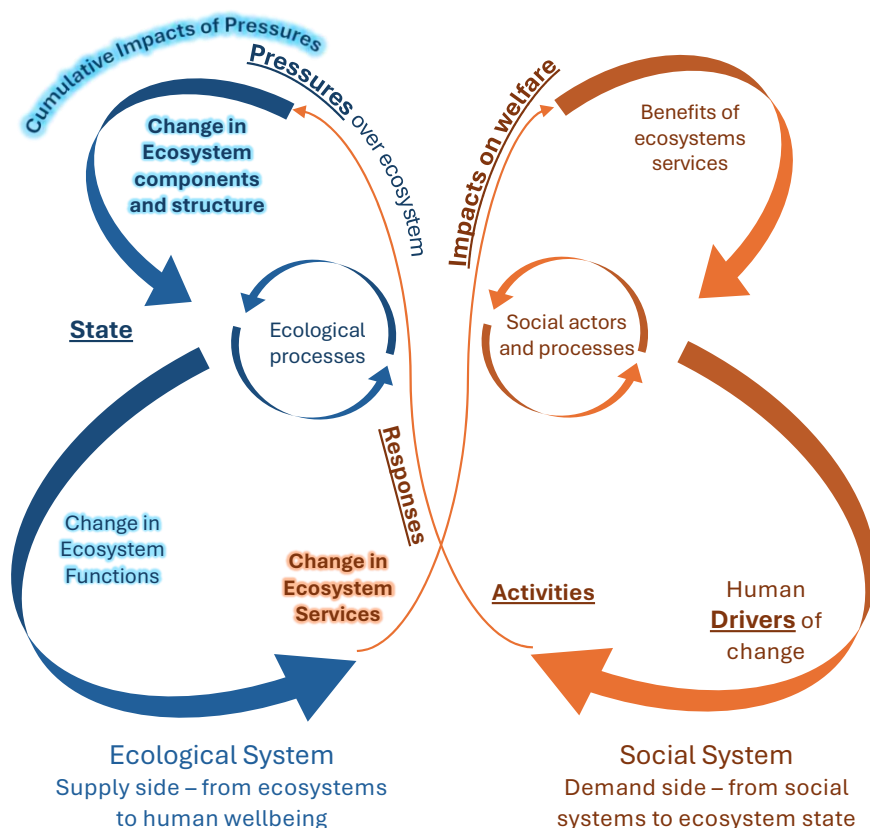


Figure 10 The DAPSIR butterfly has been adapted to explicitly include cumulative impact analysis, ecosystem functioning, and service supply change analysis (adapted from Armoskaite et al. 2023 and Elliot and O'Higgins 2020).

Ecosystem state is assessed based on the geospatial data, providing an insight into habitat and species presence on the seabed. Assessment of ecosystem functions, indicating ecosystem state, and ecosystem service supply as a measurement of impacts on human welfare, is assessed using the expert knowledge and linkage-based ecosystem service analysis method described above (Armoskaite 2020; Armoskaite 2021). To graphically represent ecosystem functioning and service supply, the contribution values from Armoskaite et al. (2020) are combined with spatial habitat data gathered during the project to reveal areas of particular importance. Biophysical data collected at LHEI over time, including during the Life REEF project, indicate a significant decrease in algae cover in the Gulf of Riga. Data on habitat composition at various time frames were used to assess species cover and service supply change. The Halpern et al. (2008) cumulative pressure and impact analysis approach was combined with the ecosystem services analysis method to investigate and map links between pressures and impacts on human welfare.

Next, a detailed explanation of methods for mapping ecosystem functioning and service supply and assessing cumulative pressure, impact, and service supply change is outlined.

2.1 Mapping current ecosystem functioning and service supply

Each ecosystem component has a 'contribution value,' which can be given a geospatial dimension (Armoskaite et al. 2023) using data on ecosystem component presence. QGIS was used to map the contribution values from Armoskaite et al. (2020) using geospatial marine habitat and ecosystem component data from LHEI, including the geospatial data collected during the Life REEF project. Figure 11 is an example of marine habitat data used for the analysis.

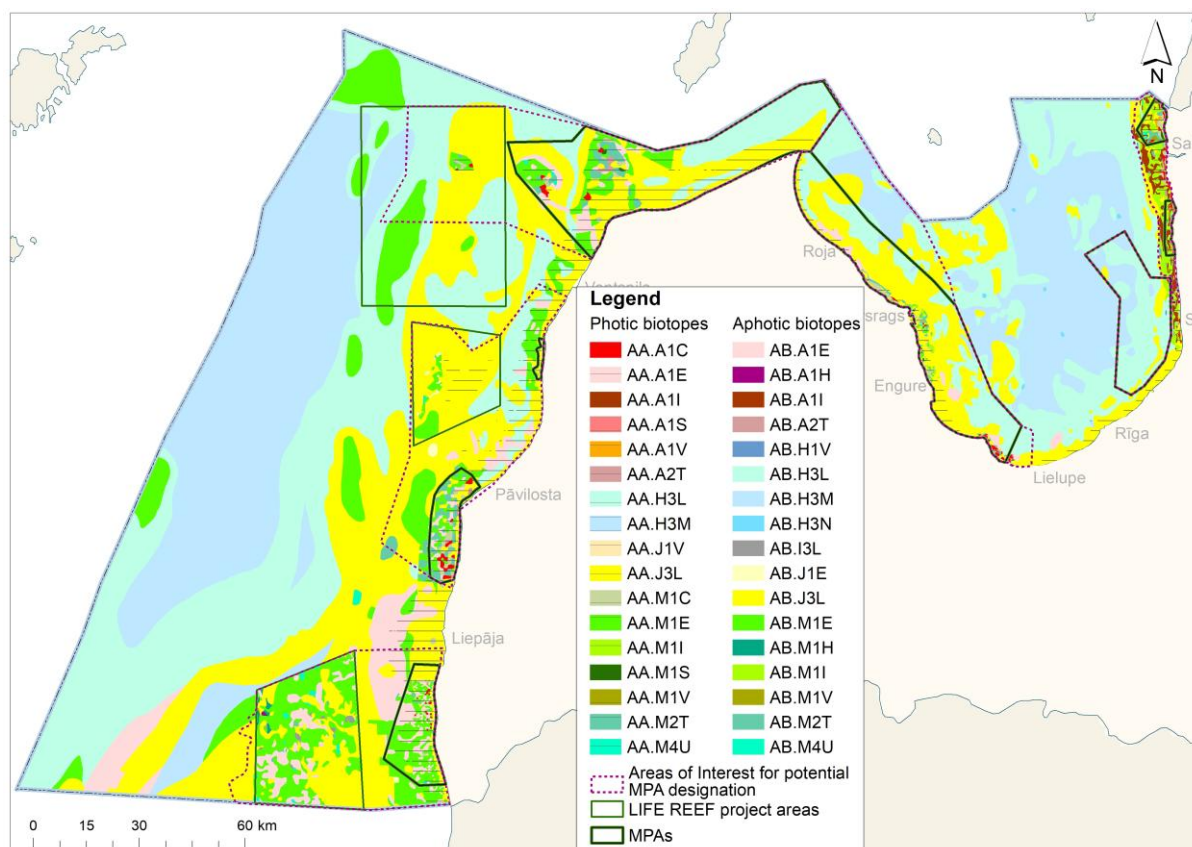


Figure 11 Map of marine habitats categorised according to the HELCOM HUB (2013) classification system. AA.A- Baltic photic rocks and boulders, AB.A-Baltic aphotic rocks and boulders, AA.M- Baltic photic mixed substrate, AB.M- Baltic aphotic mixed substrate, AA.J- Baltic photic sand, AB.J- Baltic aphotic sand, AB.H-Baltic aphotic mud, AD.N- Baltic photic pelagic, above halocline, AE.N- Baltic aphotic pelagic, above halocline.

Contribution values can be mapped per ecosystem component, however in this study they were summed up for several components per cell to provide an understanding of locations of ecosystem functions and service supply.

2.2 Change analysis

Perennial algae are a defining species of a stony reef. However, perennial brown algae, *Fucus vesiculosus*, cover surveys in the MPAs Eastern coast of the Gulf of Riga and Western coast of the Gulf of Riga before and since 2020 suggest a significant decrease in overall *Fucus* cover across the coastal area 4.5 – 6m deep (Figure 12).

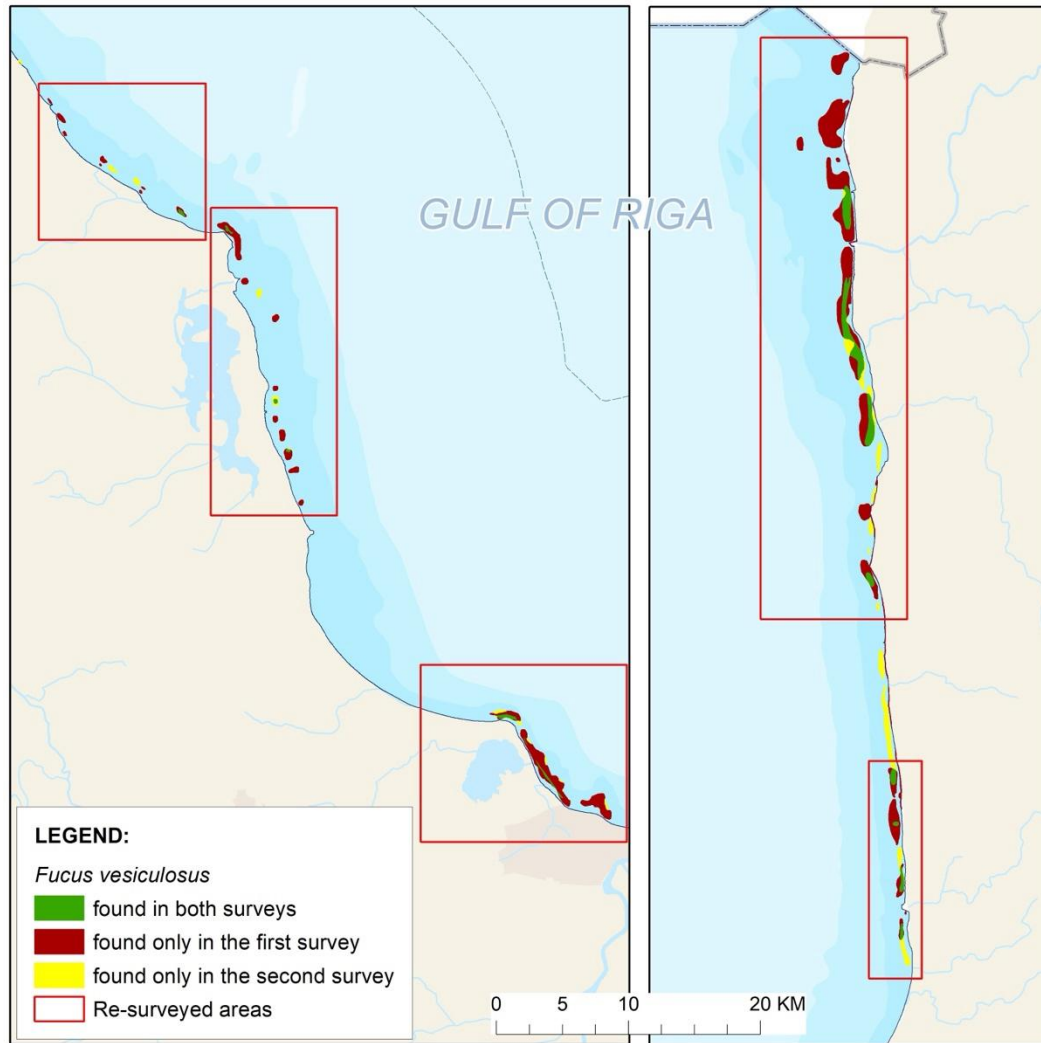


Figure 12 Distribution of a key stony reef species, perennial macroalgae *Fucus vesiculosus*, in surveyed sites.

In the Eastern coast of the Gulf of Riga MPA, the decrease was around 64% between 2009 and 2022, and around 54% in the Western coast of the Gulf of Riga MPA between 2015 and 2024 (Table 2).

Table 1 Change *Fucus* cover (ha) in the MPAs Eastern coast of the Gulf of Riga and Western coast of the Gulf of Riga based on surveys before and after 2020.

MPA	Species	Area surveyed (ha)											Area before 2020 (ha)	Area after 2020 (ha)	Remaining cover %
		Cover % increase				Cover % decrease				Cover % unchanged					
		from 0 to <=1%	from 0 to >1%	from <=1% to >1%	total	from 0 to <=1%	from 0 to >1%	from <=1% to >1%	total	>1%	<=1%	0			
Eastern coast of the Gulf of Riga	Fucus	175,7	78,2	127,2	381,2	224,9	660,8	1175,8	2061,6	89,5	197,5	20180,2	2475,7	893,0	36%
Western coast of the Gulf of Riga	Fucus	67,1	36,1	25,6	128,8	107,4	408,6	265,7	781,8	187,8	67,0	12547,6	1062,1	491,0	46%

The results of the species cover analysis were used to estimate changes in ecosystem functions and services in the two MPAs.

2.3 Pairing cumulative impact and ecosystem service analysis to assess change in ecosystem service supply

Understanding individual and cumulative impacts on ecosystems and the services they provide is vital for marine planning. A geospatial method for analysing relative ecosystem functioning and service supply has been developed to support this, building on Halpern et al.'s cumulative impact (CIA) approach (2008) to complement the landscape-based ecosystem service analysis methodology described in chapter 1.1.2 (Armoskaite et al. 2023). An assessment was conducted for the Gulf of Riga to demonstrate the combined method. In this scenario, fishing for herring in the Gulf of Riga was reduced by 50% (Armoskaite et al. 2023). The assessment used the MYTILUS and QGIS software using HELCOM's ecosystem component sensitivity matrix, geospatial ecosystem component data, and ecosystem component contribution values from Armoskaite et al. (2020).

3 Findings

Results of current ecosystem functioning and service supply analysis across the Latvian marine waters, and results of retrospective change analysis for the Gulf of Riga, are presented in this section. The results of the current ecosystem's functioning and service supply analysis across Latvian marine waters are presented in this section. Ecosystem services are split into three groups - cultural, provisioning, regulating and maintenance services. Ecosystem functions include refuge and shelter, benthic spawning and nursery habitats and benthic and pelagic primary production, microbial transformations, fish feeding grounds, filtration of suspended matter, and accumulation of materials.

3.1 State of ecosystem functioning

Figure 13 depicts areas important for benthic spawning and nursery habitats and primary production. These functions are primarily linked to photic hard and mixed substrate benthic habitats, which are characterised by perennial and annual algae largely within the coastal waters.

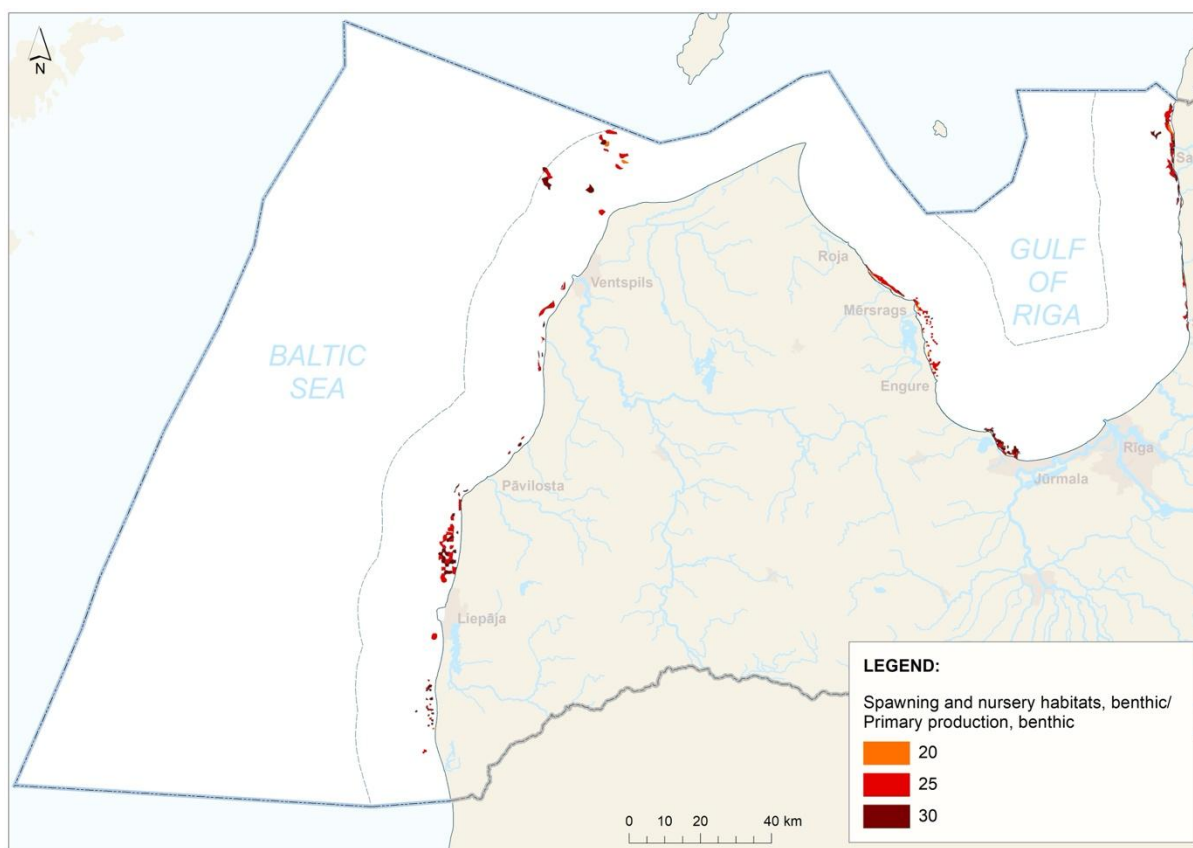


Figure 13 Areas with benthic habitats and species important in maintaining spawning and nursery habitat and primary production. A higher value indicates a more substantial contribution.

Figure 14 depicts important refuge and shelter areas created by benthic habitats. These are primarily photic and aphotic hard and mixed substrate benthic habitats, the most important of which are characterised by perennial algae.

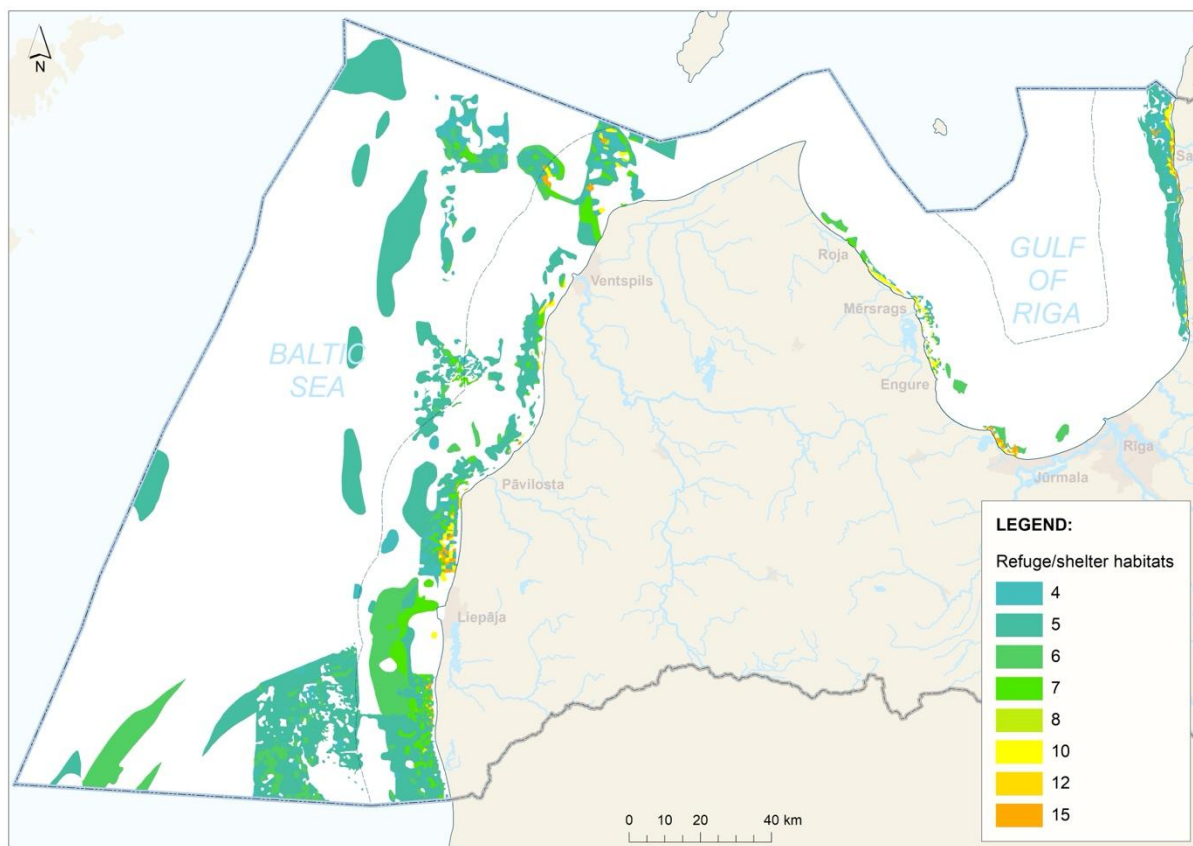


Figure 14 Areas with benthic habitats and species that are important in providing refuge and shelter. A higher value indicates a more substantial contribution.

Figure 15 depicts areas important for microbial transformation, primarily linked to photic and aphotic soft substrate benthic habitats and, albeit to a much lesser degree, photic and aphotic mixed benthic and pelagic habitats.

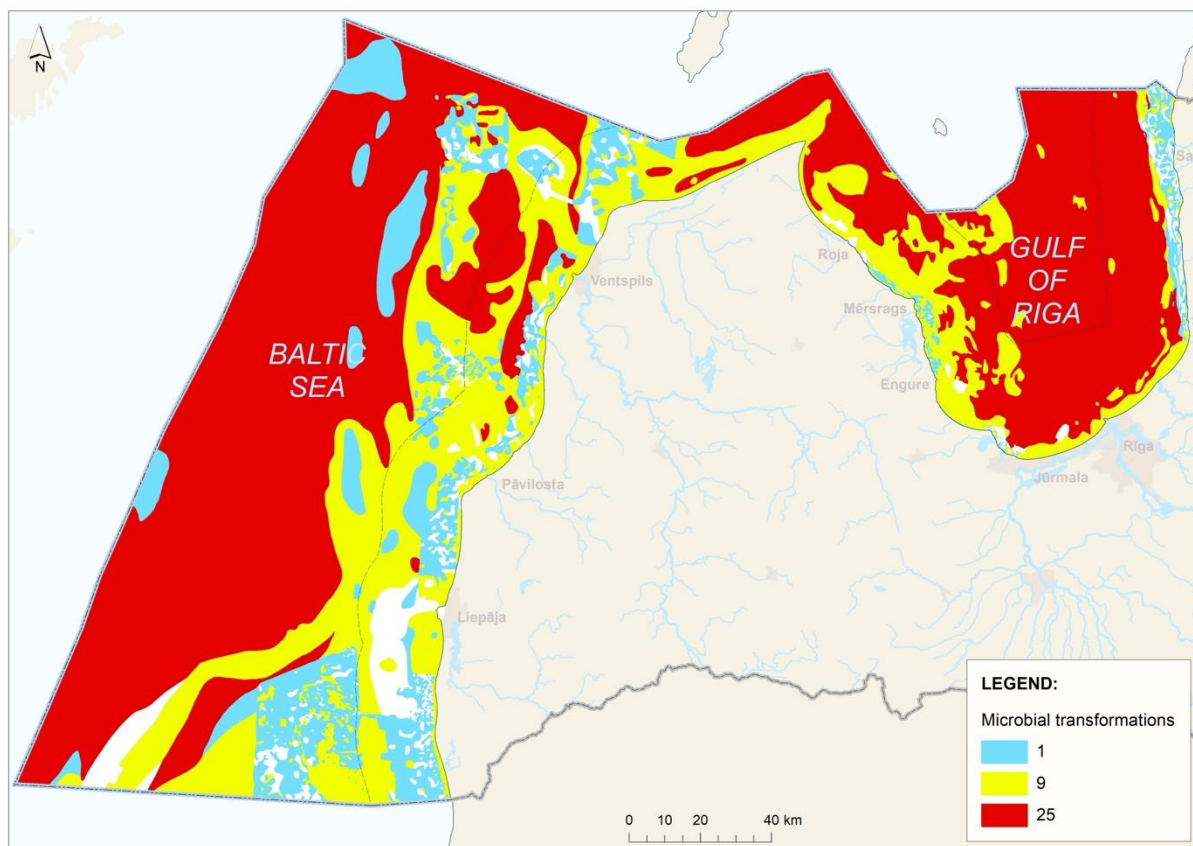


Figure 15 Areas with habitats and species performing microbial transformation. A higher value indicates a more substantial contribution.

Figure 16 depicts important fish feeding grounds provided by benthic habitats, primarily photic and aphotic soft substrate benthic habitats characterised by infaunal bivalves, polychaetes and crustacea, and to a lesser degree, photic hard, mixed and aphotic mixed substrate covered by bivalves.

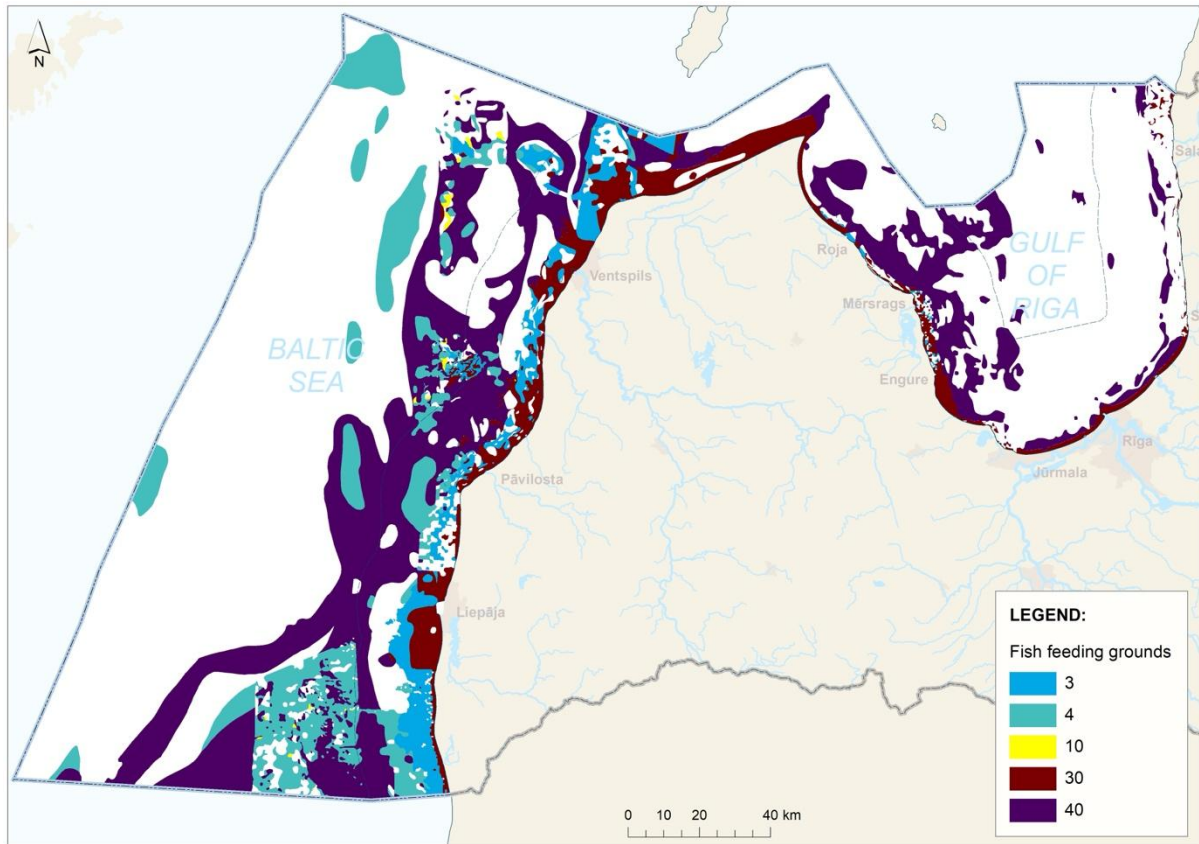


Figure 16 Areas with habitats and species important for maintaining fish feeding grounds. A higher value indicates a more substantial contribution.

Figure 17 depicts areas essential for the filtration of suspended matter. Filtration is performed mainly by bivalves, found on hard, mixed and, at times, soft substrates in photic and aphotic conditions.

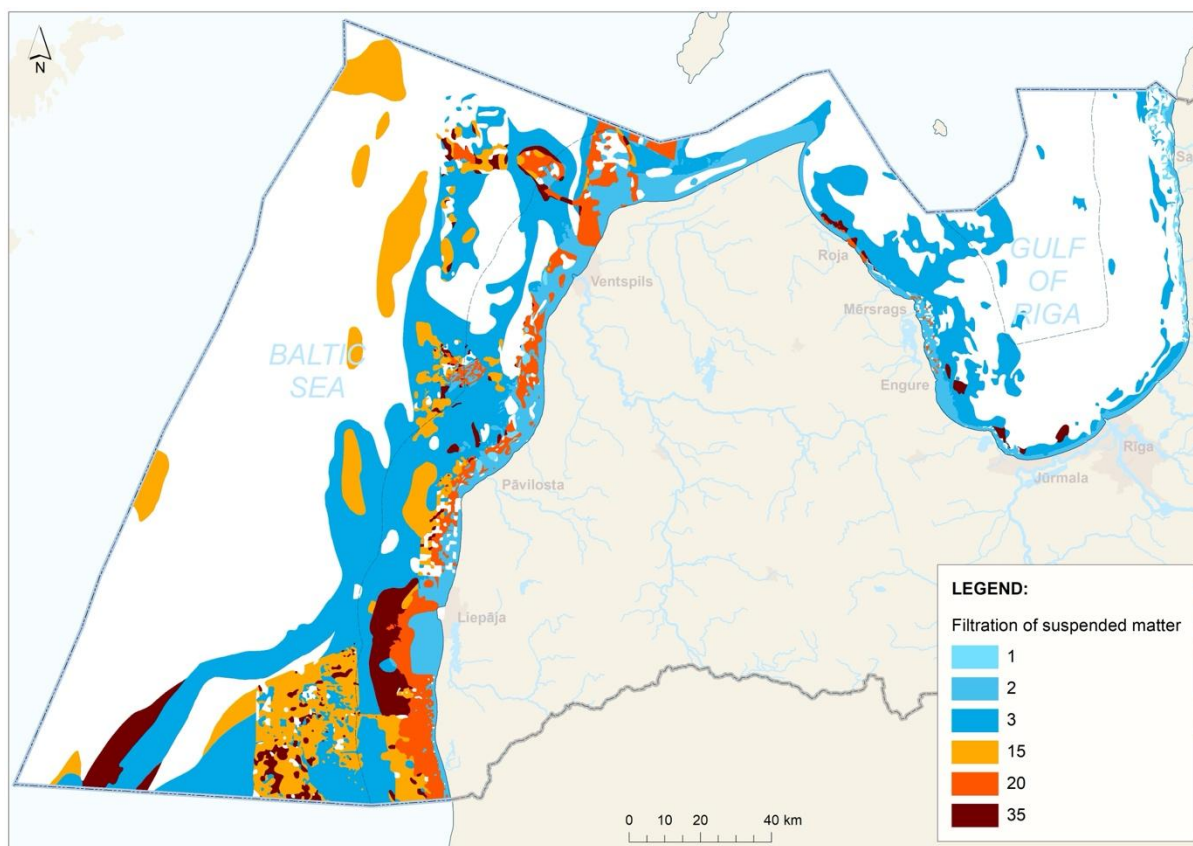


Figure 17 Areas with habitats and species important for filtering suspended matter. A higher value indicates a more substantial contribution.

Figure 18 depicts aphotic soft substrate benthic habitats characterised by infaunal polychaetes and crustaceans essential for accumulating materials.

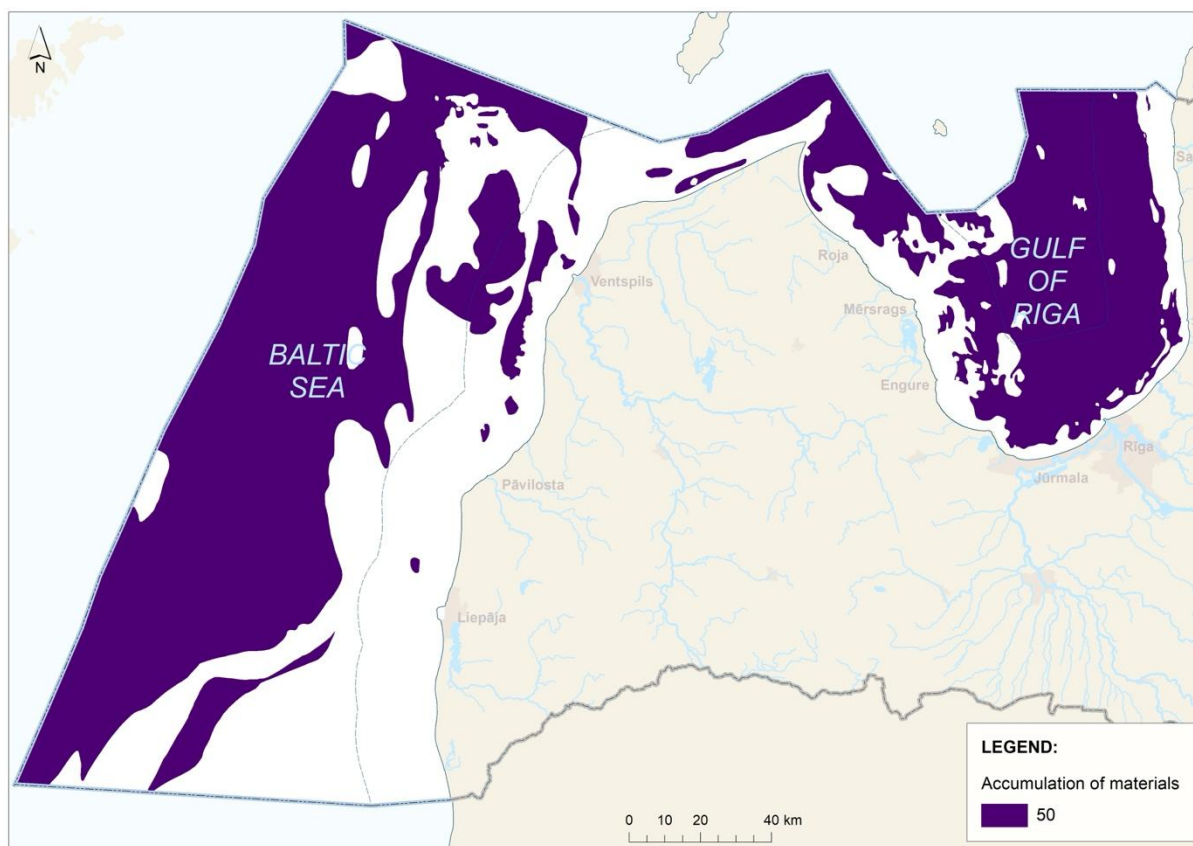


Figure 18 Areas with habitats and species important for accumulating materials. A higher value indicates a more substantial contribution.

3.2 Ecosystem service supply

Figure 19 shows the areas important for providing regulating and maintenance ecosystem services. The highest-scoring habitats, indicated by the darker shades of brown, are primarily located far from the coastline. These are primarily aphotic, soft sediment characterised by infaunal polychaetes and crustaceans, which accumulate materials and perform microbial transformations, underpinning the ecosystem service physicochemical retention of pollutants and contributing significantly to global climate regulation (by carbon sequestration), hazardous substances accumulation and transformation, nutrient regulation by denitrification and by phosphorus burial.

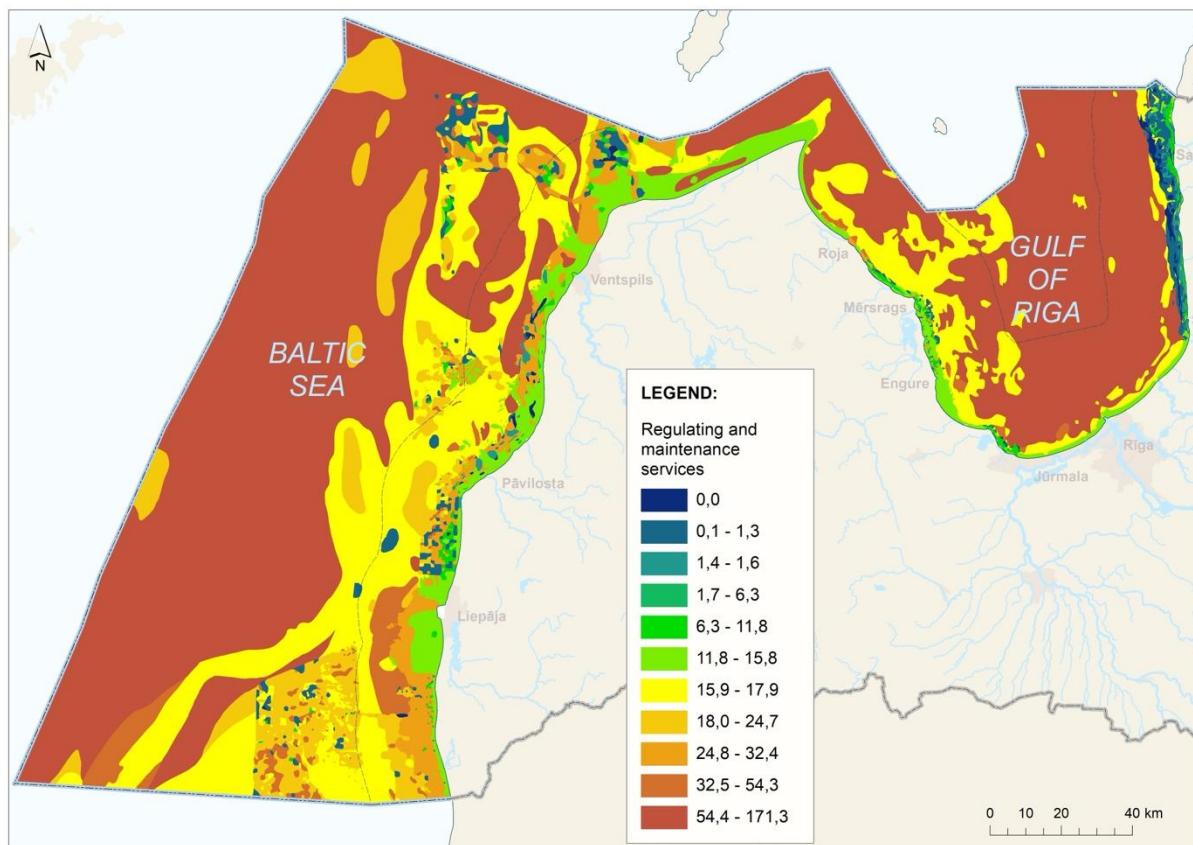


Figure 19 Areas with habitats and species important for providing regulating and maintenance ecosystem services. A higher value indicates a more substantial contribution.

Figure 20 shows the areas essential for providing provisioning ecosystem services. The highest-scoring areas, indicated by the darker shades of brown, include habitats dominated by bivalves (in the photic and aphotic zone and on soft, mixed and hard substrate) and perennial and annual macroalgae.

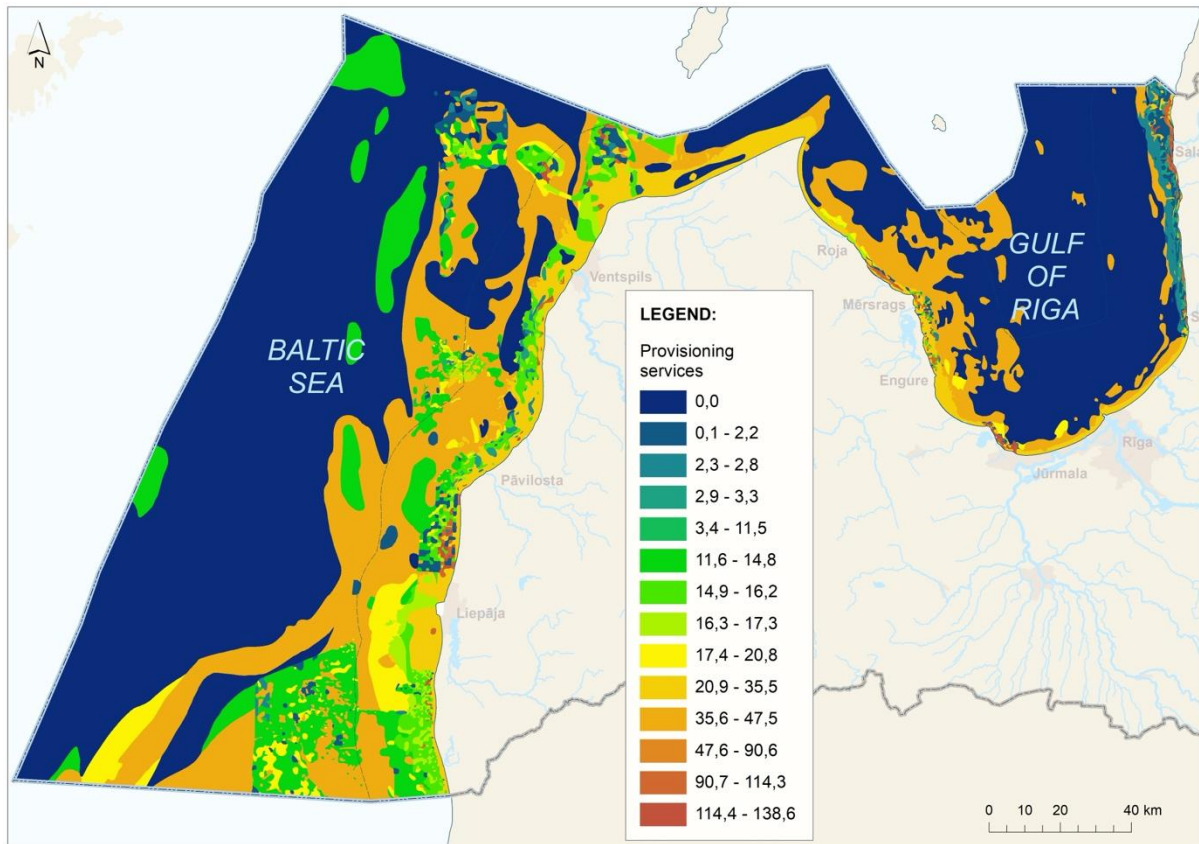


Figure 20 Areas with habitats and species important for providing provisioning ecosystem services. A higher value indicates a more substantial contribution.

Figure 21 shows the areas essential for providing cultural ecosystem services. The darker shades of brown indicate the highest-scoring areas. These areas include habitats dominated by bivalves (in the photic and aphotic zone and on soft, mixed and hard substrate) and perennial and annual macroalgae, and are important photic and aphotic pelagic habitats, as well as polychaetes and crustaceans on soft substrate in the aphotic zone.

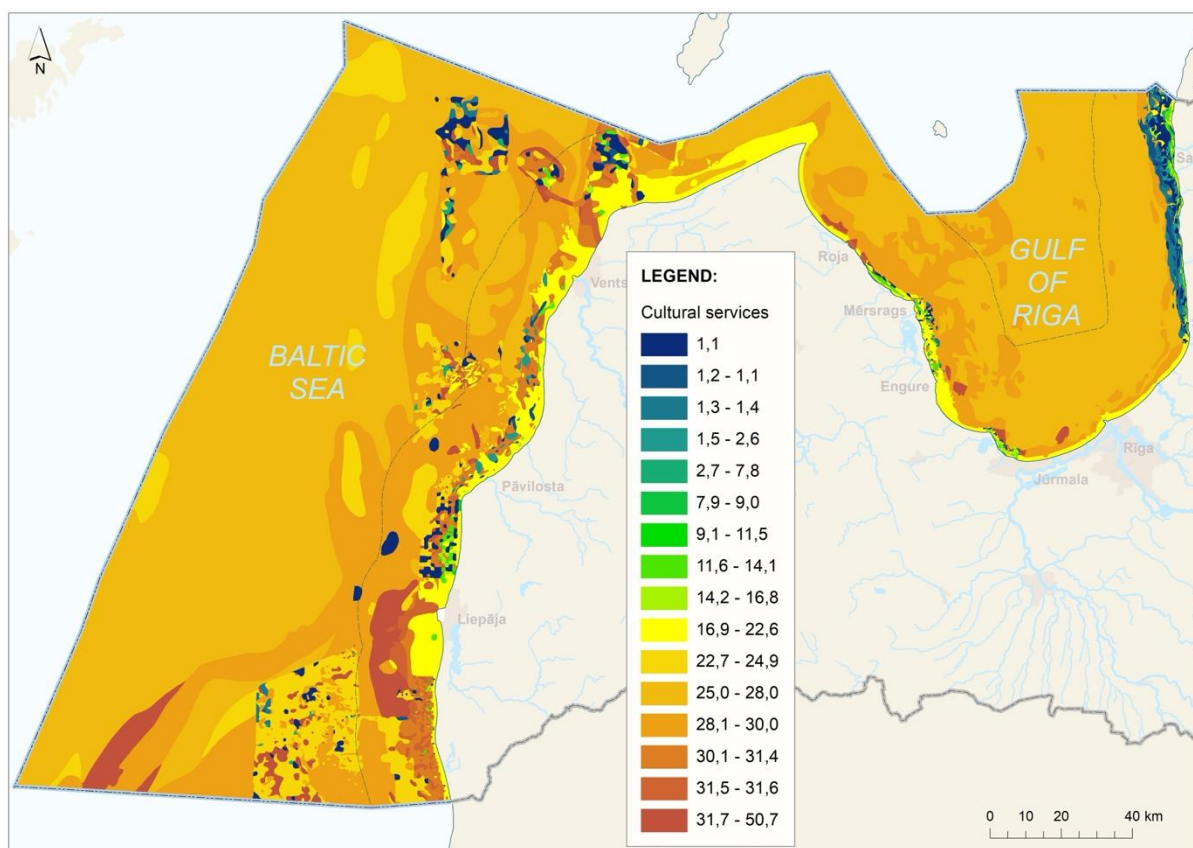


Figure 21 Areas with habitats and species important for providing cultural ecosystem services. A higher value indicates a more substantial contribution.

3.3 Change in ecosystem functioning and service supply since 2020

The functions and services an ecosystem provides are not constant, as they are highly dependent on the ever-changing composition of habitats. Table 3 depicts the change in ecosystem functioning and service supply based on the observed decrease in perennial algae in the Western and Eastern Gulf of Riga MPAs.

Table 2 Relative decrease in ecosystem functioning and service supply due to decreased perennial algae across the Eastern coast of the Gulf of Riga to 36% of cover and the Western coast of the Gulf of Riga to 46% cover.

Ecosystem function and service type		Change (%)	
		AJT Rīgas līča austrumu piekraste	AJT Rīgas līča rietumu piekraste
Functions	Spawning & nursery habitats, benthic	-35,22	-29,71
	Spawning, nursery & feeding habitats, pelagic	0,00	0,00
	Refuge/shelter habitats	-8,81	-7,44
	Primary production, benthic	-88,67	-74,81
	Primary production, pelagic	0,00	0,00
	Fish feeding grounds	0,00	0,00
	Filtration of suspended matter	-4,83	-4,08
	Transport of materials & dispersal	0,00	0,00
	Accumulation of materials	0,00	0,00
	Microbial transformations	-0,67	-0,56
Regulation and maintenance services	Nutrient regulation (by denitrification)	-0,48	-0,40
	Nutrient regulation (by N, P burial)	0,00	0,00
	Nutrient regulation (by nutrient incorporation in biomass)	-4,72	-3,99
	Nutrient regulation (by N assimilation)	0,00	0,00
	Hazardous substances accumulation & transformation	-2,06	-1,74
	Physicochemical retention of pollutants	0,00	0,00
	Carbon sequestration	-2,96	-2,50
Provisioning services	Wild plants	-24,98	-21,07
	Plant energy	-24,98	-21,07
	Materials from algae	-24,98	-21,07
	Wild fish, pelagic- herring	-8,81	-7,43
	Wild fish, pelagic- sprat	-0,07	-0,06
	Wild fish, benthic-flounder	-10,15	-8,57
	Wild fish, benthic- cod	-1,69	-1,43
	Wild fish, benthic-round goby, eelpout	-12,46	-10,51
	Fishmeal	-6,44	-5,44
Cultural services	Water environment for recreation	-0,77	-0,65
	Water environment for science & education	-6,11	-5,16
	Water environment for cultural & historical heritage	-0,06	-0,05
	Water environment for spiritual experience	-0,42	-0,35
	Existence of habitats & species	-5,65	-4,77
	Water environment for enjoyment of seascape	-0,40	-0,33

The ecosystem functions most significantly affected were benthic primary production, which decreased from 89% to 75%, and benthic spawning and nursery habitats, which decreased from 35% to 30%. This was followed by a decrease of 8.8 % and 7.4 % in refuge and shelter habitats and 4.8% and 4% in filtration of

suspended matter in the sites surveyed in the Eastern coast of the Gulf of Riga MPA and the Western coast of the Gulf of Riga, respectively.

Out of the three ecosystem service groups, provisioning services were the most affected. Provisioning services were reduced by an average of 13% on the eastern coast of the Gulf of Riga and 11% on the western coast of the Gulf of Riga. The most impacted provisioning services in both areas were services directly reliant on the availability of algae as a raw material. These services decreased by almost 25% in the sites surveyed in the Eastern coast of the Gulf of Riga and by 21% in the sites in the Western coast of the Gulf of Riga. Fish-related provisioning services (e.g. the availability of flounder and herring, and fish for fishmeal production), primarily related to the reduced availability of spawning and nursery habitats, decreased by around 6.6% in the Eastern coast of the Gulf of Riga MPA and by 5.5% in the Western coast of the Gulf of Riga MPA.

Cultural services decreased by an average of 2.2% on the Eastern coast of the Gulf of Riga and by 1.9% on the Western coast of the Gulf of Riga. In both areas, the most impacted cultural services were water environment for science and education and the existence of habitats and species. Together, these services decreased by 5-6% in both areas.

Regulation and maintenance decreased by an average of 1.5% in the sites surveyed on the Eastern coast of the Gulf of Riga and by 1% on the Western coast. On both sides, the most impacted regulation and maintenance services include nutrient regulation by nutrient incorporation in biomass, carbon sequestration and hazardous substances accumulation and transformation. At the sites surveyed on the Eastern coast of the Gulf of Riga MPA, nutrient regulation by nutrient incorporation in biomass decreased by close to 5% and the Western coast of the Gulf of Riga by 4%, carbon sequestration decreased by 3% on the Eastern coast and by 2.5% on the Western coast of the Gulf of Riga, and hazardous substances accumulation and transformation decreased by around 2% at the sites surveyed on both sides of the Gulf.

3.4 A combined method for analysis of change in multiple ecosystem services simultaneously in response to changes in cumulative impacts: a Gulf of Riga test case.

The Halpern et al.'s (2008) cumulative assessment model utilises geospatial pressures, ecosystem component distribution data, and expert estimates of ecosystem component sensitivity to pressures. The output is a cumulative impact index per 1 km² cell, which accounts for species sensitivity to pressures and pressures—species spatial overlap and provides an overview of impact hot and cold spots. The results may help determine the suitability of activities in specific locations from an ecosystem perspective. Ecosystem services are underpinned by a range of ecosystem functions and components, under pressure from human activities. As outlined in chapter 1.1.2, following the Armoskaite et al. (2020) linkage-based methodology, experts assess the relative value of the links between components, functions, and services, forming a basis for estimating each component's contribution to service supply. Contribution values are adjusted using a coefficient of change derived through expert knowledge and geospatial analysis describing changes in habitats and species. Central to the method is the same ecosystem geodata used in the service supply analysis and mapping, and the cumulative impact assessment (Figure 22; Armoskaite et al. 2023).

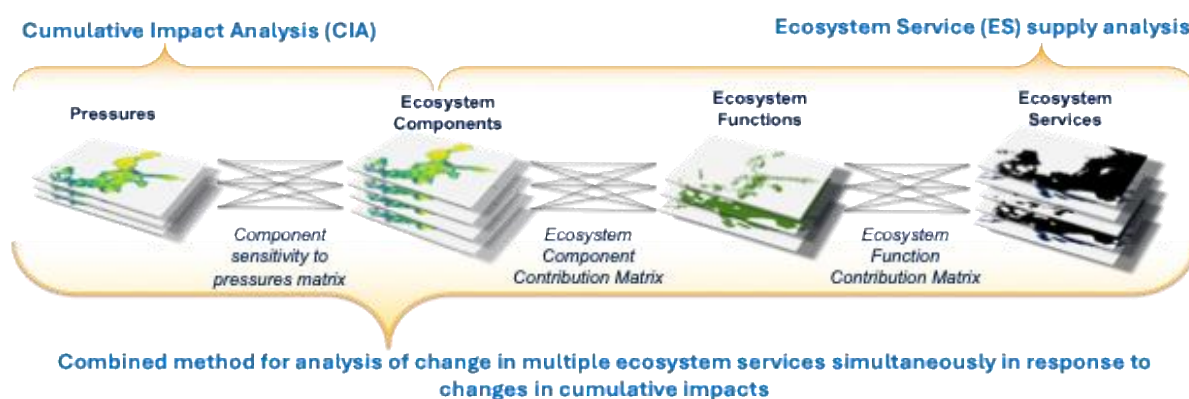


Figure 22 A conceptual model for the methodology for combining the Halpern et al. (2008) CIA method and the linkage-based ecosystem service supply analysis tool. The conceptual model presents input requirements (e.g., ecosystem component sensitivity matrix) and DAPSIR butterfly model elements assessed, as well as their interconnections.

To pair the methods, the first step is to calculate the per-cell change in cumulative impact index values by running two assessments – a reference and a new scenario – and dividing the new scenario by the reference scenario (Figure 23).

Steps for pairing the CIA and ES methodologies:

- 1 Run separate reference CIA & ES assessments.
- 2 Run a new, pressure-adapted CIA scenario with updated human pressures.
- 3 Divide the new CIA scores by the reference CIA scores to determine the relative change in cumulative impact.
- 4 Divide ecosystem component contribution values by the relative change in cumulative impact scores to calculate the change in ES supply.

Figure 23 Four shows the four main steps for conducting an ecosystem service supply change assessment based on relative geospatial change in cumulative index values.

The next step is to ensure that the service supply (ecosystem component contribution values) is mapped using the ecosystem maps used in CIA. To map the ecosystem service supply with impact index values applied, maps of ecosystem service supply for the area are divided by the change in cumulative impact index values (step 4 in Figure 23). Finally, a change in ecosystem service supply, that is, the per-cell relative change, can be calculated by subtracting the reference ecosystem service supply scenario from the new supply scenario.

Figures 24 and 25 depict the outcomes of an assessment for the Gulf of Riga to demonstrate the methodology and depicts a scenario where the fishing for herring in the Gulf of Riga was reduced by 50%.

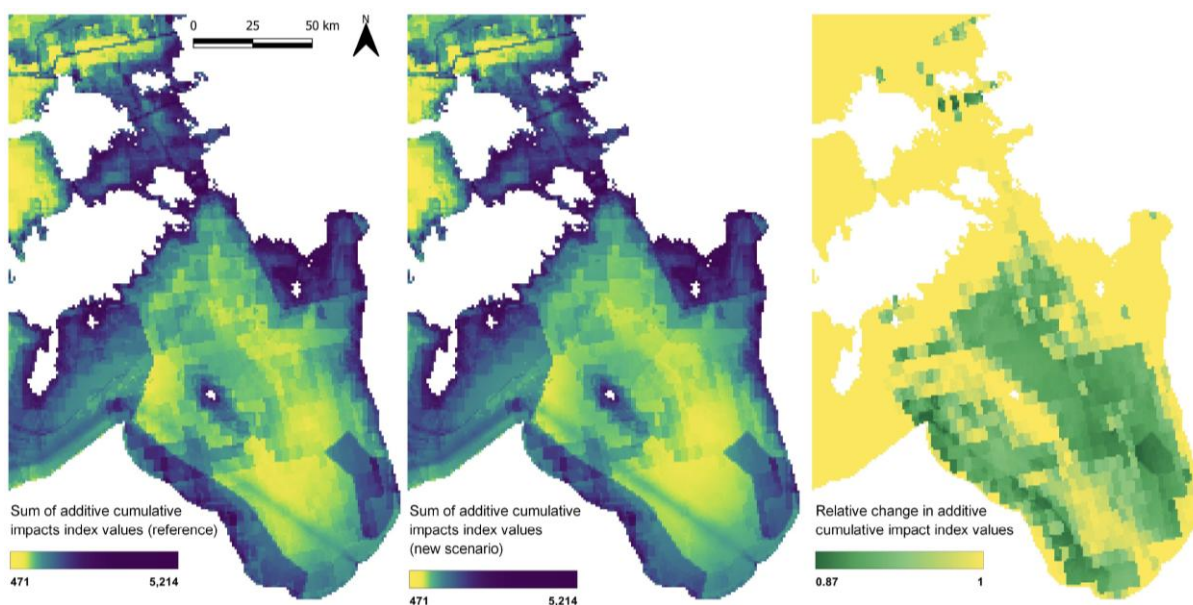


Figure 24 Cumulative impact reference, new scenario and relative change assessment results. In the relative change map, cumulative impact increased if above 1, not changed if 1, or decreased if below 1 within the cell. Image source: Armoskaite et al. 2023.

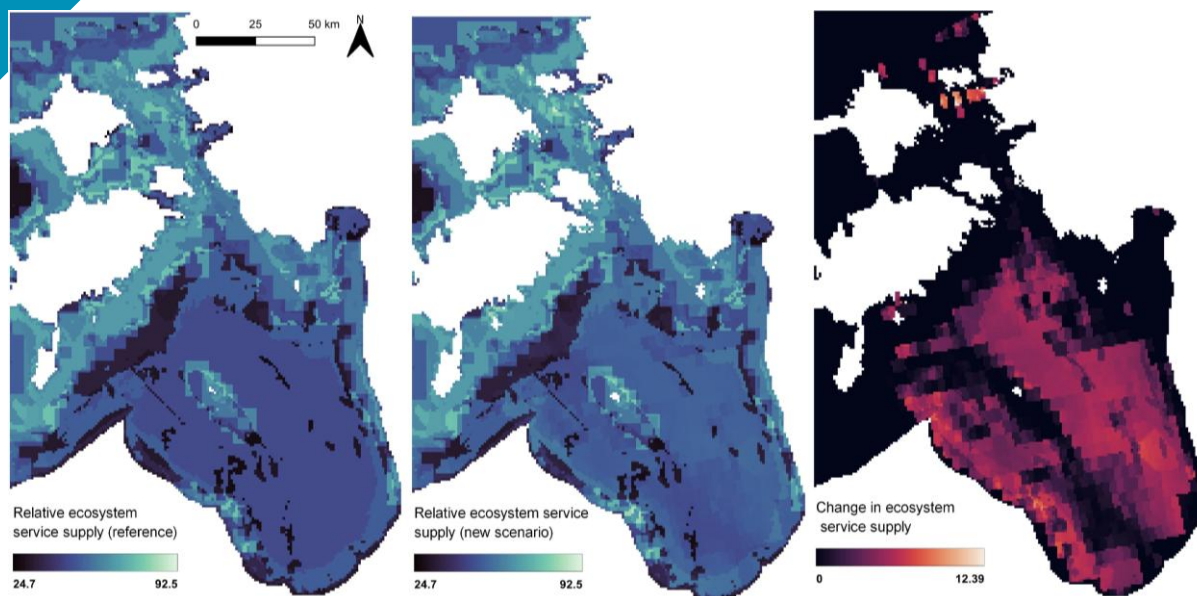


Figure 25 Ecosystem service supply reference, new scenario based on the relative change in additive cumulative impact index values and the relative change in ecosystem service supply assessment results. In the relative change map, cumulative impact increased if above 1, not changed if 1, or decreased if below 1 within the cell. Image source: Armoskaite et al. 2023.

4 Conclusion

This study demonstrates that all marine habitats provide ecosystem services; however, some contribute more to specific services. Macroalgae and mussel-dominated benthic habitats, that is, protected stony reefs, provide a large array of ecosystem functions and services. In some cases, they are the sole providers.

Change analysis using the most up-to-date field observations from the Gulf of Riga suggests there has been a significant decrease in macroalgae cover. In the Eastern coast of the Gulf of Riga MPA, the decrease was around 64% between 2009 and 2022, and around 54% in the Western coast of the Gulf of Riga MPA between 2015 and 2024. Ecosystem functions most significantly affected include benthic primary production, with a decrease of around 89% to 75%, and benthic spawning and nursery habitats decreased from 35% to 30%.

While in this change assessment the focus was on macroalgae, further analysis of habitat composition changes and successional shifts would support a more detailed analysis of ecosystem functioning and service supply change. In some cases, the disappearance or decrease of one species may mean that a different species takes up the available space on mixed or hard substrate, if the conditions are right, resulting in a drastic change in the types of services the stony reef supplies, as illustrated in the retrospective study of three Latvian MPA sites revealed major shifts in habitat composition and the cover of key habitat-engineering species between 2006–2019 and 2016–2019 (Armoskaite et al. 2021). Notable changes were observed in the relative cover of *Mytilus trossulus*, perennial algae, barnacles, and, to a lesser extent, annual algae and sparse epibenthic macrocommunities. These successional shifts were closely linked to changes in ecosystem functions and service supply, and primarily driven by pressures such as the spread of invasive species beyond MPA boundaries (Armoskaite et al. 2021).

The combined cumulative impacts (CIA) and ecosystem service (ES) supply analysis methodology is advantageous because they provide an overview of ecosystem state change through CIA and an indication of the potential impacts of ecosystem state change on human well-being through the analysis of ES.

Combining the methodologies provides a more complete representation of social-ecological systems. Further, lays the foundations for further monetary and non-monetary benefits, and potentially for beneficiary and benefit distribution analysis. Additional testing of the method with other pressures and methodology development is needed to support various other types of graphic representation of the results.

5 References

- Armoskaite, A.; Puriņa, I.; Aigars, J.; Strāķe, S.; Pakalniņe, K.; Frederiksen, P.; Schrøder, L.; Hansen, H.S. 2020. Establishing the links between marine ecosystem components, functions, and services: An ecosystem service assessment tool. *Ocean and Coastal Management*. 193. doi.org/10.1016/j.ocecoaman.2020.105229.
- Armoskaite, A.; Aigars, J.; Hansen, H.S.; Andersone, I.; Schrøder, L.; Strāķe, S. 2021. Assessing change in habitat composition, ecosystem functioning and service supply in Latvian protected stony reefs. *Journal of Environmental Management*. 298. doi.org/10.1016/j.jenvman.2021.113537.
- Armoskaite, A.; Aigars, J.; Andersone, I.; Bonnevie, I.M.; Schrøder, L.; Strāķe, S.; von Thenen., Hansen, H.S. 2023. Setting the scene for a multi-map toolset supporting maritime spatial planning – mapping pressures and relative cumulative effects to ecosystem services. *Frontiers in Marine science*. 10:1213119. doi.org/10.3389/fmars.2023.1213119
- Biggs, R., Clements, H., de Vos, A., Folke, C., Manyani, A., Maciejewski, K., Martín-López, B., Preiser, R., Selomane, O., Schlüter, M. 2022. What are social-ecological systems and social-ecological systems research? In: Biggs, R., de Vos, A., Preiser, R., Clements, H., Maciejewski, K., Schlüter, M. (eds) *The Routledge Handbook of Research Methods for Social-Ecological Systems*.
- European Commission 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). <http://data.europa.eu/eli/dir/2008/56/oj>
- Frederiksen, P., Morf, P., von Thenen, M., Armoskaite, A., Luhtala, H., Schiele, K.S., Strake, S., Hansen, H., 2021. Proposing an ecosystem services-based framework to assess sustainability impacts of maritime spatial plans (MSP-SA). *Ocean and Coastal Management*. 208. doi.org/10.1016/j.ocecoaman.2021.105577
- Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., et al. 2008. A global map of human impact on marine ecosystems. *Science* 319, 5865, 948–952. doi: 10.1126/science.1149345
- HELCOM, 2013a. Red List Biotope Information Sheets (BIS), A Background Document for the 2013 HELCOM Ministerial Meeting, Copenhagen.
- HELCOM, 2013b. HELCOM HUB – technical report on the HELCOM underwater biotope and habitat classification Balt. Sea Environ. Proc. No., 139.
- Potschin-Young, M., Burkhard, B., Czúcz, B., and Santos-Martín, F., 2018. Glossary of ecosystem services mapping and assessment terminology. *One Ecosystem* 3: e27110. doi.org/10.1051/shsconf/20185801025
- Preiser, R., Schlüter, M., Biggs, R., García, M.M., Haider, J., Hertz, T., and Klein, L. 2022. Complexitybased social- ecological systems research: philosophical foundations and practical implications. In: Biggs, R., de Vos, A., Preiser, R., Clements, H., Maciejewski, K., Schlüter, M. (eds) *The Routledge Handbook of Research Methods for Schlüter et al., 2019*
- Binder, C. R., Hinkel, J., Bots, P. W. G., and Pahl-Wostl, C. 2013. Comparison of frameworks for analyzing social-ecological systems. *Ecol. Soc.* 18, 4, 26. doi: 10.5751/ES- 05551-180426
- Gómez, C. M., Delacámara, G., Arévalo-Torres, J., Barbière, J., Barbosa, A. L., Boteler, B., et al. 2016. The AQUACROSS innovative concept. deliverable 3.1 (European Union's Horizon 2020 Framework Programme for Research and Innovation grant agreement No. 642317). Available at: <https://aquacross.eu/sites/default/files/D3.1%20Innovative%20Concept.pdf>.
- Patricio, J., Elliot, M., Mazik, K., Padopoulou, K.N., Smith, C.J., 2016. DPSIR—Two Decades of Trying to Develop a Unifying Framework for Marine Environmental Management? *Frontiers in Marine Science*. 3. doi.org/10.3389/fmars.2016.00177
- Reckermann, M., Omstedt, A., Soomere, T., Aigars, J., Akhtar, N., Beldowska, M., et al. 2022. Human impacts and their interactions in the Baltic Sea region, earth syst. *Dynam* 13, 1–80. doi: 10.5194/esd-13-1-2022
- Sharpe, L. M., Hernandez, C. L., and Jackson, C. A. (2020). "Prioritizing stakeholders, beneficiaries, and environmental attributes: a tool for ecosystem-based management," in *Ecosystem-based management, ecosystem services and aquatic biodiversity. theory, tools, and applications*. Eds. T. O'Higgins, M. Lago and T. DeWitt (Springer), 189–211. Available at: https://link.springer.com/chapter/10.1007/978-3-030-45843-0_10.

