KLAIPĖDA UNIVERSITY

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ECOSYSTEM SERVICE ASSESSMENTS OF THE COASTAL ZONE: CASE STUDIES AND MANAGEMENT IMPLICATIONS

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PAKRANČIŲ ZONOS EKOSISTEMINIŲ PASLAUGŲ VERTINIMAS: KONKREČIŲ ATVEJŲ ANALIZĖ IR POVEIKIS VALDYMUI

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Abstract

Coastal ecosystems, crucially supporting biodiversity and human well-being, are increasingly threatened by anthropogenic pressures. This thesis applies the concept of ecosystem service assessments in coastal management, offering novel methodologies and insights to address these challenges. The study explores the ecological functions and socio-economic values of diverse coastal habitats in the Baltic Sea, focusing on estuaries, sandy beaches, coastal lagoons, and macrophyte beds. The main aim is to enhance assessment methods for coastal ecosystem services, supporting management and policy implementation. For this, the main management issues were addressed within four assessment methods that were applied in this thesis (i.e. MESAT) and further developed (i.e. future scenarios, management scenarios and spatial habitat assessments). The results validate the assessment methods, showing their effectiveness in evaluating coastal ecosystem services and guiding management decisions. The developed ES assessment approaches and methods offer a useful toolkit for coastal management, applied in urban planning, beach management, coastal protection, and habitat restoration. The applicability and transferability of the developed assessment approaches are tested internationally, demonstrating their potential for addressing coastal management challenges beyond the Baltic Sea region. Furthermore, a SWOT analysis identifies the strengths (interdisciplinary, holistic), weaknesses (limited reliability, oversimplification), opportunities (policy integration, international harmonization), and threats (loss of scientific interest, competing approaches) when applying the ES concept in coastal management, guiding future research directions and applications. By enhancing our understanding of coastal ecosystems and their services, this study aims to support sustainable management practices and promote the conservation of coastal biodiversity.

Key words

scenario assessment, policy implementation, stakeholder involvement, anthropogenic impacts, sustainable management

Reziumė

Pakrančių ekosistemos, svarbios biologinei įvairovei ir žmonių gerovei, patiria vis didesnį antropogeninį poveikį. Šioje disertacijoje remiantis ekosisteminių paslaugų vertinimo koncepcija pateikiama įžvalgų bei siūloma naujų metodų, skirtų spręsti pakrančių valdymo iššūkiams. Tyrime nagrinėjamos įvairių Baltijos jūros pakrančių buveinių ekologinės funkcijos ir jų socialinė bei ekonominė vertė, daugiausia dėmesio skiriant estuarijoms, smėlėtiems paplūdimiams, pakrančių lagūnoms ir makrofitų sąžalynams. Pagrindinis tikslas – patobulinti pakrančių ekosistemų paslaugų vertinimo metodus, padedančius įgyvendinti aplinkos apsaugos politiką. Šiuo tikslu pagrindiniai pakrančių valdymo klausimai buvo sprendžiami taikant šiuos vertinimo metodus, t. y. MESAT įrankį bei jo modifikacijas pritaikant ateities ekosistemų būklės scenarijų bei valdymo scenarijų vertinimui ir taikant erdvinį buveinių vertinimą. Gauti rezultatai patvirtino, kad vertinimo metodai yra pagrįsti ir efektyvūs vertinti pakrančių ekosistemų paslaugoms ir siūlyti valdymo sprendimams. Sukurtas priemonių rinkinys ekosisteminėms paslaugoms vertinti gali būti pritaikytas šiose pakrančių valdymo srityse: pakrančių miestams planuoti, paplūdimiams valdyti, pakrantėms apsaugoti ir buveinėms atkurti. Vertinimo metodų pritaikomumas išbandytas tarptautiniu mastu, pademonstruotas jų veiksmingumas sprendžiant pakrančių lagūnų valdymo problemas ne tik Baltijos jūros, bet ir kituose regionuose, pvz., Viduržemio jūros. Be to, atlikus SSGG analizę nustatytos stipriosios (tarpdisciplininis, holistinis požiūris), silpnosios (ribotas patikimumas, pernelyg didelis supaprastinimas) galimybės (politikos integravimas, tarptautinis suderinamumas) ir grėsmės (mokslinio susidomėjimo praradimas, konkuruojantys požiūriai bei įsitikinimai) taikant ekosisteminių paslaugų koncepciją pakrančių valdymo srityje, apibrėžtos tolimesnių mokslinių tyrimų kryptys ir koncepcijos taikymo galimybės. Šiuo tyrimu siekiama gilinti supratimą apie pakrančių ekosistemų teikiamas ekosistemines paslaugas, remti tvarų valdymą ir skatinti pakrančių biologinės įvairovės išsaugojimą.

Reikšminiai žodžiai

Scenarijų vertinimas, politikos įgyvendinimas, suinteresuotųjų šalių įtraukimas, antropogeninis poveikis, tvarus valdymas.

Contents

List of original publications

The material of this study was presented in five original publications, published in peer-reviewed scientific journals, referred to in the text by their Roman numbers:

I. Schernewski G, Paysen P, Robbe E, Inácio M, Schumacher J (2019). Ecosystem service assessments in water policy implementation: An analysis in urban and rural estuaries. Front. Mar. Sci. 6: 163, https://doi.org/10.3389/fmars.2019.00183

II. Robbe E, Woelfel J, Balčiūnas A, Schernewski G (2021). An impact assessment of beach wrack and litter on beach ecosystem services to support coastal management at the Baltic Sea. Environ. Manage. 68: 835-859, https://doi.org/10.1007/s00267-021-01533-3

III. Schernewski G, Voeckler LN, Lambrecht L, Robbe E, Schumacher J (2022). Building with nature - ecosystem service assessment of coastal-protection scenarios. Sustainability 14: 15737, https://doi.org/10.3390/su142315737

IV. Robbe E, Rogge L, Lesutienė J, Bučas M, Schernewski G (2024). Assessment of ecosystem services provided by macrophytes in Southern Baltic and Southern Mediterranean coastal lagoons. Environ. Manage, https://doi.org/10.1007/s00267-024-01955-9

V. Schernewski G, Robbe E (2023). Ecosystem Service Assessment in European Coastal and Marine Policies. In: H. Schubert, F. Müller (eds.): Southern Baltic Coastal Systems Analysis. Ecological Studies 246, 347-366, https://doi.org/10.1007/978-3-031-13682-5

Author's contributions

I. E. Robbe carried out the assessments of Warnow Estuary, analyzed the data, provided figures and text segments for the manuscript and commented on it.

II. E. Robbe developed the assessment approaches, carried out the assessments, analyzed and visualized the data and wrote the manuscript.

III. E. Robbe provided the assessment tool, supported in scenario development and assessments, provided data visualizations and commented on the manuscript.

IV. E. Robbe developed the assessment approaches, carried out the assessments, analyzed and visualized the data and wrote the manuscript.

V. E. Robbe carried out the literature research and shared the writing of the manuscript with the other author.

Additional publications by the author of the thesis

I. Robbe E, Schernewski G, Inácio M (2018). Assessment of Coastal and Marine Ecosystem Services and its importance within Environmental Policy Implementation. In: Marine Ecosystem Services. Ed. by L. Berger. Bonn: Bundesamt für Naturschutz (BfN-Skripten 521), 978-3-89624-258-7, https://doi.org/10.19217/skr521

II. Piehl S, Hauk R, Robbe E, Richter B, Kachholz F, Schilling J, Lenz R, Fischer D, Fischer F, Labrenz M, Schernewski G (2021). Combined approaches to predict microplastic emissions within an urbanized estuary (Warnow, Southwestern Baltic Sea). Front. Environ. Sci. 9: 616765, https://doi.org/10.3389/fenvs.2021.616765

III. Schernewski G, Radtke H, Robbe E, Haseler M, Hauk R, Meyer L, Piehl S, Riedel J, Labrenz M (2021). Emission, transport, and deposition of visible plastics in an estuary and the Baltic Sea – a monitoring and modeling approach. Environ. Manage. 68: 860-881, https://doi.org/10.1007/s00267-021-01534-2

IV. Baccar Chaabane A, Robbe E, Schernewski G, Schubert H (2022). Decomposition behavior of biodegradable and single-use tableware items in the Warnow estuary (Baltic Sea). Sustainability 14: 2544, https://doi.org/10.3390/su14052544

V. Haseler M, Ben Abdallah L, El Fels L, El Hayany B, Hassan G, Escobar-Sánchez G, Robbe E, von Thenen M, Schernewski G, Nassour A (submitted). Assessment of Beach Litter Pollution in Egypt, Tunisia, and Morocco: A Comprehensive Study of Macro and Meso-litter on Mediterranean Beaches. Environmental Monitoring and Assessment

Abbreviations

Abbreviation	Explanation
BW	Beach wrack
ES	Ecosystem Services
GES	Good Ecological Status
HD	Habitats Directive
IF	Impact Factor
IS	Impact Score
MESAT	Marine Ecosystem Services Assessment Tool
RI	Relative Importance
SD	Standard Deviation
WFD	Water Framework Directive

1

Introduction

Coastal ecosystems, as the transition zone between land and sea, are highly dynamic and biologically productive. They include a variety of habitats ranging from estuaries, coastal lagoons, salt meadows, coastal wetlands, sandy or stony beaches to seagrass and macrophyte beds. They provide important biological ecosystem structures, functions and processes, for example, the provision of nursery grounds for fish and birds (Kraufvelin et al. 2018), cycling and storage of nutrients (Herbert 1999), carbon sequestration and storage (Beaumont et al. 2014), the protection of the shorelines from erosion (Spalding et al. 2014), and containing and preserving the high diversity gene pool (Burke et al. 2001).

As coastal areas constitute a hub of human activities, coastal ecosystems are under severe pressure. Especially in the last decades, they face ongoing and rapid degradation due to intensive human use. Ongoing population growth sums up to 9.7 billion in 2050 (UN DESA 2021) fostered in particular by urbanization processes in coastal areas. As a consequence, pressures due to human activities increase dramatically. Main pressures include higher rates of waste production (i.e. coastal pollution and marine litter) especially from increasing tourism activities (UNEP 2021). Additionally, agricultural loads during the last decades caused nutrient enrichment and eutrophication of coastal ecosystems, particularly lagoons (Bartoli et al. 2018, Žilius et al. 2018, Friedland et al. 2019). Besides, coastal ecosystems are highly affected by consequences of climate change as coastal hazards including flooding and sea level rise (Neumann et al. 2015), changes of riverine discharges into the lagoons, associated hydrodynamics (Idzelytė et al. 2023) and increased nutrient loadings from the watersheds (Čerkasova et al. 2019). These pressures cause the urgent need for management actions and implementing policies in order to safeguard healthy coastal ecosystems supporting its sustainable use by humans.

Several environmental policies aiming to combat ecosystem degradation are in place. Important EU water protection policies include the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) both aiming at good ecological or environmental states of all surface, transitional, coastal and marine waters. Another major EU policy for nature conservation is the Biodiversity Strategy 2030 encompassing as central parts the Habitats Directive (HD), the Birds Directive and the Natura 2000 ecological network of protected areas. One of the main objectives of the strategy is to maintain and restore ecosystems and their services (target 2 from 6). Main challenge is the lack of implementation taking place at insufficient rate.

The ecosystem services concept, formerly aroused out of the need for nature conservation already in the 1960 from ecological economics (Costanza et al. 1998), can serve as a suitable tool for supporting policy implementation. As an opportunity to support implementation processes, ecosystem services became partly embedded in recent EU policies (Bouwma et al. 2018). Ecosystem services are defined as direct or indirect benefits to humans (Millennium Ecosystem Assessment 2005). While several classification systems exist, this study is based on the Common International Classification of Ecosystem Services (CICES) according to Haines-Young & Potschin-Young (2018), who differentiate between three main categories: provisioning services, regulating and maintenance services, and cultural services. Coastal ecosystems, for example, provide habitat for fish, which can be used for human nutrition (Burke et al. 2001). Seagrass or emergent macrophyte beds can serve as wave attenuators, and thus bear coastal protection functions (Spalding et al. 2014). Especially with regard to tourism, coastal ecosystems have an important socio-economic value, indicated by high tourism numbers in coastal areas (Eurostat 2023). Ecosystem service assessments can measure and visualize these benefits of ecosystems to humans.

To assess these services, a vast pool of ES assessment methods exist being compiled and described in Harrison et al. (2018) who also provide a decision-tree for method selection. Most ES research focuses on terrestrial ecosystems, as assessing marine and coastal ES faces some specificities and difficulties at the land-sea interface (Liquete et al. 2013). However, in the last decade many studies also focused on coastal and marine ecosystems. In the Baltic Sea, Kuhn et al. (2021) identified main knowledge gaps especially within the marine policy context and a lack of harmonized ES approaches and definitions. While Heckwolf et al. (2021) provide a systematic review on Baltic coastal ES, Schumacher et al. (2021) provide a spatial ES approach across the land-sea interface. Inácio et al. (2018) developed the Marine Ecosystem Service Assessment Tool (MESAT) tailor-made for assessing relative changes in the provision of ES of coastal waters. Although assessment indicators are provided, for example by von Thenen et al. (2020) providing a first indicator-pool for coastal and marine ES assessments or by Liquete et al. (2013), their application for assessing coastal and marine ecosystem services remain a challenge especially within concrete management and policy implementation cases. This challenge is further complicated when taking into account specific local socio-economic contexts, for example rural development, urban planning, sustainable tourism, nature conservation, coastal protection and various other priority areas.

The central hypothesis of this thesis is that effective operationalization of ecosystem service assessments tailored to specific management concerns, such as beach cleaning, coastal protection and habitat conservation, supports the implementation of coastal management strategies and policies. Thus, this thesis addresses key challenges in integrating ecosystem services into coastal management and policy implementation, including the high time demands of assessments, the absence of end-user-oriented approaches, and the lack of harmonized assessment methods. By testing this hypothesis deductively through a series of case studies, this thesis aims to derive management implications to guide conservation and management efforts in the coastal zone.

1.1. Aim and objectives

The aim of this thesis is to methodologically improve and develop assessment methods for coastal ecosystem services applied to concrete case studies across various management issues in order to demonstrate management implications considering the value of nature to human well-being.

The specific objectives are:

1. to apply the semi-quantitative MESAT approach to evaluate relative changes in ES provision by comparing historic and present states of a heavily modified coastal water body to show benefits of reaching water policy targets, specifically achieving formerly good ecological states (GES) according to the WFD;
2. to further develop a qualitative ES approach through the future scenario assessment, comparing present states with politically desired future states of coastal water bodies to show stakeholders´ perception and acceptance of implementing WFD measures to achieve GES and urban planning measures;
3. to integrate quantitative and qualitative ES approaches into the management scenario assessment, comparing present states (or baseline) with potential management scenarios of concrete measures implemented at defined study

sites allowing for direct comparison to support decision-making for a variety of coastal management measures;

4. to further develop a spatial ES approach, incorporating the habitat assessment, mapping and extrapolation, that allows to assess and compare the ES potential of different macrophyte habitats in order to support nature policies;
5. to test the applicability and transferability of developed assessment methods and approaches across various international coastal management issues and zones, specifically in the Baltic and Mediterranean Seas.

1.2. Novelty of the study

This study presents a holistic overview of ecosystem service inventories of estuaries, sandy beaches, coastal lagoons and macrophytes in the Baltic Sea and the Mediterranean Sea.

In order to overcome the experienced shortcomings of the Marine Ecosystem Service Assessment Tool (MESAT) (Inácio et al. 2018), the developed future scenario assessment shifted from the indicator-based comparison of historic states to an expert-based scenario assessment of hypothetical future states (Paper I). Therein, real urban planning documents were integrated.

In the next step, the management scenario assessment evaluated the impact of concrete management measures on coastal ecosystem services, such as beach cleanings (Paper II) or coastal protection systems (Paper III). Thus, the management scenario assessment facilitates the evaluation and comparison of management options (scenarios) and decision making for implementation. The scenario development is a major new component that allows for constructing scenarios based on real management practices, enabling the support of decision making and the drawing of management recommendations.

One main innovative aspect of the methodological development is the utilization of online and/or hybrid methods. Due to COVID-19, the assessment approaches needed to be further developed and adapted to facilitate participatory stakeholder involvement via digital and online formats, such as remote individual assessments, online discussions, and online survey. An easily adaptable tool for online stakeholder involvement is provided with the scenario management assessment (Paper II), while the spatial habitat assessment specifically supports online expert involvement (Paper IV).

Another major innovation of the scenario assessment approach is the introduction of the "Relative Importance" score, which ranks ecosystem services according to their local importance based on the stakeholder perceptions. This score is crucial for drawing management implications.

Further methodological development resulted in the spatial habitat assessment on the ecosystem service potential of macrophytes, employing a comparative approach instead of absolute values. This methodology integrates results from both the indicator-based approach and scenario management assessment. Utilizing existing indicators initially selected for coastal and marine ecosystem services (von Thenen et al. 2020), this assessment further refined, adapted and differentiated them, incorporating macrophyte expert input such as indicator ranking (Paper IV). The result is a comprehensive list of ecosystem services and corresponding assessment indicators tailored specifically for macrophytes.

Another novel aspect of this study is the tested applicability and transferability of the management scenario assessment approach to other coastal areas worldwide, here for North African Bizerte Lagoon (Tunisia) (Paper IV) and sandy beaches in Egypt, Morocco and Tunisia (submitted manuscript).

1.3. Scientific and applied significance of the results

The present research explores the effects of changes in ecosystem states on their provision of ecosystem services comparing historic (1880 and 1960), present (2018) and future states (2040) of water bodies. Results show several opportunities for application within WFD implementation, for example by comparing ES provided by different ecological states showing benefits of improved water quality, and within urban planning by evaluating different urban development measures regarding the highest well-being (Paper I).

To find solutions for human-made problems, for example plastic pollution and marine litter as identified in the additional Papers II to V, an anthropocentric approach as the ecosystem services seems beneficial. ES assessments for coastal and marine ecosystems often too broad and not suitable for concrete measure implementation, which is why in this study ES assessment approaches are tested, applied and further developed for concrete case studies.

This study fills a gap between ecosystem service assessments existing in scientific literature and their practical applications in coastal management and policy implementation in the Baltic Sea. An inventory of ecosystem services at Baltic sandy beaches is provided including an impact assessment of beach litter and beach wrack on its provision, which is the base for concrete recommendation for a sustainable beach management, such as cleaning methods (Paper II).

Another important coastal management issue, where this study makes an original contribution to, is the coastal protection system. The approach was tested and found to be a suitable method for informally evaluating coastal management measures comparing conventional and new, innovate, building-with-nature scenarios. The potential for practical application of the assessment approach for complementing formal planning and implementation processes was identified (Paper III).

The study offers some important insights into the perceived benefits provided by macrophyte habitats showing trade-offs and synergies of their ecosystem services. This research contributes to a deeper understanding of the value of macrophyte habitats from human perspective to protect and conserve them. The findings should support a sustainable management of macrophyte-dominated shallow coastal areas. (Paper IV)

The tool could be applied for education and training purposes. For example, it was used by several students (>10) for conducting their bachelor and master theses, partly published in Schernewski et al. (2023), von Thenen et al. (2023). Besides, the tool was successfully used within teaching (i.e. master courses on "Coastal and marine management" and "Coastal Engineering"), where students assessed the ecosystem services provided by management scenarios that were developed by their own.

Both the management scenario approach and the spatial habitat approach are easily adaptable to other coastal areas internationally as they are based on international scientific classifications (i.e. CICES, EUNIS), monitoring schemes (i.e. OSPAR) and/or legislations (i.e. WFD, HD). Scenario results are partly even transferable, when characteristics of the assessed ecosystem are similar, e.g. similar coastal lagoons or sandy beaches. The management scenarios for sandy beaches were transferred to Southern Mediterranean beaches in North-Africa (i.e. Egypt, Tunisia and Morocco) and successfully applied with a student group and stakeholders (unpublished data).

1.4. Scientific approval

Results of this study were presented in 5 international and 3 national conferences and seminars:

1. EU CONEXUS – Smart urban coastal sustainability days 2021, La Rochelle, France, April 2021
2. ESP Europe Conference 2021, Tartu, Estonia, June 2021
3. Littoral Conference, Costa da Caparica, Portugal, September 2022
4. Alternet – 16th Alternet Summer School: Biodiversity and societal transformation: perspectives on science and policy, Perresque, France, September 2022
5. ESP Europe Conference in Heraklion, Greece, October 2022
6. End-user workshop Ecocarpet, MRI, Klaipeda, Lithuania, 4th of October 2022
7. MRI Thursday seminars, Klaipeda, Lithuania, 2021 and 2022
8. ZUG Networking Event Marine Litter, Berlin, Germany, 16th of October 2023

2

Materials and methods

In order to apply and further develop the Marine Ecosystem Service Assessment Tool (MESAT; Inácio et al. 2018), the methodological development involved the following four steps (Figure 1). The following main relevant issues of Baltic coastal ecosystems within coastal management and policy implementation were addressed: 1) poor water quality, or poor ecological states, regarding the implementation of EU water policies such as the WFD, 2) increasing litter pollution and beach wrack accumulations causing high cleaning costs for municipalities, 3) coastal erosion and the need for coastal protection, and 4) decreasing habitat quality and biodiversity, and the need for conservation, for example of macrophytes, within the implementation of EU nature polices such as HD.

First, the semi-quantitative approach of MESAT was applied to the topic of EU water policy implementation. Therein, the relative changes in ES provision were assessed by comparing historic (ecosystem in GES) and present (ecosystem not in GES) states in order to show benefits of implementing policy targets, here, achieving formerly good ecological states.

Second, the focus was shifted to a qualitative approach comparing present states to hypothetical future states, here based on the assumption that the GES according to the WFD has been achieved and urban planning measures have been implemented.

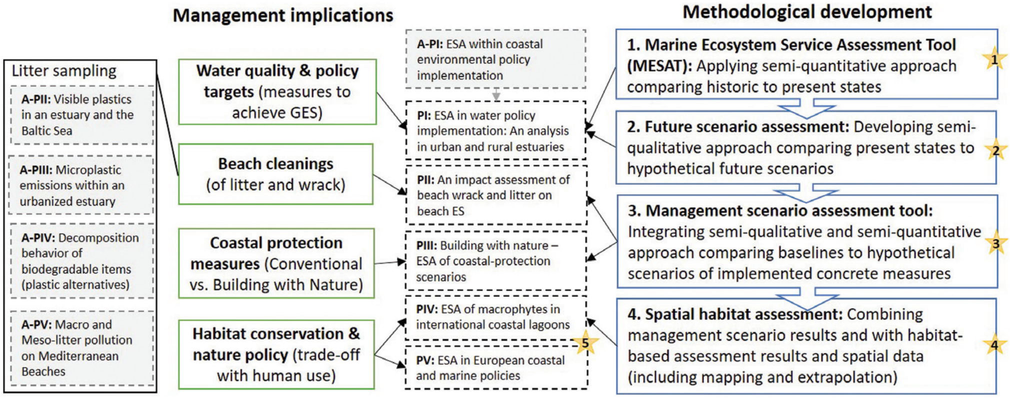

Figure 1. Overview of study design including research objectives (indicated by stars) and respective publications (P) and additional papers (A-P) of this thesis.

Third, the management scenario assessment tool integrates a quantitative and qualitative approach enabling direct comparisons to support the implementation of concrete management measures. For this, a stakeholder-based qualitative approach was developed and applied to assess the relative changes in ES provision by comparing present states (baseline) to hypothetical future scenarios which represent specific management measures such as beach cleanings (Paper II), coastal protection systems (Paper III), and macrophyte recovery (Paper IV).

Forth, the spatial scale of the assessment approach was expanded into a quantitative and qualitative approach tested by focusing on macrophyte habitats. The relative changes in ES potential were assessed by comparing different spatial units (i.e. habitat-based assessment) and generating scenario maps.

2.1. Study area

As a semi-enclosed inland sea, the Baltic Sea is located in Northern Europe surrounded by nine countries: Denmark, Germany, Poland, Lithuania, Latvia, Estonia, Russia, Finland and Sweden. The Baltic Sea is characterized by strong gradients from North to South and West to East in terms of temperature, salinity and depths. On average, the low temperature and salinity lead to low biodiversity and limited productivity. The surface area covers 420,00 km^2 with a relatively huge catchment area of 1,729,500 km^2 inhabited by approximately 85 million people (Schiewer 2008). Among the largest brackish seas worldwide, the Baltic Sea is intensively used by humans and faces high pressures. For example, nutrient inputs by the seven biggest rivers (Daugava, Gota, Nemunas, Neva, Oder, Tornio and Vistula) draining 50% of the catchment area are a major cause for eutrophication (Raudsepp et al. 2019). Other main pressures typically occurring in the Baltic Sea range from non-indigenous species, underwater sound, fisheries, shipping and habitat loss. Regarding marine litter, the state of pollution of the Baltic Sea is with 50 to 300 items per 100 m relatively low compared to other seas (Helsinki Commission 2018). Furthermore, coastal tourism in the Baltic Sea region shows increasing trends since a decade. For example, an approximately increase of 5% yearly was recorded between 2013 and 2019 with its peak in 2019 with 200 million overnight stays (Eurostat 2023). Due to COVID-19 tourist numbers decreased significantly in the years 2020 and 2021, but are recovering fast. To combat these pressures, 13.8% of the Baltic Sea (57,105 km^2) are already protected under the Natura 2000 network covering 32% of the nearshore EU zone of the Baltic Sea (European Environment Agency 2015).

The main study area of this thesis are shallow coastal areas of the Baltic Sea with special focus on German and Lithuanian estuaries, beaches, shorelines and lagoons and their management issues (Figure 2). Due to its characteristics as an inland sea and limited water exchange with the North Sea, the Baltic Sea is sensitive to eutrophication. According to the WFD, the coastal waters of the Baltic Sea are predominantly in an unsatisfactory state, as one third was rated each as “moderate”, “poor” or “bad”, which is also true specifically for approximately 50% of coastal waters regarding their status of macrophytes (Umweltbundesamt 2017). However, in the Curonian lagoon, for example, although historical data show a decline of submerged macrophytes due to eutrophication, more recent data show an increase of charophytes again (Sinkevičienė et al. 2017). Contrarily, emergent macrophytes such as reed show tendencies to grow in monocultures and hamper biodiversity (Sweers et al. 2013). Besides, municipalities and resorts face a significant challenge with seasonal beach cleanings, as the accumulation of beach wrack and litter poses nuisances for tourists (Corraini et al. 2018). For example, Chubarenko et al. (2021) reported that a small municipality in Germany (Island of Poel) with approximately 2,500 inhabitants managed on average 3,000 m3 of beach wrack (i.e. mainly seagrass and macroalgae) annually, imposing costs of 200,000 € per year. Moreover, in the southern Baltic Sea region, the absolute sea-level rise has recently reached approximately 2 mm/year. Due to its glacial sediments, the southern Baltic Sea coasts experience significant erosion, leading to an average coastal retreat rate exceeding 1 m/year (Weisse et al. 2021). Up to 10% of the German Baltic coastline lacks already today sufficient protection that would require investment costs from 1.7 to 4.8 billion € (van der Pol et al. 2021).

Additionally, the study area encompasses case studies conducted along the North African coast of the Mediterranean Sea. In contrast to the Baltic Sea, the semi-enclosed Mediterranean Sea, surrounded by the three continents of Europe, Africa and Asia, is characterized by high temperatures (Mediterranean climate) and high salinity (negative water budget). Despite its rich biodiversity, the Mediterranean Sea faces

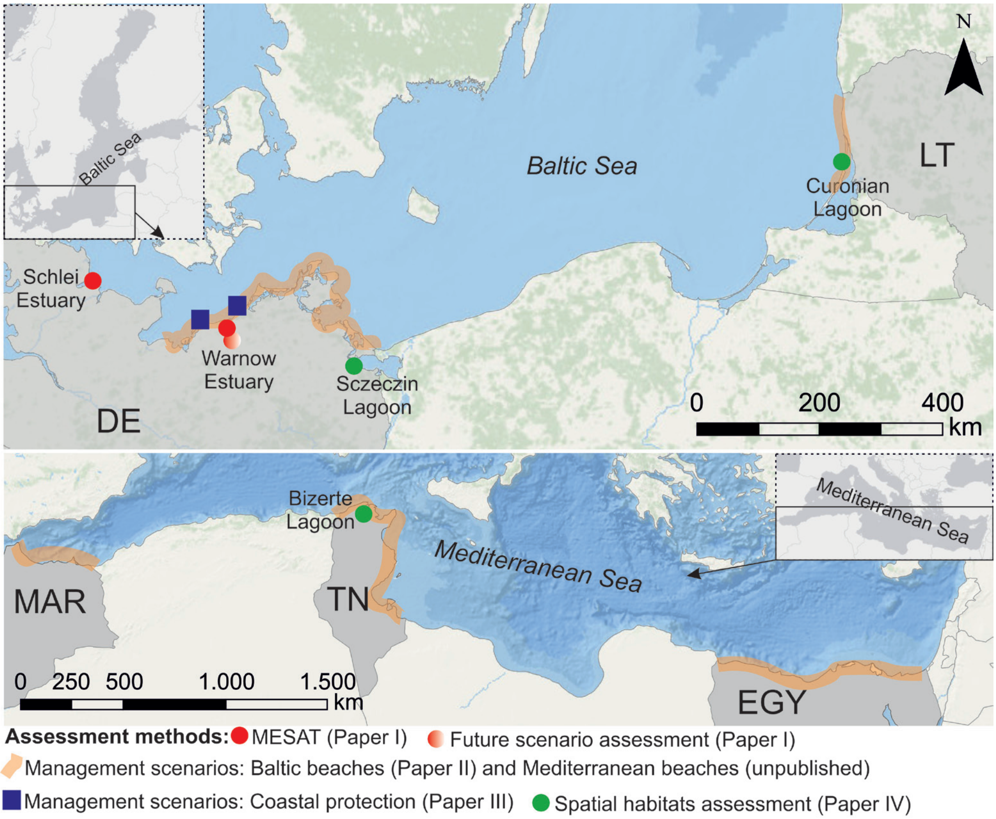

Figure 2. Map of the Baltic Sea and the Mediterranean Sea as an overview to show case studies ranging from estuaries, beaches and shores, to coastal lagoons and applied methods.

numerous environmental challenges, including habitat degradation, overfishing, pollution, and invasive species. Besides, the Mediterranean Sea region attracts millions of tourists annually, making it economically significant for local communities. The primary focus of the study area is the Bizerte lagoon, which has been significantly altered and extensively utilized by humans since the 1950s, primarily for fishing and shellfish farming (Khammassi et al. 2019). The lagoon is highly industrialized, with around 130 factories nearby, resulting in pollution from both urban and industrial sources (El Mahrad et al. 2020). Despite being considered to have a satisfactory ecological status 15 years ago (Afli et al. 2008), the lagoon now shows signs of eutrophication due to high nutrient levels (Zaabar et al. 2017). The lagoon's biodiversity is limited compared to other Mediterranean waters, mainly due to its fluctuating environmental conditions being also connected to Ichkeul Lake, a National Park and UNESCO World Heritage Site.

The main management issues of the Baltic Sea and Mediterranean Sea were addressed within the four assessment methods that were applied in this thesis (i.e. MESAT) and further developed (i.e. future scenarios, management scenarios and spatial habitat assessments). In total twelve study sites in the Baltic Sea and the Mediterranean Sea were investigated (see Figure 2) and eight assessments carried out (see Table 1). In the respective publications, detailed descriptions of the study sites are provided.

Table 1. List of all developed and applied assessment methods (DE = Germany, LT = Lithuania, TN = Tunisia)

Method	Topic	Study area	Assessors	Assessment format	Assessment units [S=Scenario; 0=Baseline]
MESAT *(Paper I)*	Good ecological status according to WFD	Warnow and Schlei Estuary (DE)	Self-assessor	Indicator-based	Initial state 1: Very good ecological state (1880) Initial state 2: Good ecological state (1960) Current state: Poor ecological state (2018)
Future scenario *(Paper I)*	Good ecological status according to WFD (incl. urban planning)	Warnow Estuary (DE)	Experts (19)	In-person workshops	S.0. Current state (2018) S.1.a. Future state of Northern industrial part (2040) S.1.b. Future state of Southern urban part (2040)
Management scenario *(Paper II)*	Beach wrack and litter accumulations	Baltic sandy beaches (DE, LT)	Stakeholders (39)	Online workshops and surveys	S.0. Clean(ed): no litter, no BW S.1. Not clean(ed): with litter S.2. Cleaned: no litter but BW S.3. Not clean(ed): with litter and BW
			Self-assessor	Literature-based	
Management scenario *(Paper III)*	Conventional coastal protection measures	Dierhagen (DE)	Experts (17)	In-person and online workshops	S.0. Natural beach – No groins S.1. Protected beach – Native wood groins S.2. Protected beach – Infested groins by shipworm S.3. Protected beach – Tropical wood groins
			Self-assessor	Literature-based	

Method	Topic	Study area	Assessors	Assessment format	Assessment units [S=Scenario; 0=Baseline]
Management scenario *(Paper III)*	"Building with nature" coastal protection measures	Heiligendamm (DE)	Experts (27)	In-person and online workshops	S.0. Current coastal protection state of groin system S.1. Sand nourishment for broad beach S.2. Mussel farm and pier S.3. Submerged macrophytes (mainly seagrass)
			Self-assessor	Literature-based	
Management scenario *(Paper IV)*	Macrophytes and ecological status of coastal lagoons	Szczecin Lagoon (DE), Curonian Lagoon (LT)	Stakeholders (12), Experts (12), Graduate students (5)	In-person and online workshops	S.0.a. Poor ecological state: no macrophyte coverage S.0.b. Plus fishing traps and groins S.1.a. Moderate ecological state: moderate macrophyte coverage S.1.b. Plus fishing traps S.2. Good ecological state: high macrophyte coverage
		Both + Bizerte Lagoon (TN)	Self-assessor	Literature-based	
Spatial habitat assessment *(Paper IV)*	ES potential of macrophytes	Shallow coastal areas (DE, LT)	Experts (11)	Remote, individual	1. Seagrass beds 2. Seaweed communities 3. Charophytes 4. Pondweed 5. Reed and tall forb communities 6. Salt meadows (dominated by *Salicornia spp.*) 7. Salt meadows (dominated by *Aster tripolium*)
			Self-assessor	Indicator-based	
Mapping and extrapolation *(Paper IV)*	Macrophytes and ecological status of coastal lagoons	Szczecin Lagoon (DE)	Self-assessor	Spatially explicit data	S.0. Extrapolated current macrophyte vegetation S.1. Current spatial use mainly recreation on water and fisheries S.2. Potential spatial use under nature protection and GES
				Management scenario results	

First, this study assessed the ecosystem services provided by estuaries, namely by the urban Warnow Estuary compared to the rural Schlei Estuary, both at the German Baltic Sea coast (Paper I), focusing thematically on urban planning and the implementation of WFD measures. Here, MESAT was applied and complemented with a scenario-based ES assessment for a hypothetical "Warnow 2040" scenario. Moving further to the sea, the second focus area is the land-sea interface, thus beaches and the outer coast. In Paper II, the ecosystem services of Baltic sandy beaches were assessed, mainly in Germany and Lithuania, comparing different management measures by the scenario assessment. Furthermore, also ecosystem services provided at artificially protected coasts under different protection scenarios were assessed and compared (Paper III). Third, another focus area lies on the inner coastal waters and lagoons. In Paper IV, ES of macrophyte-dominated shallow areas, especially lagoons, were assessed, exemplarily the German part of Szczecin Lagoon and Lithuanian part of Curonian Lagoon. Macrophyte management scenarios were assessed as well as habitat-based ES potential and assessment indicators identified. Finally, to test transferability and international applicability of the scenario-based ES assessment approach, the study investigated also ES provided by macrophytes in Bizerte Lagoon in Tunisia (Southern Mediterranean) (Paper IV).

2.2. Definition of used ecosystem services terminology

As ES research evolved relatively fast over the last decades, one of its main challenges is finding a common language within its diverse scientific landscape (Villamagna et al. 2013). In literature different ES terminology can be found varying between provision and supply (Maes et al. 2012), potential and flow (Burkhard et al. 2014), supply-demand budget (Burkhard et al. 2012) and capacity (Villamagna et al. 2013). Besides, definitions of these terms also vary across authors. In this thesis the terms ES provision, flow and potential are used and for better understanding described here in detail.

Ecosystem service flow: refers to the real supply or actual use, as also defined by Villamagna et al. (2013) as the production of a service received by humans. Bagstadt et al. (2013) defines the flow as “the transmission of a service from ecosystems to people” also pointing out the ambiguous definitions in literature.

Ecosystem service potential: can be defined as an ecosystem’s potential or capacity to provide services based on socio-ecological system properties and functions (Balzan et al. 2018). Other authors, for example, refer to it as capacity (Villamagna et al. 2013), the “hypothetical yield” of ecosystem services (Burkhard et al. 2012), potential supply and/or stocks (Burkhard et al. 2014) or ecosystem potential (Depellegrin et al. 2016). In this thesis the definition was expanded to be ecologically sustainable, thus the potential includes a balanced ecosystem state without causing a regime shift.

Ecosystem service provision: is the most general term, describing ecosystem services per se and can be interpreted as both potential or flow (Beier et al. 2008).

2.3. Application of Marine Ecosystem Service Assessment Tool

In this study the Marine Ecosystem Service Assessment Tool (MESAT) developed by Inácio et al. (2018, 2019) was applied and further developed. MESAT is a spreadsheet-based tailor-made tool for assessing relative changes in the provision of ES of specific transitional and coastal water bodies between two different points in time. The initial or historic status of a water body (initially assumed to be at least in a "good ecological state" according to the WFD) is compared to the present status (mostly describing the "poor ecological state"), aiming to integrate ES assessments into management strategies of EU policies (i.e. WFD). Assumptions on GES were based on definitions and classification of the WFD, which also aimed to enable the approach to be suitable and applicable within policy implementation. The tool assesses 31 ES by a set of 54 indicators mainly based on CICES (Haines-Young and Potschin-Young 2018). Initially developed as a (semi-) quantitative approach, main sources of data for the indicator-based assessment are preferably observational and crisp data, then literature and modelling data and if needed expert judgements. The scoring scheme for assessing the relative change in ES provision is based on a logarithmic scale including 11 classes of change (Table 2). Besides, MESAT can also be used as a qualitative approach using stakeholders and/or experts using the same scoring scheme.

Table 2. Scoring scheme for assessing the relative change in ES provision between two points in time (initial and present status) originally applied by quantitative indicator-based approach.

-5	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**
very high decrease	high decrease	moderate decrease	low decrease	very low decrease	**no change**	very low increase	low increase	moderate increase	high increase	very high increase
<1/4.1	*1/2.5 – 1/4.1*	*1/1.7 – 1/2.5*	*1/1.3 – 1/1.7*	*1/1.1 – 1/1.3*		*1.1 – 1.3*	*1.3 – 1.7*	*1.7 – 2.5*	*2.5 – 4.1*	*>4.1*

In this study, the original indicator-based MESAT approach was applied to the Warnow Estuary and the Schlei Estuary (Paper I) comparing their historic states of 1880 and 1960 (reference states of high and good ecological states according to the WFD) to the current state.

2.4. Assessment of future scenarios of ecological states

Built upon the indicator-based MESAT approach, a simplified scenario-based approach was further developed targeting future ecological states (i.e. improved water quality) using stakeholder perceptions and/or expert knowledge. This future scenario assessment compares the current state of a water body to a hypothetical future state (i.e. ecological states according to WFD).

One scenario was developed subdivided into Northern and Southern part of the Warnow Estuary (Figure 3) in order to assess urban planning measures and water policy implementation (i.e. GES of WFD) (Paper I). Additional to the baseline scenario, representing the current poor state of the Warnow Estuary in 2018, one scenario of the future hypothetical state in 2040 was developed. Therein, real urban development plans were considered and a successful implementation of the WFD was assumed (i.e. having achieved the GES). The Warnow Estuary was subdivided into the Northern industrial part dominated by the shipping channel and harbor area and the urban Southern part with recreational focus. Experts used the MESAT scoring scheme (Table 2) for assessing the relative change in ES provision, using same list of ES as used in MESAT approach.

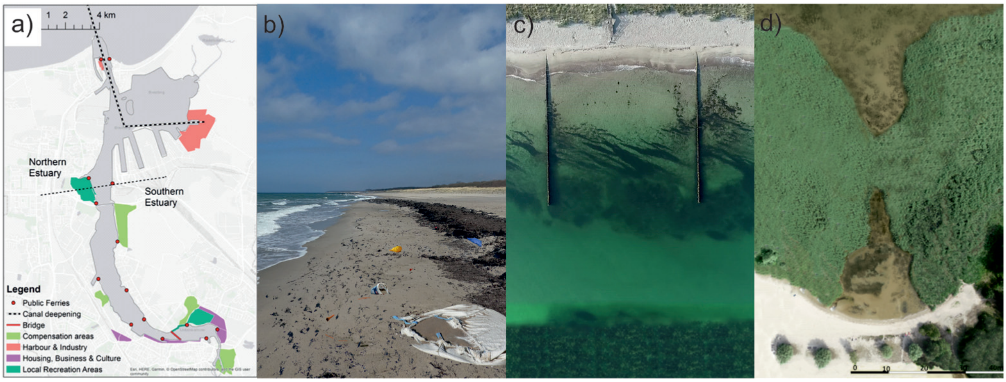

Figure 3. Examples for visualization of future scenario assessment, a) urban planning of "Warnow 2040" (Paper I), and management scenarios assessments, thus b) beach management (Paper II), c) coastal protection (Paper III), and d) macrophyte management (Paper IV).

2.5. Assessment of management scenarios of concrete measures

Based on the future scenario assessment and its shortcomings, the management scenario assessment was developed enabling comparisons between present states (baseline scenario) to hypothetical management scenarios representing concrete management measures. The management scenarios assessment follows a three-steps process: 1) scenario development, 2) selection of relevant ecosystem services, and 3) participatory and/ or literature-based ecosystem service assessment.

Step 1: Scenario development. The most important step prior to the ecosystem service assessment is the scenario development in order to ensure data quality (i.e. avoid inconsistencies) and applicability of results. The scenario development follows the main steps of the Formative Scenario Analysis according to Scholz and Tietje (2002). Therein, scenarios are defined as hypothetical future states of a system which support the understanding of their system dynamics. In this study, the baseline scenario usually constitutes of the current situation or state of the study area that is targeted to be managed. At least one hypothetical scenario is needed to be compared to the baseline scenario. The number of scenarios varies between two (e.g. "Warnow 2040") to three scenarios (e.g. coastal protection measures). A set of assumptions and system variables need to be well-defined that are crucial to the ecosystem state and its change in order to construct potential developments (Scholz and Tietje 2002), thus management scenarios (i.e. measures). To guarantee consistency of scenarios, the most decisive factors within the system are identified and tested for causal relations and dependencies. As the developed scenarios are the object of the ES assessments, concise scenario descriptions and visualizations (see Figure 3) are essential including the concrete purpose of the assessment. Besides, concrete times and explicit spatial areas need to be defined. As there is interpretation bias when working with different people, this supports a common understanding and can avoid misunderstandings.

In total four management scenario assessments were developed and carried out (listed in Table 1), that cover the main management issues being identified: beach management, coastal protection (two assessments) and habitat conservation. These direct comparisons allow for supporting decision-making and policy implementation, here exemplarily within beach and coastal protection management. Main aims were to develop an end-user friendly tool, looking into hypothetical future states, that support stakeholder involvement and give concrete management recommendations.

First, having the aim of assessing the impact of marine litter and beach wrack on Baltic sandy beach ecosystem services, four beach scenarios were developed representative for common management measures in the Baltic Sea (Paper II). The baseline scenario shows a common Baltic sandy beach without accumulations of beach wrack nor marine litter either naturally or cleaned for tourism purposes (i.e. most common management practice). The Scenarios 1 to 3 represent different states of beach wrack and litter accumulations (excluding micro litter). Second, with the aim of evaluating different coastal protection systems (after final construction), four scenarios were developed representing conventional hard structures (i.e. groins). Third, three scenarios on innovative nature-based solutions (i.e. seagrass meadows, mussel farm, sand nourishment) as coastal protection measures were evaluated and compared. More details are described in Paper III. Forth, the aim of Paper IV was to assess the impact of a prospective good ecological state (GES) of coastal lagoons on service provision as perceived by stakeholders to visualize the impact of improved water quality and macrophyte habitats. The scenarios showing a coastal transect typical for the Szczecin and/or Curonian Lagoon represent different ecological states according to the WFD (poor, moderate, good) and different management measures, i.e. fisheries and coastal protection.

Step 2: Selection of ecosystem services. Depending on the subject of assessment, for example the Warnow Estuary or a sandy beach, a set of relevant ecosystem services provided by the respective study area were pre-selected by experts. Ecosystem services were adapted from the widely accepted and used classification CICES (V.5.1) according to Haines-Young and Potschin-Young (2018). Explicit selection process and comprehensive lists of all ecosystem services selected are provided in the respective publications.

Step 3: Scenario assessment. The developed management scenarios were assessed using stakeholders´ perception and/or expert knowledge. Prior to the application of the ES assessment, respective assessment guidelines including descriptions on scenarios and services for experts and/or stakeholders were developed. First, participants were asked to assess the Relative Importance (RI) of each service. It indicates how important each ES is perceived relatively to the overall ES provision of the given transect or study site. The RI scoring scheme ranges exponentially from [0] to [8] (Table 3).

Table 3. Scoring scheme for assessing the Relative Importance (RI) for the ecosystem services

0	1	2	4	8
Not relevant	low importance	moderate importance	high importance	very high importance

Afterwards, participants assessed the impact score (IS; or relative change), in Paper II also referred to as impact factor (IF) for each scenario compared to the baseline scenario. The impact values are defined by stakeholders´ perceptions and knowledge indicating how the ES are changed or impacted by the scenarios, thus different states. The scoring scheme ranges from high negative [-3] to high positive impacts [+3] (Table 4). In some assessments (Paper III and IV), another class was added for very high positive or negative impacts [+/-4]. Different assessment formats were tested including in-person workshops, individually or in groups (Paper I), online workshops and hybrid formats using a spreadsheet tool and discussions (Paper II), and online surveys (Paper II) (see Table 1).

Table 4. Scoring scheme for assessing the Impact Score (IS) of scenarios on the ecosystem services

-3	-2	-1	0	1	2	3
high negative	moderate negative	low negative	no impact	low positive	moderate positive	high positive

Additionally, a literature-based assessment was carried out with the aims of reducing subjectivity and bias of stakeholder results, identifying and filling knowledge gaps, as well as to compare stakeholder perception and literature data. Literature-based results include observational and crisp data, further expert knowledge and lessons learnt from expert and discussion results. Besides, in Paper II and III results of RI and IF (or IS) were combined by a simple multiplication (RI in % × IF = IS) in order to calculate a weighted IS. In Paper II, the literature-based assessment was further divided into the potential supply or stock ("potential") and the real supply or actual use ("flow").

2.6. Spatial habitat assessment

As one key biological quality element of the WFD, macrophytes and their ecological importance are well reflected within EU water policies. However, their socio-economic importance in particular their role in supporting cultural ecosystem services, are often overlooked.

The spatial habitat assessment combined and further developed the quantitative (i.e. indicator-based) and qualitative (i.e. expert knowledge) approaches. Assessment results aim to support EU nature policies (i.e. HD) and to provide spatially explicit data for specific management units. The habitat assessment was applied and tested to Baltic submerged and emergent macrophyte habitats (i.e. shallow coastal areas), combined with management scenario results and further extrapolated to an entire management unit, here exemplarily to the Kleines Haff of the Szczecin Lagoon (German part).

Selection of ecosystem services and assessment indicators. First, a set of relevant ES provided by macrophytes was selected derived from their ecological functions and processes (Hossain et al. 2017) and international literature on ES classifications (CICES V.5.1 according to Haines-Young and Potschin-Young 2018, Burkhard et al. 2014). The importance and comprehensibility of selected services (including descriptions) were tested in expert workshops, and further adapted. In a second step, a set of assessment indicators for each service was compiled. The indicators are mainly based on the indicator pool by von Thenen et al. (2020), complemented and adapted by local experts. Then macrophyte experts were asked to rank three most suitable and important indicators per service, which was then tested and used for indicator-based assessments (i.e. literature research).

Assessment of ecosystem service potential provided by macrophyte habitats. The main aim of the habitat approach is to assess and compare the ES potential of submerged and emergent macrophyte habitats along the land-sea gradient (detailed descriptions in Paper IV). The selection of macrophyte habitats based on following criteria: a. most dominant species and habitats of the study areas (i.e. lagoons and shallow coastal areas), and b. most important species and habitats from a management perspective. Seven habitats were selected: 1) seagrass beds on mixed sediment habitats, 2) seaweed communities on mixed sediment habitats, 3) charophytes on mixed sediment habitats, 4) pondweed on mixed sediment habitats, 5) reeds and tall forb communities, 6) saltmarshes dominated by *Salicornia* and other annuals, 7) salt meadows dominated by *Aster tripolium*. Experts assessed the ES potential of these macrophyte habitats within the total area of 100m2 for all habitats according to HD definition considering all shallow coastal areas of the Baltic Sea between 1.5 and 12 psu. Definitions are based on and adapted from the HD and categories from the European Nature Information System (EUNIS 2022). Experts were asked to assess the ecologically sustainable ES potential for all services per habitat (detailed definition in Chapter 2.2.). The assessment scoring as shown in Table 5 ranges from "very low" [1] to "very high" [5] potential or "none" [0]. This scoring scheme was also used for the complementary indicator-based assessment carried out subsequently. As this highly complex approach requires high expertise, during June and September 2022 eleven macrophyte experts from different institutions (i.e. research institutions, state authority) of Germany and Lithuania carried out the habitat assessment (including indicator selection) individually and remotely. The approach complemented the management scenario assessment described in Chapter 2.5.

Table 5. Scoring scheme for assessing the ecological sustainable potential of ecosystem services

0	1	2	3	4	5
none	very low	low	moderate	high	very high
	<1/4.1	*1/2.5 – 1/ 4.1*	*1/1.7 – 1/2.5*	*1/1.3 – 1/1.7*	*1 – 1/1.3*

Mapping and spatial extrapolation of assessment results. In the next step, results of the management scenario assessment and the habitat assessment were combined and spatially extrapolated. This method followed the aims of identifying relevant areas for applying scenario results most suitable for management measures to mitigate trade-offs between human use and nature protection. Spatially explicit data on human uses were combined with habitat distribution and scenario results, here exemplarily for the Kleines Haff of the Szczecin Lagoon (German part).

The current submerged vegetation (i.e. angiosperms and charophytes) was mapped based on Paysen (2016) and Porsche et al. (2007), then the potential distribution of macrophytes using a depth limit of 3 meters according to Porsche et al. (2007). A coastal zone of 1,000 meters along the shoreline was defined, and areas with similar conditions to Scenario 1 (current state of Bellin beach) were selected for extrapolation, considering factors such as vegetation, beach access, proximity to urban settlements, and recreational use (beach tourism). Combining spatial data and the RI values from scenario assessment, the current spatial use (representing Scenario 1) was mapped for the extrapolated areas, including macrophyte habitats, recreational use, and fisheries. For Scenario 2, the potential spatial use was mapped under the assumption of achieving GES, establishing nature-protected areas, and subsequently prohibiting fisheries. The increase or decrease in spatial uses was evaluated between Scenario 2 and Scenario 1, considering habitats, recreational use, fisheries, and nature protection, and linked to the impact values of the stakeholder-based scenario assessment.

3

Results and discussion

3.1. Retrospective application of MESAT for implementing WFD goals

The original indicator-based MESAT approach was applied to the Warnow Estuary and Schlei Estuary in Northern Germany. Therein, the ES provision of each waterbody was compared to its reference state in 1880 (high ecological status according to the WFD) and current state, as well as the state of 1960 (good ecological status according to the WFD) compared to current state. The latter was separated into the WFD water bodies, i.e. inner and outer Warnow Estuary and inner, middle and outer Schlei Estuary.

Assessment results shown in Figure 4 indicate a similar temporal development of ES provision for both estuaries. This can be clearly seen for provisioning services as well as cultural services. Provisioning services are for both estuaries only of minor importance over the assessed time period, as only few were existent at all or decreased considerably (e.g. harvesting and processing of reed). On the other hand, cultural services gained in importance and provision significantly for both estuaries, with some exemptions: decrease in sacred and religious related activities and the bequest value.

Main weaknesses of the assessment are the underlying indicators and their interpretation as also discussed in Inácio et al. (2018). First, indicators of the same service

	Ecosytem Service classes	Warnow 1880	Warnow 1960 Inner	Warnow 1960 Outer	Schlei 1880	Schlei 1960 Inner	Schlei 1960 Middle	Schlei 1960 Outer	Indicators
Provisioning ES	P1. Plants outputs	-5	-1	-2	0	0	0	0	Harvest, № of Species
	P2. Animals outputs	-2	-3	-1	-2	3	3	3	Landings, key market species
	P3. Animals aquaculture	0	0	0	0	0	0	0	Harvest, № of Species
	P4. Plants aquaculture	0	0	0	0	0	0	0	Harvest, № of Species
	P5. Drinking water	0	0	0	0	0	0	0	Amount of water
	P6. Materials for processing	-5	0	0	-5	-5	-5	-5	Harvest
	P7. Materials for agriculture	-5	0	0	0	0	0	0	Harvest
	P8. Non-drinking water	-5	0	0	0	0	0	0	Amount of water
	P9. Energy from biota	0	0	0	0	0	0	0	Amount of plant and animal based resources
	P10. Physical energy	0	0	5	0	0	0	0	Amount of abiotic resources
Regulating ES	R1. Nutrient retention	5	2	3	1	3	2	2	N-fixation*, burial, denitrification
	R2. Pollutant dilution	5	5	5	0	0	0	0	Beach closures*
	R3. Mass stabilization	-5	-1	-4	-5	3	2	3	Habitat extension
	R4. Mass flows	-5	0	0	0	0	0	0	Sediment accumulation rate
	R5. Flood protection	-1	-1	-1	-1	0	1	1	Shoreline erosion rate*, wave height*, design-basis flood
	R6. Nursery grounds	-3	0	-1	-2	1	0	1	Habitat diversity, bottom oxygen*, Secchi depth, species distribution, nursery areas & protection
	R7. Pest control	-4	-2	0	-5	-1	-1	-1	Harmful algal blooms*, alien species*
	R8. Fixing processes	1	3	3	1	0	0	0	Nitrogen removal, water residence time
	R9. Chemical conditions	2	3	1	0	-1	-1	-1	Nutrient concentration*, salinity, oxygen concentration
	R10. Climate regulations	4	0	2	3	2	1	3	C stock & sequestration, pH, primary production
	R11. Regional regulation	-5	0	0	0	0	0	0	Evaporation rate
Cultural ES	C1. Experiental use	5	4	5	5	5	5	5	Participation in biota-related activities
	C2. Physical use	5	4	5	5	4	3	5	Tourists, ship berths, tourist boats
	C3. Scientific & educational	5	4	5	5	3	3	3	Scientific & educational publications, documentaries, exhibitions
	C4. Culture & heritage	5	5	5	5	5	5	5	Cultural and heritage sites
	C5. Ex-situ entertainment	5	5	5	5	5	5	5	Movies and broadcasts in the area
	C6. Aesthetic	5	4	5	5	5	5	5	Pictures
	C7. Symbolic	5	5	5	5	5	5	5	Red List and iconic species
	C8. Sacred & religious	-2	-3	-2	5	-3	0	4	Religious events
	C9. Existence & health	5	0	0	0	0	0	0	Health treatments & institutions
	C10. Bequest	0	0	0	5	5	5	5	Marine protected areas

Figure 4. Results of MESAT approach applied to the Schlei Estuary and Warnow Estuary (Northern Germany) (reprinted from Paper I).

partly counteracted and balanced each other out, which caused a loss of valuable data, for example pest control assessed by harmful algal blooms (+4) and invasive species (-2). Second, some indicators needed interpretation in terms of ES provision, for example, when the number of beach closures increases the service provision of "pollution dilution" (R2, Figure 4) was interpreted as decrease (or negative). Services were assessed by different numbers of indicators ranging from one to five indicators, where then the average was taken. Besides, indicators need to be suitable for all points in time assessed, which was not given. For example, movie production and photo cameras (C5 and C6 resp. in Figure 4) only became popular in the later assessment periods and partly did not even exist in 1880. These experiences are consistent with results of Inácio et al. (2019).

Despite the retrospective indicator-based assessment requires high data availability and is quite time-consuming, as it takes several months for application by a single evaluator, the main strength of this approach is that you can compare different water bodies over different points in time and gain more insights in the development of the system. The evaluators or applicants of the tool became experts of their study areas. Based on WFD definitions, results can be interpreted and used to visualize potential benefits of going back to a good ecological state from historic times in 1880 or 1960 again. However, using historic data implies biased assessment results (i.e. lack of comparability), and the state of 1880 or 1960 (i.e. good ecological state) is not reachable anymore due to the heavy anthropogenic modifications of the water bodies, e.g. harbor and shipping channel.

3.2. Application of ecosystem service assessments for future scenarios

3.2.1. Implementing WFD goals within the context of urban planning: Future Scenario "Warnow 2040"

The hypothetical future scenario "Warnow 2040" was developed based on actual urban planning measures and the assumption of having achieved the GES according to the WFD (see Table 1). The assessment scenario was subdivided into the two spatial units of the northern, industrial part of the Warnow Estuary and the southern, urban part according to the WFD water body management units.

On average, assessment results show that while assessors expected a general increase in ES provision for the southern, urban part (Figure 5b), they assumed on average an increase only for provisioning services and a decrease for regulating services for the northern, industrial part of the Warnow Estuary (Figure 5a).

During discussions, assessors addressed main weaknesses and opportunities of the approach. On the one hand, assessors mentioned the need for improved definitions, description and selection of services and indicators, suggested a smaller scoring range (-3 to +3), and criticized the subjectivity of individual results and the simplification of scenarios. On the other hand, main opportunities identified by the assessors are improved stakeholder involvement and public participation during (urban) planning

a)	Northern, industrial water body	Authors (A)			Scientists (S)											Experts (E)					Average		
	Ecosystem Service	A1	A2	A3	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	E1	E2	E3	E4	E5	A	S	E
Provisioning ES	Wild plants outputs	0	0			0			0	2			0	2					1	0	0	1	1
	Wild animals outputs	0	-3	-1		-2	2		X	2		2	-3	-1	1	2	-4	x	3	0	-1	0	0
	Aquaculture	0	0				3		X				-1						1		0	1	1
	Water discharge	0	3	2	3	3	0	3	-1	2	0	2	2	1	3	0	2	x	0	2	2	2	1
	Water extraction	0	2	2	3	2	-2		0	3		0	-2	1				0	3	-3	1	1	0
	Materials for processing & agriculture	0	0			0			X	0			-1	1					1		0	0	1
	Physical & bio-energy	2	3	1	1		3		X	4		0	0	4	X			x	3	x	2	2	3
	Navigation & waterways	4	5	3	5	5	5	5	4	5	2	4	3	4	4	3	3	2	5	5	4	4	4
	Harbours & maritime industries	4	5	2	2	5	2	2	2	2	1	3	3	4	3	3	4	3	4	4	4	3	4
Regulating ES	Burial of nutrients & organic matter	-2	0	-2	-2	-2	-3	-3	-1	-3		-3	1	-3	-2	-3	2	-2	x	0	-1	-2	-1
	Nutrient removal	-2	X	X	-4	-2	-3	0	X	-2		x	-1	-3	X	-3	0	x	x	0	-2	-2	-1
	Primary productivity	-2	-2	-3	-4	-1	-3	0	X	-2		x	-1	1	-4	-1	0	-4	-4	-3	-2	-2	-2
	Water transparency	0	5	4	3	-3	5	0	X	0		-2	-1	1	1	2	0	0	4	3	3	0	2
	Matter transformation	-2	0	-2	X	-1	-2	-1	-2	-2	-1	x	0	-1	0	-1	-3		-3	0	-1	-1	-2
	Oxygen provision	0	0	-1	2	-2	-5	0	-3	0		x	0	2	5	2	-3	1	3	0	0	0	1
	Pest control	2	0	-2	2	2	3	2	X	1	3	1	0	-2	-4		0	-4	-3	-2	0	1	-2
	Nursery grounds	-1	-5	-2		-3	-3	-5	-1	-3		x	-2	-4	-4	-3	-3	-4	2	-1	-3	-3	-2
	Habitat diversity	-2	-2	-2	2	-3	-3	-2	-1	-3	0	-2	-1	-4	-4	-2	-5	-4	3	-2	-2	-2	-2
	Mass stabilization	-1	-5	-2	2	-3	2	-1	-2	1	0	-2	-2	-4	-2	-2	-5	-1	2	-1	-3	-1	-1
	Flood protection	0	-2	-1	1	-3	-3	0	-1	0		x	-2	-2	-3	-1	0	-2	1	3	-1	-1	0
	Local climate regulation	0	0	0	0	0			1			0	-2	-1	-2	0	0	-2	x	0	0	-1	-1
Cultural ES	Bathing & sun-bathing	-1	2	2	1	-2	-2	-3	0	1	1	2	2	0	1	0	0	2	1	0	1	0	1
	Recreation & water sports	-1	2	2	1	2	-5	0	-1	1	0	-1	-3	-1	1	0	-3	0	2	0	1	-1	0
	Aesthetic experience	-1	2	3		2	-3	0	2	4	2	2	-2	0	4	0	-4	5	2	0	1	1	1
	Attractiveness for seaside housing	-1	0	1	2	0	-2	-1	1	3	-1	0	-1	0	X	0	0	x	3	0	0	0	1
	Experiential use	-1	2	1	1	0	-5	-1	-2	3		0	-2	-1	0	-3	-4	0	2	0	1	-1	-1
	Scientific & educational		3	2	4	0	-2	0	X	4	3	0	0	-1	1	0	3	0	1	0	3	1	1
	Culture & heritage		5	3	2	0	-3	0	2	3	1		-1	0	1	0	0	1	0	1	4	1	0
	Health & recuperation	-1	0	0	2		-2		0	2		-1	-1		1	0	0	0	0	0	0	0	0
	Existence & bequest	0	-5	-2	2	-1	-2	0	X	2	0	2	-1	-2	-3	-3	-5	-2	4	-5	-2	0	-2
	Average	0	1	0	1	0	-1	0	0	1	1	0	-1	0	0	0	-1	-1	2	0			

b)	Southern, urban water body	Authors (A)			Scientists (S)											Experts (E)					Average		
	Ecosystem Service	A1	A2	A3	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	E1	E2	E3	E4	E5	A	S	E
Provisioning ES	Wild plants outputs	0	0			3			X	2			3						3	-2	0	3	1
	Wild animals outputs	0	1	2		3	2		X	3		2	2	0		2	0		3	-2	1	2	1
	Aquaculture	0	0		2				X			1	2						2		0	2	2
	Water discharge	0	2	0	3	1		2	-1	2	4	0	0	1	4	0	0	X	0	2	1	2	1
	Water extraction	0	0	1	3	2	5		0	3		0	0	1				4	2	0	0	2	2
	Materials for processing & agriculture	0	0			2	1		X	0			0						0		0	1	0
	Physical & bio-energy	0	3	1	1	2	4		X	4		0	0	4	2			3	3	x	1	2	3
	Navigation & waterways	-2	5	2	3	3	5	3	-1	3	4	2	-4	3	2	4	2	2	4	4	2	2	3
	Harbours & maritime industries	-2	0	0	1	2	0	0	2	1	3	0	-2	2		0	2		-1	1	-1	1	1
Regulating ES	Burial of nutrients & organic matter	1	0	-1	0	3	3	2	0	-1		0	0	0	1	0	0	X	X	0	0	1	0
	Nutrient removal	1	X	X	3	3	2	1	X	-2	1	X	2	2	2	0	0	4	X	0	1	2	1
	Primary productivity	-2	-2	-3	-3	-2	-3	0	X	-1		X	1	1	-4	0	0	-4	-5	-3	-2	-1	-2
	Water transparency	2	5	4	4	4	5	0	2	1	1	2	1	1	3	2	2	2	4	3	4	2	3
	Matter transformation	2	0	0	X	3	0	1	0	0		X	0	1	0	0	2	0	-2	0	1	1	0
	Oxygen provision	0	0	0	3	3	4	0	-1	0		X	1	0	5	2	-3	2	4	0	0	2	1
	Pest control	2	-2	-2		2	-3	0	X	2	2	1	0	-1	-4	0	0	-4	-4	-2	-1	0	-2
	Nursery grounds	2	5	2	3	3	3	1	-1	-3	2	2	1	2	1	0	0	4	4	-1	3	1	1
	Habitat diversity	2	2	2	4	3	2	2	-1	-2		3	2	2	2	0	-4	4	4	-2	2	2	0
	Mass stabilization	1	5	3	4	3	5	2	-2	2	2	2	1	2	3		-4	3	3	-1	3	2	0
	Flood protection	0	2	1	1	2		0	0	1		X	1	-1	0	0	0	0	3	3	1	1	1
	Local climate regulation	0	0	0	2	1			0			1	1	1	1	0	0	X	X	0	0	1	0
Cultural ES	Bathing & sun-bathing	4	5	4	4	4	5	3	4	4	4	4	4	2	5	3	3	5	4	1	4	4	3
	Recreation & water sports	3	5	4	4	5	0	3	1	5	4	2	3	3	4	3	3	4	4	2	4	3	3
	Aesthetic experience	5	5	4	4	3	5	5	2	4	3	3	3	4	4	3	4	4	4	x	5	4	4
	Attractiveness for seaside housing	4	5	4	4	4	5	3	1	4	3	3	4	2	4	3	3	4	4	2	4	3	3
	Experiential use	1	5	1	3	3	-4	3	0	3		2	1	2	1	0	-3	3	3	-1	2	1	0
	Scientific & educational	3	5	2	4	3	2	1	X	4	3	3	1	3	1	2	3	2	4	1	3	3	2
	Culture & heritage	4	5	4	4	2	5	3	4	4	4	2	2	3	2	0	3	2	0	3	4	3	2
	Health & recuperation	2	0	0	4		2		3	5		2	2	1	X	0	0	X	3	0	1	3	1
	Existence & bequest	1	5	3	3	3	3	2	X	4	2	2	2	1	4	2	-4	5	4	-5	3	3	0
	Average	1	2	1	3	3	2	2	1	2	3	2	1	2	2	1	0	2	2	0			

Figure 5. Results of 19 experts, including authors of Paper I (A), scientists (S), and experts in WFD implementation (E), assessing the hypothetical future scenario "Warnow 2040" subdivided in Northern and Southern part of the water body. (reprinted from Paper I)

of measures, as applying the tool facilitates communication processes, broadens the view on knowledge of participants and supports a social learning process. These results reflect those of Souliotis and Voulvoulis (2021) pointing out the potential of ecosystem service assessments for stakeholder engagement within the implementation of WFD measures and for communication the benefits of such.

Summarizing, results of future scenario assessment show two main outcomes. First, using existent policy frameworks in practice (i.e. WFD) for stakeholder-based assessments is beneficial, as it potentially increases the acceptance of the ES approach as well as the readiness of stakeholders to get involved. Second, discussion results show that participants saw potential of the assessment for supporting public relation activities, stakeholder involvement and increasing the acceptance of implementation of WFD measures. These assumptions match the results observed in Ritzenhofen et al. (2022) assessing sea-based mitigation measure as well as in Giakoumis and Voulvoulis (2018). However, during discussion participants criticized the complexity of the developed scenario including too many parameters changed (i.e. assumed GES, urban planning measures, channel deepening etc.), which do not allow for evaluating concrete single measures but only the overall achieved targeted state of the whole water body.

3.2.2. Sandy beach management considering beach wrack and litter accumulation

Based on the lessons-learnt from the "Warnow 2040" scenario application, the scenario assessment was adapted and further developed for the assessment of Baltic sandy beaches. Two main aspects were added in Paper II: 1) assessing the relative importance (RI) of ecosystem services in order to identify local preferences, site-specifics and significance within coastal management, and 2) combining and weighting the expert-based RI values and impact score (IS) results by additional literature-based assessments.

Relative importance of ecosystem services

Aggregated results of the expert-based assessment of sandy beaches along the German and Lithuanian coast show that cultural services are of the highest importance with 52.2% of total ecosystem service provision, followed by regulating and maintenance services (37.4%) and provisioning services (10.4%) (Figure 6). The five services perceived as most important provided by Baltic sandy beaches are active recreation and tourism (10.3%), landscape aesthetics (8.5%), coastal protection/ flood control (8.5%), sediment storage and transport (8.4%) and natural heritage (7.3%). Similar to these results, Ahtiainen et al. (2019) assessed the relative importance of Baltic cultural services by allocating 100 points between eight listed services and found recreation, habitats and landscapes to be the most important services for conservation policies.

The agreement among experts is visualized by the standard deviation (or value distribution in Figure 6) of RI values. Lowest standard deviations revealed the highest expert agreement for cultural services (0.64), following by provisioning (0.88) and regulating and maintenance services (0.97). Besides, results showed little variability of assessment results among the expert groups of different countries, field and level of expertise.

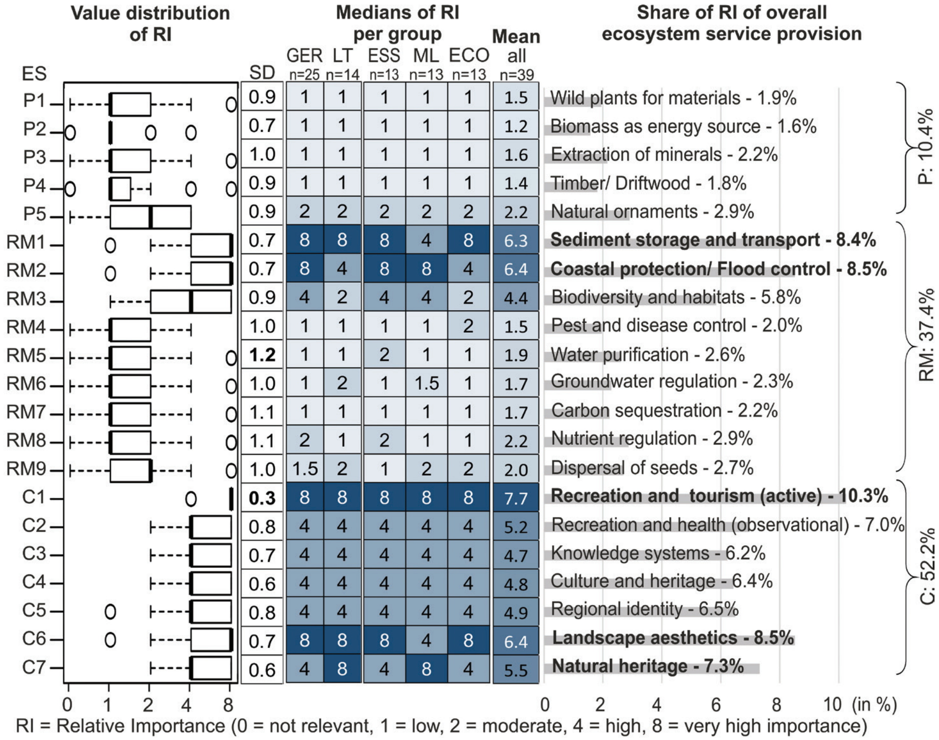

Figure 6. Expert-based results on the Relative Importance (RI) for provisioning (P), regulating and maintenance (RM) and cultural (C) services [standard deviations (SD); institutional nationality (GER Germany, LT Lithuania); field of expertise (ESS ecosystem services, ML marine litter, ECO ecology)] (reprinted from Paper II)

Impact of scenarios on ES provision

In Figure 7, impact factors (IF) given by experts and their value distribution (standard deviation) are shown for different levels of beach wrack and litter pollution scenarios of German and Lithuanian sandy beaches. Results revealed that litter (Scenario 1) had a negative impact on all cultural services but one (i.e. knowledge systems/C3). Other service categories showed only low to no effect on their provision. In contrast to that, the impact of beach wrack (Scenario 2 and 3) was overall positive on provisioning services as well as on regulating and maintenance services. Results for the impact of beach wrack on cultural services was inconsistent, showing both positive and negative values. When mixed (both litter and beach wrack), the negative impact of litter on cultural services is more dominant, while the positive impact of beach wrack prevails for provisioning, regulating and maintenance services. Highest agreement, thus lowest standard deviation (SD=0.8) was found for the litter scenario showing a clear negative impact, while higher SDs of the beach wrack scenarios (1.1 and 1.2) indicate higher disagreement. Besides, results show only little differences among expert groups.

Summarizing, results of the beach scenarios indicate that the removal of beach wrack at Baltic sandy beaches is not favorable regarding the overall ecosystem service provision. Beach wrack shows a strong positive impact on both service potential and flow. However, as also stated by Zielinski et al. (2019), beach management needs to find a compromise between conservation and recreational tourism use, of which the latter often is given priority due to high economic value in coastal regions. Another problematic aspect of beach wrack removal is that the removed biomass is often classified as waste and hampers further use (Chubarenko et al. 2021).

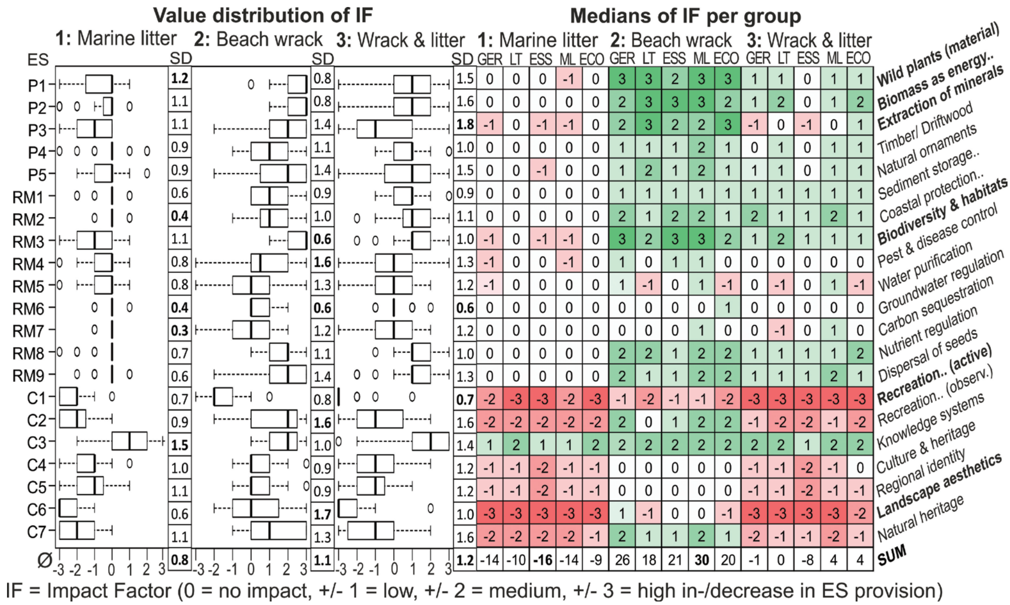

Figure 7. Expert-based results on Impact Factors (IF) of scenarios for provisioning (P), regulating and maintenance (RM) and cultural (C) services [standard deviations (SD); institutional nationality (GER Germany, LT Lithuania); field of expertise (ESS ecosystem services, ML marine litter, ECO ecology). Box-plots indicate median value, 25-75 percentile value as boxes and min-max values as whiskers, outliers are indicated with circles (reprinted from Paper II)

Combining and weighting of assessment data

The combined data-based assessment shown in Table 6 aimed at reducing subjectivity and bias of expert results. For this, a differentiation between service potential and flow was applied and compared to service provision (expert-based) in order to identify knowledge gaps, misunderstandings or systematic assessment errors, e.g. offsetting effects and thus loss of data by different interpretations of ES terminology (i.e. contradicting values).

Results of RI values, both expert- and data-based, show only minor differences. In contrast to this, the impact score results show some interesting findings. First, all cultural services were affected by the beach wrack and/or litter scenarios on the flow level, while only 24% of the potential values were changed. Second, results also revealed the different interpretations of experts when assessing the general provision. Namely. when experts were assessing the impact of litter on service provision, they were mainly referring to the flow. Contrarily, when assessing the impact of beach wrack, experts were mainly referring to the potential.

Table 6. Results of expert-based (service provision) and combined data-based assessments (service potential and flow) showing Relative Importance (RI), Impact factors (IF) and the weighted Impact Scores (RI in % x IF = IS) for all three scenarios.

Ecosystem Services	Relative Importance				1: Marine litter						2: Beach wrack						3: Beach wrack and litter					
					Impact Factor			Impact Score			Impact Factor			Impact Score			Impact Factor			Impact Score		
	Data	Experts	Data (%)	Exp. (%)	Potential	Flow	Provision	Potential	Flow	Provision	Potential	Flow	Provision	Potential	Flow	Provision	Potential	Flow	Provision	Potential	Flow	Provision
P1	1	1	1.3	1.5	0	0	0	0.0	0.0	0.0	3	2	3	4.0	2.7	4.4	3	1	1	4.0	1.3	1.5
P2	1	1	1.3	1.5	1	0	0	1.3	0.0	0.0	2	1	3	2.7	1.3	4.4	3	1	1	4.0	1.3	1.5
P3a	1	1	1.3	1.5	0	0	-1	0.0	0.0	-1.5	2	1	2	2.7	1.3	2.9	2	0.5	-1	2.7	0.7	-1.5
P3b	1		1.3		0	-1		0.0	-1.3	0.0	0	-1		0.0	-1.3	0.0	0	-1		0.0	-1.3	0.0
P4	1	1	1.3	1.5	0	-1	0	0.0	-1.3	0.0	0	-1	1	0.0	-1.3	1.5	0	-1	1	0.0	-1.3	1.5
P5	2	2	2.7	2.9	1	0.5	0	2.7	1.3	0.0	3	2	2	8.0	5.3	5.8	3	1.5	1	8.0	4.0	2.9
RM1	8	8	10.7	11.7	0.5	0.5	0	5.3	5.3	0.0	1	1	1	10.7	10.7	11.7	1.5	1.5	1	16.0	16.0	11.7
RM2	8	8	10.7	11.7	0	0	0	0.0	0.0	0.0	3	3	1	**32.0**	**32.0**	11.7	3	3	1	**32.0**	**32.0**	11.7
RM3	8	4	10.7	5.8	1	-1	-1	**10.7**	-10.7	-5.8	3	3	3	**32.0**	**32.0**	**17.5**	3	2	1	**32.0**	21.3	5.8
RM4	1	1	1.3	1.5	-1	1	0	-1.3	1.3	0.0	2	2	0.5	2.7	2.7	0.7	2	2	0	2.7	2.7	0.0
RM5	1	1	1.3	1.5	-1	1	0	-1.3	1.3	0.0	2	2	0	2.7	2.7	0.0	1	1	0	1.3	1.3	0.0
RM6	1	1.5	1.3	2.2	0	1	0	0.0	1.3	0.0	0	2	0	0.0	2.7	0.0	0	2	0	0.0	2.7	0.0
RM7	1	1	1.3	1.5	0	0	0	0.0	0.0	0.0	-1	-1	0	-1.3	-1.3	0.0	0	0	0	0.0	0.0	0.0
RM8	4	1	5.3	1.5	-2	-2	0	**-10.7**	-10.7	0.0	3	3	2	16.0	16.0	2.9	3	1	1	16.0	5.3	1.5
RM9	1	2	1.3	2.9	1	-1	0	1.3	-1.3	0.0	2	2	2	2.7	2.7	5.8	2	1	1	2.7	1.3	2.9
C1	8	8	10.7	11.7	0	-2	-2	0.0	**-21.3**	**-23.4**	0	-2	-2	0.0	**-21.3**	**-23.4**	0	-3	-3	0.0	**-32.0**	**-35.0**
C2	8	4	10.7	5.8	0	-1	-2	0.0	-10.7	-11.7	3	2	2	**32.0**	**21.3**	11.7	3	1	-1	**32.0**	10.7	-5.8
C3	2	4	2.7	5.8	1	1	1	2.7	2.7	5.8	1	1	2	2.7	2.7	11.7	1	1	2	2.7	2.7	11.7
C4	4	4	5.3	5.8	0	-2	-1	0.0	-10.7	-5.8	0	2	0	0.0	10.7	0.0	0	-1	-1	0.0	-5.3	-5.8
C5	2	4	2.7	5.8	0	-2	-1	0.0	-5.3	-5.8	0	1	0	0.0	2.7	0.0	0	-1	-1	0.0	-2.7	-5.8
C6	8	8	10.7	11.7	0	-2	-3	0.0	**-21.3**	**-35.0**	0	-1	0	0.0	-10.7	0.0	0	-3	-3	0.0	**-32.0**	**-35.0**
C7	4	4	5.3	5.8	0	-2	-2	0.0	-10.7	-11.7	0	2	1	0.0	10.7	5.8	0	1	-1	0.0	5.3	-5.8
Sum					2	-12	-12	11	-92	-95	29	26	24	149	124	75	31	11	0	156	34	-42

The weighted impact score (IS) (RI in % × IF = IS) was created to serve as an indicator for coastal management identifying trade-offs and synergies as well as comparing different management measures. For marine litter (Scenario 1), only minor trade-offs could be identified on the potential level, namely for biodiversity (RM3) and nutrient regulation (RM8). In the beach wrack scenarios (1 and 2) main trade-offs were found for regulating and maintenance services (i.e. coastal protection/RM2, biodiversity/RM3) and cultural services (i.e. active and observational recreation/C1 and C2, landscape aesthetics/C6) on the flow and provision level. A previous study on ecosystem services of Baltic lagoons (Schernewski et al. 2018) used similar but simpler importance scoring by counting number of experts considering the services as relevant or not (yes/no option only) multiplied by the "change" values.

Transfer and recommendations for management

Five management recommendations could be derived from the results of this study (detailed information can be found in Paper II): 1) remove litter, leave wrack, 2) minimize the impact of cleaning, 3) further use as a valuable resource, 4) internalize (indirect) costs of cleaning, and 5) increase awareness and environmental education, e.g. why leaving beach wrack at the shore. Besides, synergies could be found when cleaning beaches for tourism and then use it for further processing (e.g. fertilizer). Also trade-offs were identified when removing beach wrack, as it removes important biomass and attached sand from the beach, losing its capacity to protect the coast.

Contributing to the understanding of human-nature interactions between management measures and sandy beach ecosystems, this study provides the first holistic inventory of sandy beach ecosystem services including their impact of marine litter and beach wrack. In particular, this study and its results are interesting for beach managers and policymakers in the Baltic Sea, but also possibly transferrable to other similar Seas, as the Mediterranean Sea or Black Sea with similar challenges regarding beach wrack accumulations (Menicagli et al. 2022, Beltran et al. 2020).

Technical implementation

Two technical implementations of the scenario assessment were applied and tested. First, the spreadsheet-based assessment which can be also applied as paper-based version and second, the online survey (Table 7). The two methods were assessed according to pre-defined criteria allowing for direct comparison. Detailed information on the spreadsheet-based approach can be found in the methods section of this thesis, while the assessment design and exemplary webpages from the online survey can be found in Figure 6 of Paper II. Nevertheless, the main characteristic of the online survey is the step-by-step guidance over the whole assessment process. In literature, the most common online method for ES assessments are online questionnaires usually targeting cultural services (Bryce et al. 2016, Grima et al. 2020, Cabana et al. 2020). Another more innovative form of online interaction was tested by Ritzenhofen et al.

(2022) using an interactive online tool (e.g. Mentimeter) for assessing ES of mussel cultivation.

In summary, the spreadsheet assessment shows its main strength in its fast and easy technical set up, while implementing and setting up an online survey takes significantly more time. However, data acquisition of online surveys designed as common type of questionnaires are more promising in terms of respondents, as people are more used to it. Therefore, the online survey can be carried out easier and faster from the respondent's perspective, while the spreadsheet assessment is more time-demanding for the experts.

Table 7. Methodological comparison of expert-based ecosystem service assessments via spreadsheet and online survey (reprinted from Paper II)

	Spreadsheet	Online survey
Interviewer:		
Technical set up	Less time effort required At least basic software skills (e.g. excel) required	Basic programming skills recommended (html, php)
Data analysis	Easy data compilation for groups up to 50 experts (otherwise macros possible requiring programming skills) Easy and fast visualization of results for expert discussion	More complex data compilation (extraction from webpage and translation necessary)
Interviewee:		
Comprehensibility	Additional guideline necessary (pdf)	Step-by-step guidance through webpage
Practicability	More analytical details and information available (formulas, direct calculations of weighting factors, accumulated impact score) Easy and fast comparison of scores between scenarios (horizontal comparison)	Separate and direct assessment of scenarios (no misunderstandings or wrong comparisons) Common type of questionnaire (already used to) More difficult to compare and change score between scenarios No direct visualization of results or own interpretation possible
Technical usability	Internet only for down-/upload needed IT device needed (only computer) Spreadsheet software needed (excel recommended, but also usable with open source) Basic spreadsheet skills needed	Internet access needed IT device needed (computer, tablet or smartphone) No additional software or skills needed
Time requirements	30 – 60 minutes (highly depends on commenting behavior)	15 – 45 minutes (highly depends on commenting behavior)

3.2.3. Implementing conventional coastal protection measures and building-with-nature solutions

Conventional coastal protection scenarios

Three management scenarios were developed with the aim to assess the consequences of the ship worm destruction on wooden groins constituting an ongoing problem since the 1990s (Lippert et al. 2017). Groins systems are a traditional and important coastal protection measure on the southwestern Baltic Sea coast. For the management scenario assessment, different wood construction material alternatives were selected (i.e. native wood, damaged and tropical wood groins) and assessed. First, the RI of services within coastal protection scenarios was assessed being highest for cultural services, moderate for regulating and maintenance services showing two services of high importance (i.e. coastal protection and biodiversity), while provisioning services can be almost neglected (detailed results in Paper III). However, during discussions involved stakeholders showed a lack of knowledge regarding wooden groin systems. Based on this and the differences between data-based and stakeholder results, it leads to the assumption that data-based results are more reliable than results from unexperienced stakeholders (as also experienced in scenario assessments of Paper IV). Second, regarding the impact score only little differences can be found between the scenarios and between data-based and stakeholder values. Results do not show new insights, as most ecosystem services only show little to no impact by the different scenarios. Summarizing, results revealed main shortcomings during scenario development, in particular regarding selection of system variables and the set of assumptions (being insufficient or not suitable), which is why the aim of the scenario assessment could not be met.

Building-with-nature scenarios

As shown in Figure 8, three building-with-nature scenarios (i.e. sand nourishment, mussel farm and seagrass beds) were assessed and compared to a baseline scenario which represents the current groins system (Paper III). Similar to the previous groins assessment (conventional coastal protection scenarios), results on the relative importance show a low importance of provisioning services, while all cultural services are perceived as of high importance, and some regulating services of very high importance for mass stabilization, hydrological cycle and biodiversity. However, due to a high variability of relative importance values and impact factors, results indicate a high disagreement among experts which partly based on the high heterogeneity, i.e. different fields and levels of knowledge. Nevertheless, high variability in values also indicate possible misunderstandings and different interpretations. Main shortcoming

Ecosystem services			Relative Importance		1: Broad beach		2: Mussel farm		3: Seagrass	
			Literature-based	Expert groups	Literature-based	Expert groups	Literature-based	Expert groups	Literature-based	Expert groups
Provisioning	1	Reared aquatic animals for nutrition	4	1	0	0	4	3	0	0
	2	Reared aquatic animals for energy	1	1	0	0	2	1	0	0
	3	Reared aquatic animals for materials (further processing)	2	1	0	0	3	2	0	0
	4	Wild plants used for nutrition	2	2	0	0	0	0	3	1.5
	5	Wild plants used for material	2	2	0	0	1	0	3	2
	6	Wild animals for human nutrition	4	4	0	0	2	1	3	2
	7	Genetic material of plants	2	1	1	0	0	0	2	2
	8	Genetic material of animals	2	1	0	0	2	1	2	0
	9	Mineral substances for material (futher processing)	4	2	2	2	0	0	0	0
Regulation & Maintenance	1	Mediation of wastes and pollutants	4	4	-1	0	1	2	3	2
	2	Mass stabilization and control of erosion rate	8	4	2	2	2	1	4	3
	3	Hydrological cycle and water flow regulation	8	8	2	2	2	2	2	2
	4	Seed and/ or Gamete dispersal	4	4	1	0	1	2	2	2
	5	Biodiversity and habitat	8	4	2	0	1	1	4	3
	6	Pest and disease control	4	2	-1	0	-2	0	2	0
	7	Decomposition and fixing processes and their effect on sediment quality	2	2	0	0	-2	0	2	2
	8	Regulation of chemical water condition	4	4	-1	0	3	2	3	2
	9	Carbon sequestration	8	4	1	0	2	1	4	3
Cultural	1	Recreation and tourism on/in water (active)	4	4	3	2	-2	-1	2	1
	2	Recreation and tourism on land (active)	4	4	4	3	-2	0	2	0
	3	Recreation and tourism (observational)	4	4	2	1	-1	0	2	1
	4	Reserach & Education	2	4	2	2	1	2	2	2
	5	Aesthetics	4	4	3	1	-3	-2	1	0
	6	Enterainment	2	2	1	1	1	0	1	0
	7	Regional identity	2	2	2	0	-1	0	1	0
	8	Conservation value	8	4	1	0	1	0	3	1

Figure 8. Comparative ecosystem service assessment of three scenarios representing building-with-nature examples. Comparison of the literature-based and the accumulated median group scores (adapted from Paper III)

here was to not having clearly defined the assessment unit of or spatial area for the relative importance, i.e. of each service for the shown transect, for beaches in general or only in reference to the coastal protection function. Regarding the impact factors of the scenarios on service provision, assessment results show an increase in ES potentials for all three building-with-nature scenarios. First, results show that beach nourishments (Scenario 1) mainly increase the cultural services, as also stated in de Schipper et al. (2021) to be designed to enhance areas for recreational uses). Second, mussel farms (Scenario 2) mainly increase provisioning services, also reflected by Heckwolf et al. (2021) as most frequently review service category (e.g. here as raw material). Third, the main increase in provision by seagrass meadows (Scenario 3) are on the regulating and maintenance services, for example climate mitigation (Duarte et al. 2017) and coastal protection (Lima et al. 2023). In summary, stakeholders evaluated these measures as potential synergies, for example by combining the coastal protection function with increased touristic usability and attractiveness (beach nourishment), commercial activities (mussel farms) or increasing biodiversity (restoration of submerged vegetation).

Main lessons-learnt during the assessment process of building with nature-scenarios and following discussions are that the scenario assessment is well-suitable for stakeholder involvement, support dialogue between planner and the public, interdisciplinary discussions, awareness raising, and increasing the acceptance of measures. Thus, results prove its suitability for informal evaluations of different coastal protection measures, as well as for complementing formal planning and implementation processes. The benefits of embedding ecosystem services in coastal (protection) planning is also shown in Arkema et al. (2015). However, for detailed information necessary for decision-making and implementation of coastal protection measures other methods like a feasibility and cost-efficiency analysis are needed.

3.3. Ecosystem service assessment of macrophyte habitats

3.3.1. Review and importance of macrophyte assessment indicators

A comprehensive list of 25 services and 79 assessment indicators (Table 8) was provided to assess macrophyte management scenarios and habitats in shallow coastal areas especially lagoons based on WFD and HD definitions and classifications (Paper IV). Both the management scenario assessment (i.e. relative importance and impact factor) and spatial habitat assessment (i.e. mapping and extrapolation) were applied.

Table 8. List of selected ecosystem services (P – provisioning, RM – regulating and maintenance, C – cultural) provided by macrophytes and assessment indicators ranked by experts (for full list see Annex Paper IV).

Ecosystem services	Description	Indicators
P1: Marine plants used for human nutrition	Use of wild and cultivated plants as human food source or supplements, e.g. seaweeds or reed sprouts for consumption	1) Amount of harvested biomass, 2) Total sales or market value of harvested biomass, 2) Abundance/ biomass of (potential) stock/ habitat, 3) Generated income or employment (farmers, processors and/or vendors), and other: nutritional value of target species (e.g. vitamins or antioxidative capacity)
P2: Marine plants used as material (direct use, processing)	Use of wild and cultivated plants incl. fibers as material, e.g. as fertilizer in agriculture or reed for thatched roofs	1) Amount of harvested biomass, 2) Abundance/ biomass of (potential) stock/habitat/ raw material, 3) Abundance/ number of species with potential/actual use for processing
P3: Marine plants used for energy	Use of wild and cultivated plants as biomass for energy conversion	1) Amount of energy produced by harvested biomass, 2) Amount of harvested biomass, 3) Abundance/ number of species with potential/ actual energetic value, 3) Area or coverage of potential stock/habitat, and other: Biochemical methane potential (BMP)
P4: Marine animals used for nutrition, material or energy	Wild and reared animals, e.g. fish and mussels used as source for human nutrition, direct use, processing or for energy conversion	1) Amount of harvested biomass/catch/landing, 2) Abundance/ biomass of (potential) stock/habitat, 3) Total sales or market value of products
P5: Genetic material of marine plants	Seeds and spores and other plant materials that can be used to maintain or establish a new population (seed collection) or develop new varieties	1) Number of species/genes utilized, 2) Abundance/ number of species with potential/actual useful genetic material, 3) Quality of species with potential/actual useful genetic material
P6: Genetic material of marine animals	Marine animals (e.g. fish or mussels) used for replenishing stocks or breeding of new species, e.g. breeding of new oysters' strains	1) Abundance/ number of species with potential/actual useful genetic material, 2) Number of species/genes utilized, 3) Number of patents and published articles, 3) Quality of species with potential/actual useful genetic material
RM1: Mediation of wastes and pollutants	1) Bio-remediation; 2) Filtration/ sequestration/ storage/ accumulation by microorganisms, algae, plants, and animals	1) Nitrogen removal/ storage, 2) Phosphorus removal/ storage, 3) Coastal recreation associated with reduced nutrient concentration
RM2: Mediation of nuisances of anthropogenic origin	1) Smell reduction, e.g. shelter belts that filter particulates that carry odors; 2) Visual Screening: Shelter belts to screen unsightly things e.g. reed belts	1) Elevation/ height of vegetation, 2) Length of coastal vegetation, 3) Abundance/ biomass of coastal vegetation (density)
RM3: Mass stabilization and control of erosion rate	Sediment stabilization controlling or preventing erosion/ mass movements e.g. by seagrass meadows	1) Area or coverage by emerged, submerged or intertidal vegetation, 2) Shoreline erosion and/or accumulation rate, and other: Stem density and seasonality of plants (e.g. perennial, annual, litter production,…)

Ecosystem services	Description	Indicators
RM4: Hydrological cycle and water flow regulation	Regulating water flows and coastal protection, e.g. coastal habitats/ natural levees reducing wave energy and providing flood protection	1) Wave attenuation potential, 2) Shoreline erosion rate, 2) Replacement cost for coastal protection
RM5: Wind protection	Shielding people from wind e.g. reed belts alleviate onshore wind	1) Elevation/ height of vegetation, 2) Abundance/ biomass of coastal vegetation (density), 3) Length of coastal vegetation, and other: configuration of coastal vegetation including length and width, stem density
RM6: Lifecycle maintenance and pollination	Seed and/ or gamete dispersal for population maintenance, e.g. providing a habitat for native pollinators	1) Extent of nursery and feeding areas, 2) Species abundance, richness and distribution, 3) Juvenile fish density
RM7: Biodiversity and habitat	Maintaining nursery populations and habitats (incl. breeding grounds) for wild plants or animals, e.g. seagrass beds as nursery habitat for commercial fish stock	1) Species abundance, richness and distribution, 2) Extent of nursery and feeding areas, 3) Total number or coverage of protected areas, 3) Habitat health status (Habitat fragmentation index)
RM8: Pest and disease control	Providing a habitat for native pest (incl. invasive species) and disease control agents, e.g. microbial antagonists for the control of postharvest diseases	1) Presence and distribution of pests/ diseases, 2) Presence and distribution of pathogens, 3) Presence and distribution of alien species, and other: algae blooms, water exchange time
RM9: Nutrient regulation (soil quality)	Decomposition and fixing processes and their effect on sediment quality, e.g. sequester and store nutrients in sediment enhancing remineralization processes	1) Nitrogen removal/ storage, 2) Phosphorus removal/ storage, 3) Carbon stock
RM10: Regulation of water conditions	Controlling chemical condition of salt water by living processes, e.g. water purification by marine plants or animals	1) Oxygen concentration, 2) Primary production, 3) Nitrogen removal/ storage
RM11: Atmospheric composition and conditions	Regulation of air, temperature and humidity, including ventilation and transpiration, e.g. carbon sequestration	1) Primary production, 2) Carbon sequestration, 3) Carbon stock
C1: Recreation and tourism (active)	Using the environment for sports and recreation, and to help stay fit, e.g. swimming, water sports, fishing	1) Total number of tourists, 2) Available beach or recreational area, 3) Number of suppliers of recreational activities (boating, surfing, diving..)
C2: Recreation and tourism (observational)	Using nature to distress, e.g. watching seabirds, plants or marine mammals	1) Number of viewpoints/ birdwatching points, 2) Species abundance, richness and distribution, 3) Total income or market value of ecotourism, 3) Presence of endangered, protected, iconic and/or rare species or habitats
C3: Research and traditional knowledge	Studying nature for scientific purpose or the creation of traditional ecological knowledge	1) Presence of endangered, protected, iconic and/or rare species or habitats, 2) Number of patents and published articles, 3) Total income or value of research funds, and other: Number of local research institutes

Ecosystem services	Description	Indicators
C4: Education and training	Using nature for educational purposes, e.g. university courses, in-situ teaching or field trips	1) Number of educational activities (in-situ teaching or field trips), 2) Presence of endangered, protected, iconic and/or rare species or habitats, 3) Revenues or number of documentaries, books and other educational publications, and other: Educational capacity (beds in youth hostels, camp sites, educational stands…)
C5: Culture and heritage	Things in nature that help people identify with history or culture of where they live or come from; that contribute to cultural heritage.	1) Social perception of identity/heritage, 1) Presence of endangered, protected, iconic and/or rare species or habitats, 2) Number of cultural events related to the area
C6: Landscape aesthetics	The inherent beauty of nature	1) Number of pictures published on social media, 2) Hedonic pricing: cost of property next to aesthetic sites, Resident population/ Net migration, and other: Landscape richness
C7: Symbolic or religious meaning	Things in nature that have symbolic or spiritual meaning, or sacred and religious meaning.	1) Number of symbolic or religious sites (church, monuments..), 2) Number of religious events (ceremonies, wedding, funerals..), 3) Presence of endangered, protected, iconic and/or rare species or habitats
C8: Natural heritage and conservation	Things in nature that should be conserved and preserved for future generations, and have a non-use value (also existence, option or bequest value)	1) Total number or coverage of protected areas, 2) Willingness-to-pay to maintain/ preserve/conserve, 3) Presence of endangered, protected, iconic and/or rare species or habitats

Pre-defined criteria were applied for the service selection including social, economic and ecological significance, required assessment time and fair balance between service categories. In both stakeholder and literature results at least a low relative importance or higher was assigned for all services of the studied lagoons (Szczecin, Curonian and Bizerte Lagoon) proving the general suitability of selected services (see Figure 9). Cultural services are with 40% (Curonian Lagoon) and 60% (Szczecin Lagoon) ranked as of high or very high importance the most important services (>4) in the Baltic lagoons. In accordance with this, Newton et al. (2018) also identified tourism recreation together with food provision as most important for lagoons worldwide. Besides, both regulating and maintenance services as well as provisioning services were perceived more important in the Szczecin Lagoon than in the Curonian Lagoon. Except from student results (Group 3), only small differences among stakeholder and literature data were found. Thus, a high compatibility can be assumed for expert, stakeholder and literature data regarding their data reliability.

Relative Importance (RI)

Ecosystem Services	SZC LIT	SZC 1 Experts MD	SZC 1 Experts SD	SZC 2 Stakehold. MD	SZC 2 Stakehold. SD	CU LIT	CU 3 Students MD	CU 3 Students SD	BI LIT
P1: (Marine) Plants used for human nutrition	1	2	0.8	1	1.1	1	1	0.9	1
P2: (Marine) Plants used for material	4	2	1.0	2	0.9	4	1	0.9	4
P3: (Marine) Plants used for energy	1	2	0.8	1	0.9	2	1	0.7	2
P4: (Marine) Animals used for nutrition, material, energy	4	4	1.0	4	1.1	4	2	**1.4**	8
P5: Genetic material of (marine) plants	1	1	1.2	2	0.8	1	1	**1.4**	4
P6: Genetic material of (marine) animals	1	1	**1.4**	1	0.9	1	1	1.2	2
RM1: Mediation of wastes and pollutants	1	2	0.7	4	1.0	1	4	0.7	4
RM2: Mediation of nuisances (anthropogenic origin)	2	2	0.7	2	1.0	2	4	**1.8**	1
RM3: Mass stabilization and control of erosion rate	8	8	0.6	2	1.1	8	1	**1.6**	4
RM4: Hydrological cycle and water flow regulation	4	4	0.5	3	1.0	4	1	1.2	4
RM5: Wind protection	2	2	0.9	2	0.8	2	0	1.2	1
RM6: Lifecycle maintenance and pollination	4	2	0.6	2	0.9	4	1	1.2	8
RM7: Biodiversity and habitat	8	8	0.3	8	0.9	4	1	1.0	4
RM8: Pest and disease control	4	2	0.9	2	1.0	2	1	0.7	2
RM9: Nutrient regulation (soil quality)	2	2	0.6	4	0.9	2	1	1.5	4
RM10: Regulation of water conditions	8	6	0.5	3	1.2	4	1	1.5	4
RM11: Atmospheric composition and conditions	2	4	0.5	2	**1.4**	1	1	0.5	2
C1: Recreation and tourism (active)	8	8	1.2	4	0.7	8	2	1.5	2
C2: Recreation and tourism (observational)	8	8	0.5	4	0.9	8	1	1.5	2
C3: Research and traditional knowledge	4	4	0.8	2	1.0	4	8	**1.6**	4
C4: Education and training	nv	nv	nv	2	**1.3**	2	8	0.8	1
C5: Culture and heritage	4	2	0.7	3	**1.5**	4	4	1.6	4
C6: Landscape aesthetics	8	4	0.8	4	0.9	8	1	1.4	1
C7: Symbolic or religious meaning	nv	nv	nv	1	1.0	2	1	0.7	1
C8: Natural heritage and conservation	8	6	1.0	6	1.5	8	2	1.4	1

nv = no value (24)

Impact - Scenario 1

Ecosystem Services	SZC LIT*	SZC 1* Experts MD	SZC 1* Experts SD	SZC 2 Stakehold. MD	SZC 2 Stakehold. SD	CU LIT	CU 3 Students MD	CU 3 Students SD	BI LIT
P1: (Marine) Plants used for human nutrition	1	2	1.1	1	0.6	1	2	0.4	1
P2: (Marine) Plants used for material	3	2	0.7	1	0.6	3	2	0.0	2
P3: (Marine) Plants used for energy	1	2	0.9	1	0.9	1	2	0.4	1
P4: (Marine) Animals used for nutrition, material, energy	1	0.5	1.5	1	0.7	1	2	0.6	2
P5: Genetic material of (marine) plants	1	1	0.6	1	0.6	1	1	0.7	1
P6: Genetic material of (marine) animals	1	1	0.7	1	0.5	1	2	0.7	1
RM1: Mediation of wastes and pollutants	1	1	0.5	1	0.5	1	1	1.2	1
RM2: Mediation of nuisances (anthropogenic origin)	2	1.5	0.5	1	0.6	1	1	1.0	1
RM3: Mass stabilization and control of erosion rate	2	2	0.7	1	0.6	1	1	1.0	1
RM4: Hydrological cycle and water flow regulation	2	1.5	0.6	1	0.7	1	2	0.7	1
RM5: Wind protection	2	1	0.6	1	0.5	1	0	1.0	1
RM6: Lifecycle maintenance and pollination	2	1	0.6	1	0.7	2	2	0.4	2
RM7: Biodiversity and habitat	2	2	0.6	1	0.7	2	2	0.4	2
RM8: Pest and disease control	2	0.5	1.1	0	0.7	1	2	0.4	1
RM9: Nutrient regulation (soil quality)	2	1	0.7	1	0.7	1	2	0.4	1
RM10: Regulation of water conditions	2	1.5	0.5	1	0.4	1	1	0.5	2
RM11: Atmospheric composition and conditions	1	2	0.7	1	0.6	1	1	0.4	1
C1: Recreation and tourism (active)	1	0	**1.6**	0	**1.4**	1	1	**1.9**	1
C2: Recreation and tourism (observational)	1	2	0.8	1	0.8	2	2	0.4	1
C3: Research and traditional knowledge	0	1	0.6	1	0.9	1	2	0.5	0
C4: Education and training	nv	nv	nv	1	0.6	1	3	0.5	1
C5: Culture and heritage	2	1	0.8	0	0.6	1	2	0.7	2
C6: Landscape aesthetics	2	2	0.8	1	0.5	2	2	0.7	1
C7: Symbolic or religious meaning	nv	nv	nv	0	0.0	1	1	0.7	1
C8: Natural heritage and conservation	2	1	1.1	1	0.6	1	2	0.6	1

Impact - Scenario 2

Ecosystem Services	SZC LIT*	SZC 1* Experts MD	SZC 1* Experts SD	SZC 2 Stakehold. MD	SZC 2 Stakehold. SD	CU LIT	CU 3 Students MD	CU 3 Students SD	BI LIT
P1: (Marine) Plants used for human nutrition	3	4	**1.8**	1	1.1	2	3	0.4	2
P2: (Marine) Plants used for material	4	4	0.9	2.5	1.0	3	3	0.4	3
P3: (Marine) Plants used for energy	2	4	1.3	1.5	**1.3**	2	3	0.5	2
P4: (Marine) Animals used for nutrition, material, energy	4	-1	**2.9**	2	0.9	3	3	0.5	3
P5: Genetic material of (marine) plants	3	3	1.2	2	0.8	1	3	1.2	2
P6: Genetic material of (marine) animals	3	3	**1.7**	2	0.9	1	3	0.5	2
RM1: Mediation of wastes and pollutants	2	2	0.8	2	0.8	2	2	**1.9**	2
RM2: Mediation of nuisances (anthropogenic origin)	4	4	0.8	2	1.1	2	3	**1.7**	2
RM3: Mass stabilization and control of erosion rate	4	4	0.4	2	0.5	3	2	**1.4**	2
RM4: Hydrological cycle and water flow regulation	3	4	0.8	2	0.7	3	3	0.8	2
RM5: Wind protection	3	2	0.9	2	0.8	2	0	**1.5**	2
RM6: Lifecycle maintenance and pollination	3	2.5	1.1	1	1.2	3	3	0.4	3
RM7: Biodiversity and habitat	4	4	0.6	2	0.6	3	3	0.0	3
RM8: Pest and disease control	4	1.5	**1.9**	1	**1.5**	2	2	0.7	2
RM9: Nutrient regulation (soil quality)	3	3	1.1	2	0.7	3	3	0.5	2
RM10: Regulation of water conditions	4	3.5	0.9	2	0.6	3	3	0.8	3
RM11: Atmospheric composition and conditions	3	4	0.9	2	0.8	2	3	0.4	2
C1: Recreation and tourism (active)	-2	-3	0.8	-0.5	**1.6**	-2	1	**2.5**	1
C2: Recreation and tourism (observational)	3	3	0.8	3	1.2	3	3	0.0	3
C3: Research and traditional knowledge	0	2.5	**1.3**	2	1.2	0	3	0.0	0
C4: Education and training	nv	nv	nv	2	1.0	1	3	0.0	1
C5: Culture and heritage	3	1	**1.4**	0	0.8	2	3	0.4	3
C6: Landscape aesthetics	3	3	1.1	2	1.2	3	3	0.0	1
C7: Symbolic or religious meaning	nv	nv	nv	0	0.4	2	2	**1.4**	1
C8: Natural heritage and conservation	4	3.5	1.2	2	1.0	3	3	0.0	2

*Additional scoring possibility of (+/-) 4 only in workshop 1 and literature-based assessment

Figure 9. Results of scenario assessments for three lagoons (SZC=Szczecin, CU=Curonian, BI=Bizerte) on their provision of ecosystem services (P – provisioning, RM – regulating and maintenance, C – cultural). Literature results (LIT) are compared to median values (MD) and standard deviations (SD) of three workshops: (1) coastal-management experts, (2) coastal-management stakeholders and (3) student group (reprinted from Paper IV).

To test international applicability a literature-based assessment was carried out for the Bizerte Lagoon (Southern Mediterranean). Results show that cultural services are perceived significantly less important in the Bizerte Lagoon than in the Baltic lagoons, while contrarily provisioning services are most important in Bizerte Lagoon but only little in the assessed Baltic lagoons. These findings are supported by Newton et al. (2018) who assessed a relatively low monetary value of cultural services and highest for provisioning service for Bizerte Lagoon. The differences between Baltic and Mediterranean results also demonstrate that human reliance on nature is context-dependent, it encompasses aspects of different socio-cultural development, economic environment, poorer diversity and conditions of fishery resources.

3.3.2. Macrophyte management scenario assessment

With the aim of assessing the impact of a prospective good ecological state (GES) of coastal lagoons on service provision, results of Paper VI visualize the impact of improved water quality and macrophyte habitats perceived by stakeholders. The scenarios are tailor-made for the Szczecin and/or Curonian Lagoon and represent typical coastal transects differing in their ecological states according to the WFD (poor, moderate, good) and different management measures (i.e. including fisheries and coastal protection). In Figure 9, results showed that the increases of macrophyte coverage resulting from an improved ecological state are generally perceived as beneficial to humans as visualized by the overall positive impact on the provision of all service categories. Trade-offs are only found between strong macrophyte coverage (Scenario 2) and active recreation and tourism (C1) being among the most importance services in the Baltic lagoons. Another study with similar results (van Nes et al. 2002) suggests an alternative approach proposing to dedicate entire lakes (or lagoons) exclusively to recreational purposes and others solely for nature conservation. However, this strategy may not always be feasible. Comparing stakeholder and literature-based data of the scenario impact of the Baltic lagoons, only minor differences even to Bizerte Lagoon (literature data only) could be found. Contrarily to the Baltic lagoons, most striking difference to Bizerte Lagoon is the slight increase in service provision for active recreation and tourism (C1) in Scenario 2. This difference in impact values are assumed to result from different touristic activities carried out in the Baltic Sea and Mediterranean Sea, whereof the latter is more attractive for recreational activities as sun bathing, swimming and diving (due to high water transparency), also confirmed by El Mahrad et al. (2020). Nevertheless, in summary only minor differences regarding the impact of the different macrophyte scenarios were found, in terms of lagoons, service categories and standard deviations (i.e. stakeholder agreement).

3.3.3. Macrophyte habitat assessment

ES potential of macrophytes

Eleven macrophyte experts assessed and compared seven different macrophyte habitats ranging from submerged (i.e. seagrass, seaweed, charophytes, pondweed) to emergent habitats (i.e. reeds, saltmarshes dominated by *Salicornia spp*. and by *Aster spp.)*. As shown in Figure 10, the highest potential to provide ES was assigned to reeds and tall forb communities (potential value of 83.0 out of 125.0), then seagrass beds (71.0) and seaweed communities (62.0). Experts assessed pondweeds to be of lowest potential (51.0). Regarding services, all macrophyte habitats in general provide highest potential for cultural services as natural heritage and conservation (C8: 5.0), education and training (C4: 4.0) and research and traditional knowledge (C3: 4.0), but also from other service categories like genetic material of (marine) plants (P5: 4.0) and biodiversity (RM7: 4:0).

Similar to the weighted impact score described in Chapter 3.2.2, the RI values of the scenario assessments (Figure 9) are combined with the habitat potential results by simple multiplication (RI in % × ES potential). Thereby, habitats can be identified that are most important for single services. For example, combined results show that the most important habitat (i.e. of high potential) supporting the service of coastal erosion prevention (RM3) is the reed belts. Besides, results show that there is very limited potential by macrophyte habitats to support active recreation (C1), which is even affected negatively by macrophyte expansion according to impact results.

	Expert values (n=11; median values)									**Indicator values**							
	Submerged hab.				Emergent hab.					Submerged hab.				Emergent hab.			
Ecosystem services	Seagrass	Seaweed	Charophytes	Pondweed	Reeds	Salicornia sp.	Aster sp.	**Median**	**SD** (average)	Seagrass	Seaweed	Charophytes	Pondweed	Reeds	Salicornia sp.	Aster sp.	**Median**
P1: (Marine) Plants used for human nutrition	0	2	0	0	1	2.5	1	*1*	*1.1*	1.5	3.5	0	2	2.5	3	0.5	2
P2: (Marine) Plants used as material	4	2	1	1	5	0.5	0.5	*1*	*1.2*	4	5	1	1	5	2	0	2
P3: (Marine) Plants used for energy	1	1	0	1	3	0.5	0.5	*1*	*0.9*	2.5	5	0.5	0.5	5	0.5	0	0.5
P4: (Mar.) Animals used for nutrition, material, energy	3	3	1.5	2	2	0.5	0.5	*2*	*1.4*	5	2	1	1	1	1	1	1
P5: Genetic material of (marine) plants	4	3	4	3.5	3	4	3.5	*4*	*1.1*	1	1	1	1	5	1	1	1
P6: Genetic material of (marine) animals	3	3	3	2.5	2	1	2	*2*	*1.1*	5	2	1	1	1	1	1	1
RM1: Mediation of wastes and pollutants	3	3	3	3	4	2	2.5	*3*	*1.3*	1	5	1	1	3	2	2	2
RM2: Mediation of nuisances (anthropogenic origin)	2	0	1	0.5	4	1	1.5	*1*	*1.3*	2	1	1	1	3	1	1	1
RM3: Mass stabilization and control of erosion rate	4	2	3	3	5	3	3	*3*	*1.2*	3	1.5	1	0.5	5	2.5	4.5	2.5
RM4: Hydrological cycle and water flow regulation	4	2	1	1.5	4	1.5	1.5	*2*	*1.4*	2	1	0.5	0.5	5	3	3.0	2.0
RM5: Wind protection	0	0	0	0	4	1	1	*0*	*0.6*	0	0	0	0	5	1	1	0
RM6: Lifecycle maintenance and pollination	2	2	2	1	2	2	4	*2*	***1.7***	4	3.5	1	1	1	1	1	1
RM7: Biodiversity and habitat	5	5	4	4	5	3	4	***4***	*1.1*	4	4	1.5	1.5	3	2.5	2.5	2.5
RM8: Pest and disease control	3	3	3	2.5	2.5	2	2	*2.5*	*1.0*	1	1	1	1	5	1	1	1
RM9: Nutrient regulation (soil quality)	3	1	2	2.5	4	2	1.5	*2*	*1.4*	3	2	2	2	3	2	2	2
RM10: Regulation of water conditions	3	3	3	3	3	2	2	*3*	*1.1*	4	3	3	3	4	2	2	3
RM11: Atmospheric composition and conditions	3	2	2.5	2.5	4	1	2	*3*	*1.4*	5	4	1	1	5	1	1	1
C1: Recreation and tourism (active)	1	1	1	1	1	1	1.5	*1*	*1.3*	3.5	3.5	1.5	1	3	2.5	3	3
C2: Recreation and tourism (observational)	3	3	2	2	3.5	4	4	*3*	*1.3*	4	4	1.5	1.5	3	2.5	2.5	2.5
C3: Research and traditional knowledge	5	5	4	4	4	4	4	***4***	*1.1*	3	5	1	1	2	1	1	1
C4: Education and training	3	4	4	3	4	4	4	*4*	*1.2*	3.5	3	1.5	1.5	5	4	4	3.5
C5: Culture and heritage	2	3	1	1.5	3	2	2	*2*	***1.6***	5	3	2	2	5	4	4	4
C6: Landscape aesthetics	4	3	3	2	4	4	5	*4*	*1.2*	1	5	1	1	2	1	1	1
C7: Symbolic or religious meaning	1	1	0.5	0	1	1	1	*1*	*1.2*	3	2	1	1	5	2.5	2.5	2.5
C8: Natural heritage and conservation	5	5	5	4	5	5	5	***5***	*0.6*	5	3.5	1.5	1.5	5	3.5	4.5	3.5
Sum	71.0	62.0	54.5	**51.0**	**83.0**	54.5	59.5			76.0	73.5	**28.5**	29.5	**91.5**	48.5	47.0	

Figure 10. Results of ES assessment (P – provisioning, RM – regulating and maintenance, C – cultural) in macrophyte habitats of the Baltic Sea. Values indicate no potential (0) to very high potential (5). Median values and standard deviations (SD) from macrophyte experts and literature-based results are shown for each habitat (listed according to the sea-land gradient) (reprinted from Paper IV).

The indicator-based results reflect a similar pattern with main differences for two submerged habitats (i.e. pondweed, charophytes) being assessed of low potential. Literature data for these two habitats was hardly available, which is why an additional relevance indicator was introduced (i.e. number of WoS articles) and used for 60% of services causing a strong bias towards representation in literature. The discrepancy between expert knowledge and literature results indicates a lack of literature data for the two selected habitats or overrepresentation of others (i.e. reed), highlighting the need for expert knowledge for such large-scale habitat-based assessments.

In summary, main lessons-learnt for applying the habitat assessment is that it is well suitable for identifying differences between ES of macrophytes along the land-sea gradient, thus by direct comparisons instead of separate habitat assessments. Similar results are shown for large-scale assessments using ES potential matrix approaches for terrestrial, coastal and marine ecosystem types in Northern Germany (Müller et al. 2020) and ecosystems across the land-sea interface in the Baltic (Schumacher et al. 2021). Despite the application is quite limited when using indicators, for the Baltic Sea the habitat assessment works well when working with experts. Besides, a good transferability to other shallow coastal waters internationally can be assumed (as shown for the Baltic Sea and the Mediterranean Sea), in particular when data availability is low, and when adapting the assessment scheme to local habitats.

Mapping and spatial extrapolation

As a final step, lagoon-wide ES provision was extrapolated from the small-scale results of the management scenario and habitat assessment, here exemplarily for the Kleines Haff of the Szczecin Lagoon (German part) (Figure 11). Our scenario transect (see Fig. 3) encompasses an approximate area of three hectares (ha). Current submerged vegetation of the Kleines Haff extends over 5,795 ha (Fig. 11.a). Potential submerged vegetation (including angiosperms and charophytes) may increase by 78 % to an area of 10,334 ha under the premise of achieving a GES and a growth limit of up to 3m (according to Porsche et al. 2007). To extrapolate the scenario outcome to the entire area of Kleines Haff, a potential area of 2,137 ha or 25 % of the coastal zone was identified. Exemplarily, focus lies on three extrapolated areas surrounding our scenario transect (Bellin beach).

In Scenario 1, representing current use or state, emergent vegetation (primarily reed belts) covers only small areas of 20 ha (3% of the total extrapolated area) (Fig. 11.b). Contrarily, under potential use or nature protection in Scenario 2 it increases to 17 % (of the total extrapolated area) or 109 ha (Fig. 11.c). Following discussions during scenario assessments, recreational use (or area) was further subdivided for the extrapolation into activities on water and on land (primarily beach area). Recreational water use decreased from 397.57 ha (61%) to 131.13 ha (20 %), whereas recreational use on land did not change in area. Extrapolation results highlight a strong spatial tradeoff and conflict between recreational use (here mainly on water) and expansion of both submerged and emergent macrophytes.

The scenario results (Fig. 5) show a notable difference in impact values compared to our extrapolation results. While the decrease in beach activities is not evident in the extrapolation, as recreational land use remains unaffected by changes in macrophyte distribution, our scenario analysis highlights that increased emergent and submerged vegetation leads to reduced recreational activities, particularly on land. Factors such as reed belts restricting water access and obstructing views diminish bathing opportunities and beach attractiveness. Consequently, achieving GES through macrophyte recovery may not be ideal for the entire area, as it significantly hampers coastal tourism, a vital economic driver. In such cases, the removal of macrophytes from designated areas may be necessary.

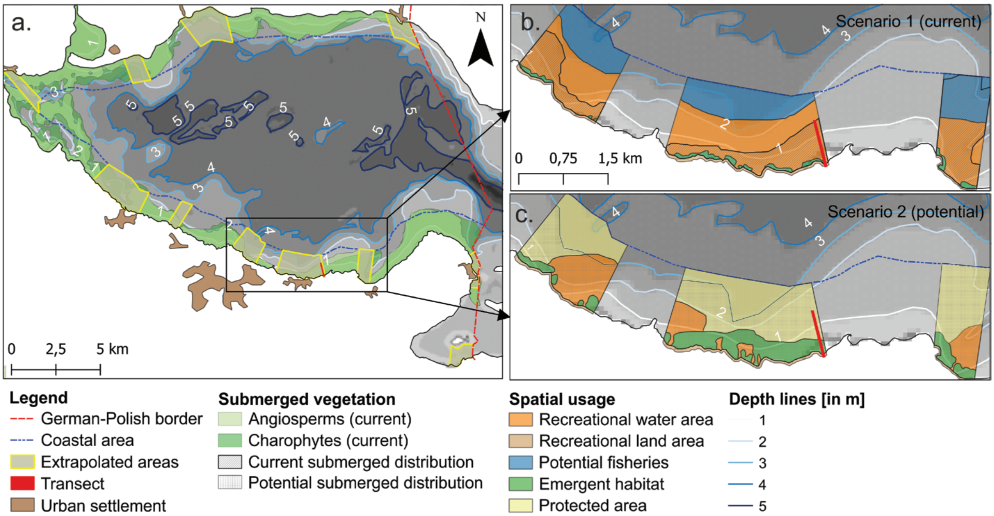

Figure 11. Spatial extrapolation maps of the Szczecin Lagoon showing all extrapolated areas of the German part Kleines Haff (a.), the current spatial use mainly recreation on water and fisheries (b. Scenario 1) and the potential spatial use under nature protection and GES (c. Scenario 2) (reprinted from Paper IV).

The identification of areas for extrapolation also highlights regions crucial for management and policy actions, particularly those with significant importance for the tourism sector. These extrapolation results can guide decision-making processes, informing the designation of nature-protected areas, fishing grounds, water sport zones, and other land use rights. In essence, while some human activities exhibit clear trade-offs concerning space, such as vegetation versus recreational areas on water, others offer synergies, like vegetation and nature protection, or do not compete for space, such as fisheries and recreational water activities.

In summary, the tested extrapolation approach can be suitable and useful within stakeholder discussion and within decision making processes for better understanding of local needs, demands and possible trade-offs or synergies. Despite these results, it can be suggested to complement or expand this approach to a participatory mapping, which was successfully applied by Karstens et al. (2018) to identify the locations for certain measures, here for floating wetlands.

3.4. Applicability and transferability of assessment approaches

During the last decades, a diverse pool of ecosystem service assessment methods was developed and offer a large range from socio-cultural methods, to biophysical and economic assessment methods (Harrison et al. 2018). When planning to apply an ecosystem service assessment, the most pivotal question is, for what purpose? Methods need to be carefully picked according to their possible outcomes in order to avoid incorrect use of the assessment results.

The developed scenario-based approach shows a broad range of possible applications within coastal management and policy implementation. Within this thesis, different fields were tested, ranging from urban planning measures and water policy (Paper I), beach management (Paper II), coastal protection measures (Paper III) and habitat restoration and nature protection (Paper IV). Other studies also applied this approach for supporting spatial planning processes (Schernewski 2023). Tested for international applicability, the management scenario assessment was successfully applied to Bizerte Lagoon in Tunisia (Paper IV) and for sandy Mediterranean beaches in North-Africa (i.e. Egypt, Tunisia and Morocco) (unpublished data). Based on these results, the approach shows general applicability and transferability to international coastal areas for a variety of management issues.

As synthesis of this thesis, a SWOT analysis was carried out stressing the main strengths, weaknesses, opportunities and threats for applying the developed ESA approaches within European coastal and marine management and policy implementation (Table 9). Summarizing, when applying with caution and well-defined outcomes, ecosystem services can be a very helpful tool in a variety of coastal management issues (as described above).

Table 9. Further developed and adapted SWOT analysis from Paper V (modified after Bull et al. 2016) on ESA in European coastal and marine management and policy implementation

Strengths - Links human and nature - Interdisciplinary - Holistic approach - Works on different scales - Conceptually simple - Supports communication - Supports public participation - Fast application possible - Broad understanding	**Weaknesses** - Limited reliability - Oversimplification - Heterogeneous approaches and low comparability - Weak scientific basis - Focus on anthropocentric-instrumental view on nature - Outcome scale dependent - Difficult to apply - Benefits unclear
Opportunities - Integration into policies - Usage in policy implementation (i.e. specific measures) - International harmonization of tools and approaches - Better understanding of human-nature interactions	**Threats** - Loss of scientific interest - Loss of interest from policy - Resistance to use results - Competing approaches - Insufficient capacity/ funding - Focus on monetary view - Misleading or biased results - Lack of experts

4

Conclusions

1. Applying the indicator-based MESAT to Baltic estuaries shows a significant increase in cultural services since 1880 (reference state for GES), despite a significant decline in regulating and maintenance services. However, comparing in particular cultural services is challenging due to the co-evolution of socio-ecological systems and the change of relevant indicators over time. Besides, achieving desired GES may be unreachable, particularly for the heavily modified Warnow Estuary. Revising reference states and values is crucial for reachable policy targets.
2. To address these limitations, the short-term future scenario assessment provides a qualitative approach to evaluate future desired states, engaging local experts in assessing the potential impact of achieving these hypothetical scenarios. Identified potential applications of this assessment include supporting awareness raising, fostering stakeholder involvement, and enhancing the acceptance of measures, as implemented by the WFD or by urban planning.
3. In order to compare, evaluate and prioritize concrete management measures, the management scenario assessment tool successfully integrates quantitative and qualitative methods, proven by the case study applications. These methods allow for evaluation and direct comparison of measures, with a baseline scenario, to support decision-making processes and stakeholder engagement

in effecting transformative change, serving as a tool for consensus building, increasing awareness, and reducing misunderstandings.

4. Assessing the Relative Importance of ecosystem services not only fosters a learning effect among stakeholders but also promotes understanding and acceptance of management measures. This process effectively visualizes the perceptions and preferences of local stakeholders, thereby facilitating informed decision-making.
5. Due to COVID-19 and social distancing, this thesis introduces innovative methods for engaging stakeholders in participatory ecosystem service assessments. These include remote assessments, surveys, online discussions, and hybrid formats. They successfully gather information reflecting the knowledge, perceptions, and opinions of stakeholders. Strengths of the online formats include high participant rates, reduced time requirements, high flexibility in scheduling and no travel time. However, a main weakness identified was moderating and activating stakeholders during online discussions, as a then still unfamiliar format.
6. Results of the spatial assessment visualize the values of single macrophyte habitats, and thus highlighting the benefits of implemented nature policies, such as achieving GES under to the WFD or enhancing biodiversity as targeted by the HD. However, while achieving GES for macrophyte recovery is desirable, it may have adverse effects on coastal tourism, e.g., restricted water access, annoyance while swimming, entanglement while boating. Thus, the spatial assessment approach facilitates discussion and the identification of trade-offs between nature protection and human activities, aiming to achieve a sustainable balance.
7. The assessment approaches (i.e. indicators, scenarios) and methods (i.e. quantitative, qualitative) were tested applicable across various topics within coastal management, including coastal protection, beach management, nature protection. While indicator-based assessments are limited to case studies with high data availability of historic and current states, scenario approaches are highly adaptable. They allow for easy and direct comparison of management measures even in data-scarce regions, which was tested successfully for other coastal zones internationally (i.e. Mediterranean Sea).

5

Recommendations

For coastal managers of local municipalities such as beach managers and tourism boards, and decision-makers of environmental agencies on municipality, national and international level

1. ***Value and communicate "invisible" benefits of beach wrack***. Indirect, often invisible ecosystem services (mostly regulating and maintenance services) can be easily overlooked. In particular, crucial services provided by beach wrack on sandy beaches include coastal protection, biodiversity and habitat provision. Ecosystem service assessments unveil direct and indirect benefits to humans making them visible and easily understandable.
2. ***Understand and compare the consequences of beach cleanings***. Current beach management practices, such as complete removal of beach wrack to meet tourism demand, highlight the trade-offs between cultural services (like beach tourism) and coastal protection, both vital for sandy beaches. Removing beach wrack through beach cleanings diminishes overall ecosystem service provision of Baltic sandy beaches. Thus, it is strongly recommended to leave beach wrack undisturbed or adopt less harmful cleaning technique.
3. ***Support nature-based solutions when planning coastal protection measures***. The evaluation of coastal protection schemes highlights that nature-based solutions offer greatest synergies and overall ecosystem service provision com-

pared to conventional methods. For example, beach nourishment is aligned with cultural services, particularly recreational beach activities, while mussel farms support provisioning services, such as animal food sources. Additionally, submerged macrophytes contribute to regulating and maintenance services, such as water quality regulation.

4. ***Use synergies and value the potential of natural resources.*** Ecosystem service assessments can uncover potential synergies between services. In the context of beach management, beach wrack removed during cleaning remains a valuable natural resource. For example, it can be further utilized for biogas production, construction material, and fertilizer. These values of natural resources or ecosystem components can be made visible and understandable, and thus are not wasted.
5. ***Visualize the benefits of macrophytes to human wellbeing***. When macrophyte coverage is high (under GES according to WFD), particularly reed belts, it is often perceived as having negative effects on beach and coastal tourism. This perception stems primarily from reduced access to water or beach, and potential annoyance or entanglement during swimming or boating. Despite both emergent and submerged macrophytes present a clear trade-off for tourism, they play crucial roles in coastal protection, maintaining water and habitat quality. As such, they should not be removed except in special cases.
6. ***Find common ground among stakeholders.*** Participatory scenario-based ecosystem service assessments support in identifying and clarifying misconceptions and misunderstanding among stakeholders. To address the main challenges of decision-making processes, such as consensus building and conflict resolution, scenario assessments can be suggested to enhance stakeholder approval or acceptance of measures (i.e. achieving a GES despite tourists´ annoyance by macrophytes).
7. ***Increase awareness among stakeholders***. Participatory scenario-based ecosystem service assessments are recommended as a tool for awareness raising and environmental education, supporting stakeholder involvement and dialogue in decision-making processes within coastal areas.
8. ***Internalize indirect costs.*** Management measures, such as beach cleanings, induce high costs for local municipalities due to human activities, such as pollution and littering. Thus, it is recommended to internalize these management costs, for example, by the polluter-pays, such as tourist tax, or producer-pays principle, such as producer tax.

6

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"I suggest to everyone: Look in the mirror. Ask yourself: Who are you? What are your talents? Use them, and do what you love."

— Sylvia A. Earle

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8

Summary in Lithuanian

ĮVADAS

Pakrančių ekosistemos, kaip tranzitinės zonos tarp sausumos ir jūros, yra labai dinamiškos ir biologiškai produktyvios. Jos apima įvairias buveines – nuo estuarijų, pakrančių lagūnų, pelkių, druskingų pievų, smėlėtų ar akmenuotų paplūdimių iki jūros žolių bei makrofitų sąžalynų. Jos užtikrina svarbias biologines ekosistemų struktūras, funkcijas ir procesus, pavyzdžiui, tam tikrais periodais tampa žuvų nerštavietėmis ir paukščių veisimosi vietomis (Kraufvelin et al. 2018), jose vyksta maisto medžiagų apykaita ir kaupimasis (Herbert 1999), anglies dioksido sekvestracija ir ilgalaikis saugojimas (Beaumont et al. 2014), užtikrinama pakrančių apsauga nuo erozijos (Spalding et al. 2014), didelės įvairovės genofondo palaikymas (Burke et al. 2001).

Pakrančių ekosistemos patiria didelį žmonijos veiklos poveikį. Ypač pastaraisiais dešimtmečiais jos nuolat ir sparčiai degraduoja dėl intensyvaus šių teritorijų panaudojimo. Prognozuojama, kad nuolatinis gyventojų skaičiaus augimas, kurį ypač skatina urbanizacijos procesai pakrančių teritorijose, lems planetos gyventojų skaičiaus padidėjimą iki 9,7 mlrd. 2050 m. (UN DESA 2021). Dėl to išaugs ir žmogaus veiklos poveikis ekosistemoms, visų pirma, didės atliekų susidarymo intensyvumas, t. y. pakrančių taršos ir jūros šiukšlių kiekio didėjimas, ypač dėl intensyvėjančio turizmo (UNEP 2021 m.). Dėl žemės ūkio veiklos baseine, pakrančių ekosistemose, ypač lagūnose, didėja maistinių medžiagų kaupimasis ir eutrofikacija (Bartoli et al., 2018, Žilius et al., 2018, Friedland et al. 2019). Be to, pakrančių ekosistemas labai veikia klimato kaitos padariniai – potvyniai, jūros lygio kilimas, kiti ekstremalūs reiškiniai (Neumann et al. 2015). Dėl šio antropogeninio poveikio reikia skubiai keisti pakrančių valdymo politiką bei įgyvendinti priemones, kurios padėtų išsaugoti sveikas pakrančių ekosistemas bei užtikrintų jų naudojimo tvarumą.

Europos Sąjungoje (ES) aplinkosaugos ir gamtosaugos politika įgyvendinama keletu krypčių, kuriomis siekiama kovoti su ekosistemų degradacija. ES vandens apsaugos politikos srityje svarbiausios dvi direktyvos – Vandens pagrindų direktyva (VPD) ir Jūrų strategijos pagrindų direktyva (JSPD), kuriomis siekiama geros visų paviršinių, pakrančių ir jūrų vandenų ekologinės arba aplinkos būklės. Kita svarbi ES gamtos apsaugos politikos dalis – Biologinės įvairovės strategija iki 2030 m., kuri apima Buveinių direktyvą, Paukščių direktyvą ir saugomų teritorijų ekologinį tinklą „Natura 2000“. Vienas iš pagrindinių Biologinės įvairovės strategijos tikslų – išsaugoti ir atkurti ekosistemas ir jų teikiamas paslaugas. Ši strategija yra ambicinga, tačiau įgyvendinama nepakankamai sparčiai.

Ekosisteminių paslaugų sąvoka, dar 1960 m. kilusi iš ekologinės ekonomikos sampratos (Costanza et al. 1998), yra pripažinta kaip tinkama politikos įgyvendinimo rėmimo priemonė. Ekosisteminių paslaugų koncepcija, kaip galimybė paremti Biologinės įvairovės strategijos iki 2030 m. įgyvendinimo procesus, iš dalies jau yra integruota į ES politiką (Bouwma et al. 2018). Ekosisteminės paslaugos apibrėžiamos kaip tiesioginė ar netiesioginė nauda žmonėms, gaunama iš ekosistemų (Tūkstantmečio ekosistemų vertinimas, 2005 m.). Nors egzistuoja kelios klasifikavimo sistemos, šiame tyrime remiamasi Bendrąja tarptautine ekosistemų paslaugų klasifikacija (CICES) pagal Haines-Young‘ą ir Potschin-Young‘ą (2018), kurioje išskiriamos trys ekosisteminių paslaugų kategorijos: aprūpinimo paslaugos, reguliavimo ir palaikymo paslaugos ir kultūrinės paslaugos. Pavyzdžiui, pakrančių ekosistemos suteikia buveines žuvims (palaikymo paslauga), kurios gali būti naudojamos žmonių mitybai (aprūpinimo paslauga). Jūros žolės ar iškilusių makrofitų sąžalynai gali tarnauti ir kaip bangų slopinimo barjeras, todėl atlieka pakrančių apsaugos funkciją (palaikymo ekosisteminė paslauga). Turizmo srityje pakrančių ekosistemos taip pat turi svarbią socialinę ir ekonominę vertę (kultūrinės ekosisteminės paslaugos). Apibendrintai vertinant ekosistemines paslaugas, galima nustatyti, kokią naudą žmonėms teikia ekosistemos.

Egzistuoja daugybė ekosisteminių paslaugų vertinimo metodų, kurių pasirinkimo sprendimų schema yra pateikiama Harrison ir kt. (2018). Dauguma ekosisteminių paslaugų tyrimų orientuoti į sausumos ekosistemas, o vertinant jūrų ir pakrančių ekosistemines paslaugas susiduriama su tam tikrais ypatumais ir sunkumais, kai yra siejama sausuma ir jūra (Liquete et al. 2013). Tačiau pastarąjį dešimtmetį tyrėjai skyrė nemažai dėmesio būtent pakrančių ir jūrų ekosistemoms. Kuhn ir kt. (2021) nustatė pagrindines žinių spragas, susijusias su pripažintų ir suderintų ekosisteminių paslaugų metodų bei apibrėžčių trūkumu Baltijos jūroje, ypač jūrų politikos įgyvendinimo kontekste. Heckwolf ir kt. (2021) pateikė sisteminę Baltijos jūros pakrančių ekosisteminių paslaugų apžvalgą, o Schumacher ir kt. (2021) bei Inácio ir kt. (2018) sukūrė jūrų ekosistemų paslaugų vertinimo priemonę MESAT, pritaikytą pakrančių vandenų ekosisteminių paslaugų teikimo santykiniams pokyčiams vertinti. Nors vertinimo kiekybiniai rodikliai yra pateikti, pavyzdžiui, von Thenen ir kt. (2020) bei Liquete ir kt. (2013), dėl erdviškai tikslių duomenų trūkumo jų taikymas pakrančių ir jūrų ekosistemoms vertinti tebėra iššūkis, ypač konkrečiose valdymo ir politikos įgyvendinimo srityse. Valdymo sprendimai gali būti ypač kompleksiški, atsižvelgiant į specifines vietos socialines ir ekonomines aplinkybes, pavyzdžiui, kaimiškų vietovių plėtrą, miestų planavimą, tvarų turizmą, gamtos apsaugą, pakrančių apsaugą ir įvairias kitas prioritetines sritis.

Pagrindinė disertacijos hipotezė teigia, kad ekosisteminių paslaugų vertinimas, pritaikytas konkrečioms valdymo sritims, pavyzdžiui, paplūdimiams tvarkyti, pakrantėms apsaugoti ir buveinėms išsaugoti, padeda įgyvendinti pakrančių valdymo strategiją ir politiką. Šiame darbe sprendžiami pagrindiniai ekosisteminių paslaugų integravimo į pakrančių valdymą ir politikos įgyvendinimą iššūkiai, įskaitant didelius vertinimo laiko poreikius bei į galutinį vartotoją orientuotų bei suderintų vertinimo metodų trūkumą. Disertacinio darbo hipotezė tikrinama dedukciniu būdu. Remiantis keleto konkrečių atvejų tyrimais, disertacijoje siekiama apibendrinti valdymo priemonių pasekmes bei pateikti gaires pakrančių zonai valdyti.

Tyrimo tikslas ir pagrindiniai uždaviniai

Šio darbo tikslas – patobulinti ir išplėsti ekosisteminių paslaugų vertinimo metodus, skirtus konkrečioms pakrančių valdymo sritimis, siekiant parodyti valdymo pasekmes gamtos vertei ir žmonių gerovei.

Buvo iškelti šie uždaviniai:

1. palyginti istorinę ir dabartinę pakrančių vandens telkinių būklę, retrospektyviai taikant pusiau kiekybinį metodą MESAT, kuriuo vertinami santykiniai ekosisteminių paslaugų pokyčiai, siekiant parodyti buvusios geros ekologinės būklės naudą praeityje;
2. plėtoti ateities scenarijų vertinimo kokybinį metodą, kuris lygintų dabartinę pakrančių vandens telkinių būklę su politikoje numatyta būsima būkle. Šis metodas skirtas parodyti, kaip suinteresuotosios šalys suvokia ir priima politikos priemonių įgyvendinimą, įskaitant GEB siekimą pagal Vandens pagrindų direktyvą, ypač pakrančių miestų planavimo kontekste;
3. plėtoti integruotą valdymo scenarijų vertinimo metodą, skirtą palyginti dabartinei būklei (bazinis scenarijus) su galimais valdymo scenarijais. Tai apima

konkrečias valdymo priemones, įgyvendinamas apibrėžtose tyrimo vietose, pasirinktuose pakrančių ruožuose;
4. toliau plėtoti erdvinį ekosisteminių paslaugų vertinimo metodą, apimantį buveinių vertinimą, žemėlapių kūrimą ir ekstrapoliaciją. Šis metodas leistų įvertinti ir palyginti įvairių makrofitų buveinių ekosisteminių paslaugų potencialą, siekiant pagrįsti gamtos apsaugos politiką;
5. išanalizuoti vertinimo metodų ir požiūrių bendrą pritaikomumą ir perimamumą tarptautiniu mastu, ypač Viduržemio jūros regione, sprendžiant įvairius valdymo klausimus, aptarti šių metodų taikymo galimybes ir apribojimus įgyvendinant pakrančių valdymo politiką.

Darbo naujumas

Šiame tyrime pateikiama holistinė Baltijos jūros estuarijų, smėlėtų paplūdimių, pakrančių lagūnų ir makrofitų ekosisteminių paslaugų inventorizacijos apžvalga.

Siekiant pašalinti pastebėtus jūrų ekosisteminių paslaugų vertinimo įrankio MESAT (Inácio et al. 2018) trūkumus, parengtame ateities scenarijų vertinime pereita nuo rodikliais pagrįsto istorinių būklių palyginimo prie ekspertinio hipotetinių ateities būklių scenarijų vertinimo (I straipsnis). Jame buvo integruoti realūs miestų planavimo dokumentai.

Valdymo scenarijų vertinimo etape buvo pateikti konkrečių valdymo priemonių, pavyzdžiui, paplūdimių tvarkymo (II straipsnis) arba pakrančių apsaugos sistemų (III straipsnis), poveikio pakrančių ekosisteminėms paslaugoms pavyzdžiai. Šis valdymo scenarijų vertinimas palengvina valdymo priemonių galimybių vertinimą ir palyginimą bei sprendimų dėl jų įgyvendinimo priėmimą. Scenarijų kūrimas yra svarbus naujas komponentas, leidžiantis kurti realia valdymo praktika pagrįstus scenarijus, padedančius priimti sprendimus ir parengti valdymo rekomendacijas.

Vienas iš pagrindinių metodikos plėtros aspektų yra internetinių ir (arba) mišrių metodų taikymas. Dėl COVID-19 pandemijos vertinimo metodus reikėjo toliau plėtoti ir pritaikyti, kad būtų sudarytos palankesnės sąlygos dalyvauti suinteresuotosioms šalims, naudojant skaitmenines ir internetines priemones, pavyzdžiui, nuotolinius individualius vertinimus, internetines diskusijas ir apklausas. Lengvai pritaikoma internetinė suinteresuotųjų šalių dalyvavimo priemonė pateikta II straipsnyje, o ekspertų dalyvavimo internetu vertinant erdvines buveines pavyzdys pateiktas IV straipsnyje.

Dar viena svarbi scenarijų vertinimo metodo naujovė – įvestas „santykinės svarbos“ balas, pagal kurį ekosistemų paslaugos vertinamos atsižvelgiant į jų svarbą vietos lygmeniu, remiantis suinteresuotųjų šalių nuomone. Šis balas yra labai svarbus nustatant valdymo pasekmes konkrečioje vietovėje.

Toliau tobulinant metodiką buvo atliktas makrofitų ekosisteminių paslaugų potencialo erdvinis buveinių vertinimas, taikant lyginamąjį metodą. Šioje metodikoje integruoti rodikliais pagrįsto metodo ir valdymo scenarijaus vertinimo rezultatai. Naudojant esamus rodiklius, atrinktus pakrančių ir jūrų ekosistemų paslaugoms (von Thenen et al. 2020), šiame vertinime jie buvo toliau tobulinami, pritaikomi ir diferencijuojami, įtraukiant makrofitų ekspertų vertinimą, pavyzdžiui, rodiklių reitingavimą (IV straipsnis). Pateikiamas išsamus ekosisteminių paslaugų ir atitinkamų vertinimo rodiklių, pritaikytų specialiai makrofitams, sąrašas.

Išbandytas valdymo scenarijų vertinimo metodo pritaikomumas tiriant kitas pakrančių teritorijas, šiuo atveju, Šiaurės Afrikos Bizerto lagūną (Tunisas) (IV straipsnis) ir smėlio paplūdimius Egipte, Maroke ir Tunise (pateiktas rankraštis).

Rezultatų mokslinė ir praktinė reikšmė

Šiame tyrime nagrinėjamas ekosistemų būklės pokyčių poveikis jų teikiamoms ekosisteminėms paslaugoms, lyginant istorinę (1880 ir 1960 m.), dabartinę (2018 m.) ir būsimą (2040 m.) vandens telkinių būklę. Yra keletas galimybių pritaikyti šiuos rezultatus įgyvendinant Vandens pagrindų direktyvą, pavyzdžiui, palyginti skirtingos ekologinės būklės pakrantės lagūnų teikiamas ekosistemines paslaugas bei pademonstruoti geresnės vandens kokybės naudą, planuojant miestus, vertinant įvairias miestų plėtros priemones, siekiant didžiausios ekonominės gerovės (I straipsnis).

Papildomuose II–IV straipsniuose nagrinėjama jūros tarša plastiku ir jūros šiukšlėmis. Norint rasti šios problemos sprendimą, yra labai naudinga ją nagrinėti būtent iš antropocentrinio požiūrio perspektyvos kreipiant dėmesį į ekosistemų teikiamą naudą. Pakrančių ir jūrų ekosistemų ekosisteminių paslaugų vertinimai dažnai būna pernelyg platūs ir sudėtingi konkrečioms priemonėms nagrinėti, todėl šiame tyrime ekosisteminių paslaugų vertinimo metodai testuojami, taikomi ir toliau plėtojami būtent konkrečių atvejų studijose.

Šiuo tyrimu užpildoma spraga tarp mokslinėje literatūroje pateikiamų ekosisteminių paslaugų vertinimų ir jų praktinio pritaikymo Baltijos jūros pakrančių valdymui ir politikos įgyvendinimui. Pateikiamas Baltijos jūros smėlio paplūdimių ekosisteminių paslaugų sąrašas, įskaitant paplūdimių šiukšlių ir bangų poveikio paslaugų teikimui vertinimą bei konkrečias rekomendacijas dėl tvaraus paplūdimių valdymo (II straipsnis).

Kita svarbi pakrančių valdymo sritis, kuri nagrinėjama šiame darbe, yra pakrančių apsaugos sistema. Nustatyta, kad ekosisteminių paslaugų metodas yra tinkamas vertinti pakrančių valdymo priemones, lyginant įprastus ir naujus, inovatyvius, „kūrimo su gamta“ (angl. k. *building-with-nature*) scenarijus. Vertinimo metodo pritaikymas praktikoje papildytų formalius planavimo ir įgyvendinimo procesus (III straipsnis).

Tyrimas pateikia keletą svarbių įžvalgų apie makrofitų buveinių teikiamą naudą, parodo ekosisteminių paslaugų kompromisus ir sinergiją. Tikimasi, kad šis tyrimas padės geriau suprasti makrofitų buveinių teikiamą naudą žmogui, siekiant jas išsaugoti. Išvados turėtų padėti tvariai valdyti makrofitais apaugusias seklias pakrančių teritorijas (IV straipsnis).

Šiame darbe išvystytą ekosisteminių paslaugų vertinimo priemonę skirtingiems valdymo scenarijams naudojo studentai (>10), rengdami bakalauro ir magistro darbus, šie darbai iš dalies buvo publikuoti (Schernewski et al. 2023, von Thenen et al. 2023). Be to, ši priemonė buvo sėkmingai naudojama mokymo procese (t. y. magistrantūros kursuose Pakrančių ir jūrų valdymas ir Pakrančių inžinerija), kurių metu studentai vertino ekosistemų paslaugas pagal jų pačių parengtus valdymo scenarijus.

Tiek valdymo scenarijų metodą, tiek erdvinių buveinių metodą galima pritaikyti tarptautiniu mastu, nes jie pagrįsti tarptautinėmis mokslinėmis klasifikacijomis (pvz., CICES, EUNIS), stebėsenos sistemomis (pvz., OSPAR) ir (arba) teisės aktais (pvz., Vandens pagrindų direktyva, Buveinių direktyva). Scenarijų rezultatus iš dalies galima perkelti tiesiogiai, jei vertinamos ekosistemos savybės yra panašios, pvz., panašios pakrantės lagūnos ar smėlėti paplūdimiai. Smėlėtų paplūdimių valdymo scenarijų vertinimo metodika buvo pritaikyta pietinės Viduržemio jūros dalies paplūdimiams Šiaurės Afrikoje (t. y. Egipte, Tunise ir Maroke) ir sėkmingai išbandyta su studentų grupe ir suinteresuotosiomis šalimis (nepublikuoti duomenys)..

Rezultatų aprobavimas

Šio tyrimo rezultatai buvo pristatyti penkiose tarptautinėse konferencijose ir trijuose nacionaliniuose seminaruose:

1. EU CONEXUS. Išmaniųjų miestų pakrančių tvarumo dienos, Prancūzija; La Rošelis, 2021 m. balandžio mėn.;
2. EPP Europos konferencija, Tartu, Estija, 2021 m. birželio mėn.;
3. Litoralės konferencija, Kosta da Kaparica, Portugalija, 2022 m. rugsėjo mėn.;
4. 16-oji Alternet vasaros mokykla: *Biodiversity and societal transformation: perspectives on science and policy*, Perresque, Prancūzija, 2022 m. rugsėjo mėn.;
5. EPP Europos konferencija, Heraklionas, Graikija, 2022 m. spalio mėn.;
6. Baigiamasis vartotojų seminaras *Ecocarpet*, Klaipėda, Jūros tyrimų institutas, 2022 m. spalio 4 d.;
7. Jūros tyrimų instituto Ketvirtadienio seminarai 2021 ir 2022 m.;
8. ZUG tinklaveikos renginys „Jūrų šiukšlės“, Berlynas, 2023 m. spalio 16 d.

Disertacijos struktūra

Disertacijos santrauką sudaro: įvadas, medžiaga ir metodai, rezultatai ir diskusija, išvados, rekomendacijos, literatūros sąrašas. Disertacijos santraukos apimtis – 83 puslapiai. Disertacijos santraukoje panaudoti 77 literatūros šaltiniai. Disertacijos santrauka parašyta anglų kalba. Joje yra 8 lentelės ir 11 paveikslų.

TYRIMŲ MEDŽIAGA IR METODAI

Siekiant taikyti ir toliau plėtoti jūrų ekosistemų paslaugų vertinimo priemonę (MESAT; Inácio et al. 2018), metodika buvo kuriama tam tikrais etapais, schematiškai pavaizduotais 1 pav. Buvo nagrinėjamos šios aktualios Baltijos jūros pakrančių ekosistemų valdymo ir politikos įgyvendinimo sritys: 1) prasta vandens kokybė arba prasta ekologinė būklė, susijusi su ES vandens politikos, t. y. Bendrosios vandens pagrindų direktyvos (BVPD), įgyvendinimu; 2) didėjanti tarša šiukšlėmis ir paplūdimių sąnašomis, dėl kurių tvarkymo savivaldybės patiria dideles išlaidas; 3) pakrančių erozija ir pakrančių apsaugos poreikis; 4) mažėjanti buveinių kokybė ir biologinė įvairovė bei poreikis išsaugoti makrofitų buveines, įgyvendinant ES gamtos politiką, Buveinių direktyvą.

REZULTATAI IR DISKUSIJA

Retrospektyvus MESAT taikymas siekiant pademonstruoti BVPD tikslus

MESAT metodas buvo taikomas Warnow ir Schlei estuarijoms Šiaurės Vokietijoje, lyginant jų dabartinę ekosisteminių paslaugų būklę su 1880 m. ir 1960 m. buvusiomis būklėmis, kurios pagal BVPD laikomos, atitinkamai, labai geros ir geros ekologinės būklės etalonais. Rezultatai parodė panašias ekosisteminių paslaugų kaitos tendencijas abiejose estuarijose: laikui bėgant, kultūrinių paslaugų svarba didėjo, o aprūpinimo paslaugos išliko ne itin reikšmingos. Metodo trūkumas tas, kad rodikliai neretai prieštarauja vienas kitam ir gautus rezultatus reikia interpretuoti, be to, skirtingais laikotarpiais tam tikri rodikliai gali būti neaktualūs. Nepaisant to, kad metodas reikalauja daug duomenų ir laiko, jis suteikia įžvalgų apie sistemos plėtrą ir papildomų ekspertinių žinių. Tikslus ankstesnių ekologinių būklių atkūrimas neįmanomas dėl antropogeninių pokyčių, dėl to remiantis istoriniais duomenimis gali būti gauti klaidinantys rezultatai apie geros ekologinės būklės ekosistemų teikiamas paslaugas. Nepaisant to, šio vertinimo rezultatai padeda įsivaizduoti galimą būklės atkūrimo naudą įgyvendinant BVPD priemones.

Ekosisteminių paslaugų vertinimo taikymas ateities scenarijų analizei

Pirma, hipotetinis ateities scenarijus „Warnow 2040“ buvo parengtas remiantis miestų planavimo priemonėmis ir numatant pasiektą gerą ekologinę būklę pagal BVPD. Ekspertai numatė, kad pietinėje miesto dalyje ekosisteminių paslaugų potencialas didės, o šiaurinėje pramoninėje dalyje tendencijos gali būti nevienareikšmės. Diskusijose išryškėjo poreikis patobulinti apibrėžtis ir įtraukti suinteresuotąsias šalis, buvo kritikuojamas scenarijų rengimo sudėtingumas, nes jis komplikuoja atskirų priemonių vertinimą.

Antra, scenarijaus vertinimas buvo pritaikytas Baltijos jūros smėlio paplūdimiams. Jis apėmė santykinės ekosisteminių paslaugų svarbos vertinimą ir ekspertų nustatytų verčių derinimą su literatūroje pateikta informacija apie galimą scenarijaus poveikį, išreikštą balais (4 lentelė). Rezultatai parodė, kad svarbiausios yra kultūrinės paslaugos, o jūros šiukšlės daro joms neigiamą poveikį, tačiau jūros bangavimas turėjo nevienareikšmį poveikį ekosisteminėms paslaugoms. Valdymo rekomendacijos, atitinkamai, galėtų būti paplūdimių valymo poveikio mažinimas bei jūros bangų, kaip energijos ištekliaus, panaudojimas. Techninis įgyvendinimas apėmė skaičiuoklės lentelių bei internetinių apklausų metodus, kurių kiekvienas turėjo privalumų ir trūkumų, susijusių su patogumu naudotojui ir duomenų rinkimu. Iš esmės šis tyrimas gilina supratimą apie žmogaus ir gamtos sąveiką paplūdimių ekosistemose ir suteikia vertingų įžvalgų Baltijos jūros regiono ir kitų šalių politikos formuotojams ir įgyvendintojams.

Trečia, vertindamos įprastinius pakrančių apsaugos ir kūrimo su gamta scenarijus, suinteresuotosios šalys pabrėžė, kad joms trūksta žinių apie medinių pakrantės įtvirtinimų sistemas. Duomenimis grįsti rezultatai buvo laikomi patikimesniais už nepatyrusių suinteresuotųjų šalių pateiktus rezultatus. Nepaisant to, kad scenarijų poveikio balai mažai skyrėsi, buvo pastebėta scenarijų rengimo trūkumų, ypač parenkant sistemos kintamuosius ir prielaidas. Kūrimo kartu su gamta scenarijai atskleidė didesnį ekosisteminių paslaugų potencialą, o suinteresuotosios šalys juos vertino kaip galimą sinergiją, didinančią rekreacinį naudojimą, komercinę veiklą ir biologinę įvairovę. Vertinimo procesas yra tinkamas suinteresuotųjų šalių dalyvavimui, tarpdisciplininėms diskusijoms ir priemonių priimtinumo didinimui visuomenėje, tačiau sprendimams priimti ir įgyvendinti reikalinga išsamesnė analizė.

Makrofitų buveinių ekosisteminių paslaugų vertinimas

Apžvalgoje pateikiamos 25 makrofitų teikiamos ekosisteminės paslaugos – nuo aprūpinimo (pvz., maistu, medžiagomis, energija) iki reguliavimo ir palaikymo (pvz., maistmedžiagių sulaikymo, erozijos kontrolės) ir kultūrinių paslaugų (pvz., rekreacijos, švietimo). Atliekant vertinimą buvo remiamasi suinteresuotųjų šalių apklausomis bei literatūrinių duomenų analize, kurios atskleidė didelę kultūrinių paslaugų svarbą Baltijos jūros pakrantės lagūnose. Metodo pritaikomumas buvo patikrintas Bizerto lagūnoje (Tunisas), atsižvelgiant į tai, kad ekosisteminių paslaugų svarba ir jų vertinimas gali skirtis dėl socialinių, kultūrinių bei ekonominių veiksnių skirtumų Baltijos jūros ir Viduržemio jūros, Afrikos žemyno pakrantėse.

Atlikus buveinių vertinimą nustatyta, kad nendrės turi didžiausią suminį ekosisteminių paslaugų potencialą. Atlikus erdvinę ekstrapoliaciją, galimo makrofitų plitimo atveju išryškėjo kompromisai tarp rekreacinio vietovės naudojimo ir gamtos apsaugos. Šis metodas gali būti naudingas suinteresuotųjų šalių diskusijoms ir sprendimų priėmimo procesams, analizuojant vietovės valdymo prioritetus.

Vertinimo metodų pritaikomumas ir perdavimas

Ekosisteminių paslaugų vertinimo metodai yra naudingas pakrančių valdymo priemonių rinkinys, taikytinas įvairiuose pakrančių regionuose miestų planavimo, paplūdimių tvarkymo, pakrančių apsaugos ir buveinių atkūrimo srityse. SSGG (SWOT) analizė atskleidė jo privalumus (tarpdiscipliniškumas, holistiškumas), trūkumus (ribotas patikimumas, pernelyg didelis supaprastinimas), galimybes (politikos integravimas, tarptautinis suderinamumas) ir grėsmes (mokslinio susidomėjimo praradimas, vertinimo šališkumas). Atidus taikymas ir aiškūs tikslai yra labai svarbūs siekiant maksimaliai padidinti šio metodų rinkinio naudą sprendžiant įvairius pakrančių valdymo iššūkius.

IŠVADOS

1. MESAT rodikliais grindžiami Baltijos jūros estuarijų vertinimo rezultatai parodė, kad nuo 1880 m. kultūrinės paslaugos išaugo, nors ekologinė būklė pablogėjo, o reguliavimo ir palaikymo paslaugų teikimas sumažėjo. Politiniu požiūriu pageidaujama gera ekologinė būklė gali būti sunkiai pasiekiama kai kuriuose vandens telkiniuose, ypač smarkiai pakeistose ekosistemose, tokiose kaip Varnos upės žiotys. Dėl to reikia atidžiai peržiūrėti ir pritaikyti referencines būkles ir jų vertes konkrečiai vietovei. Dėl socialinės-kultūrinės ir ekologinės sistemų koevoliucijos kultūrinės ekosisteminės paslaugos, laikui bėgant, tapo sunkiai palyginamos taikant rodiklius.
2. Siekiant išspręsti šią problemą, ateities scenarijų vertinimui pristatomas pusiau kokybinis metodas, kuriame dalyvauja vietos ekspertai, vertinantys pageidaujamos būklės pasiekimo hipotetinį poveikį artimiausioje ateityje. Galimos šio vertinimo taikymo sritys apima visuomenės informavimą, suinteresuotųjų ša-

lių įtraukimą ir Bendrosios vandens pagrindų direktyvos bei miestų planavimo priemonių priimtinumo didinimą.

3. Konkrečių atvejų tyrimai parodė, kad valdymo scenarijų vertinimas sėkmingai integruoja kiekybinius ir kokybinius metodus, siekiant palyginti, įvertinti ir nustatyti prioritetus konkrečioms valdymo priemonėms. Šie metodai leidžia tiesiogiai lyginti priemonių įgyvendinimo ir bazinį scenarijus, siekiant susitarimo tarp suinteresuotųjų šalių, didinti informuotumą ir mažinti nesusipratimus.
4. Ekosistemų paslaugų santykinės svarbos vertinimas ne tik skatina suinteresuotųjų šalių mokymąsi, bet ir valdymo priemonių supratimą ir priėmimą. Šis vertinimo proceso elementas atspindi suinteresuotųjų šalių suvokimą ir poreikius, taip palengvindamas sprendimų priėmimų pagrindimą.
5. Dėl COVID-19 pandemijos ir socialinės atskirties šiame darbe buvo sukurti metodai, leidžiantys suinteresuotosioms šalims bei ekspertams vertinti ekosistemines paslaugas nuotoliniu būdu – nuo individualių nuotolinių vertinimų, internetinių diskusijų ir apklausų iki hibridinių formatų. Internetinių vertinimo formatų privalumai – didelis dalyvių skaičius, mažesni laiko poreikiai, didelis lankstumas planuojant bei išvengiant kelionės nepatogumų. Pagrindinis nuotolinių metodų iššūkis – suinteresuotųjų šalių moderavimas ir įtraukimas į internetines diskusijas, kurių formatas turėtų būti iš anksto apgalvotas ir išbandytas.
6. Šiame darbe pateikti erdvinio vertinimo rezultatai vizualizuoja skirtingų makrofitų buveinių vertes ir taip atskleidžia gamtos politikos įgyvendinamo naudą, pavyzdžiui, siekiant geros ekologinės būklės remiantis BVPD, arba biologinės įvairovės išsaugojimo pagal Buveinių direktyvą. Nors makrofitų atsikūrimas gali prisidėti prie siekiamos geros ekologinės būklės, tai gali turėti neigiamo poveikio turizmui, kuris yra labai svarbus ekonominis veiksnys lagūnų pakrančių teritorijose. Siekiant tvarios pusiausvyros, erdvinio vertinimo metodas gali padėti aptarti ir nustatyti gamtos apsaugos ir žmogaus veiklos kompromisus.
7. Išbandyti kiekybiniai ir kokybiniai vertinimo metodai, paremti rodikliais bei scenarijų vertinimu, taikytini įvairioms pakrančių valdymo sritims, tokioms kaip pakrančių apsauga nuo erozijos, paplūdimių tvarkymas, gamtosauga. Rodikliais grindžiamus vertinimus galima taikyti tik tais atvejais, kai yra pakankamai duomenų apie istorinę ir dabartinę būklę, o scenarijų metodai yra lankstesni duomenų pakankamumo prasme. Jie leidžia palyginti valdymo priemones regionuose, kuriuose trūksta duomenų, pvz., Viduržemio jūros Afrikos žemyno pakrantės Bizerte lagūnoje.

REKOMENDACIJOS

Rekomendacijos pakrančių valdytojams ir sprendimų priėmėjams, atsakingiems už aplinkos apsaugos politikos įgyvendinimą.

1. ***Suprasti į paplūdimį išmetamų dumbli***ų / m***akrofitų*** sąnašų teikiamą ***naud***ą ***ir*** šią informaciją perteikti ***savivaldybėms.*** Netiesioginės ekosistemų paslaugos (dažniausiai reguliavimo ir palaikymo paslaugos) gali būti nepastebėtos ir dažnai lieka nepripažįstamos. Organinių sąnašų sankaupų smėlio paplūdimiuose teikiamos svarbiausios paslaugos yra pakrančių apsauga ir biologinės įvairovės bei buveinių palaikymas. Ekosisteminių paslaugų vertinimo procese tiesioginė, o ypač netiesioginė nauda žmonėms gali būti pateikta aiškiau ir lengviau suprantama.
2. ***Suprasti ir įvertinti paplūdimių tvarkymo pasekmes***. Norint išsaugoti tvarias pakrančių ekosistemas, labai svarbu suprasti ir nustatyti ekosisteminių paslaugų kompromisus pakrančių valdymo srityje. Dabartinė smėlio paplūdimių tvarkymo veikla, kurios esmė visiškas paplūdimių sąnašų sankaupų šalinimas, atskleidžia pagrindinius kompromisus tarp svarbiausių kultūrinių paslaugų, ypač paplūdimių turizmo veiklos – deginimosi ir maudymosi, ir pakrančių apsaugos. Paplūdimių sąnašų šalinimas, t. y. paplūdimių valymas, nėra palankus bendram ekosisteminių paslaugų teikimui Baltijos jūros paplūdimiuose. Todėl rekomenduojama palikti paplūdimių sąnašas ten, kur jos natūraliai buvo išmestos, arba bent jau taikyti mažiau intensyvų valymą.
3. ***Planuojant pakrančių apsaugos priemones siūlyti pasitelkti gamta pagrįstus sprendimus***. Lyginant įprastines pakrančių apsaugos schemas su gamta pagrįstais sprendimais ir vertinant jų teikiamas ekosistemines paslaugas, pastebėta, kad gamta pagrįsti sprendimai daugiau prisideda prie sinergijos ir bendros naudos. Pavyzdžiui, paplūdimių papildymas smėliu rodo sinergiją su kultūrinėmis paslaugomis (t. y. rekreacinės veiklos paplūdimyje), midijų fermos teikia aprūpinimo paslaugas (t. y. maisto produktai), o povandeniniai makrofitų sąžalynai – reguliavimo ir palaikymo paslaugas (pvz., vandens kokybės reguliavimas).
4. ***Pasinaudoti sinergija ir optimaliau / tvariau*** išnaudoti gamtos išteklių potencialą. Vertinant ekosistemines paslaugas galima nustatyti jų galimą sinergiją. Pašalinus paplūdimių sąnašas, įskaitant makrofitus, valymo procese, šie vertingi gamtos ištekliai gali būti toliau panaudoti įvairiais būdais, pvz., biodujų gamybai, statybinėms medžiagoms (net jei jos užterštos jūros šiukšlėmis) ir trąšoms. Šių gamtos išteklių ir ekosistemos komponentų vertę galima padaryti labiau suprantamą ir tvariau panaudoti.
5. ***Pabrėžti makrofitų naudą žmonių gerovei***. Tyrimo rezultatai parodo, kad didelis makrofitų padengimas, ypač nendrių juostos, turi neigiamą poveikį paplūdimiams ir pakrančių turizmui. Tokiose vietose mažėja galimybės mau-

dytis ar degintis, taip pat maudantis ar plaukiojant valtimi gali kilti susierzinimas įsipainiojus į makrofitus ar jų sąnašas. Nors tiek helofitai, tiek panirę bei plūdurlapiai makrofitai yra aiškiai nepalankūs turizmui, jie yra labai svarbūs pakrančių apsaugai, vandens ir buveinių kokybei, todėl neturėtų būti šalinami arba turėtų būti šalinami tik ypatingais atvejais.

6. ***Ieškoti bendro pagrindo susitarimui tarp suinteresuotųjų šalių.*** Dalyvavimas skirtingų scenarijų ekosisteminių paslaugų vertinimuose padeda identifikuoti ir paaiškinti suinteresuotųjų šalių klaidingas nuostatas ir nesusipratimus. Todėl, siekiant spręsti pagrindinius sprendimų priėmimo proceso iššūkius, susijusius su konsensuso siekimu ir konfliktų sprendimu, galima pasiūlyti atlikti scenarijų vertinimus. Tai padėtų suinteresuotosioms šalims labiau pritarti priemonėms, pavyzdžiui, siekiant pagerinti ekologinę būklę, nepaisant to, kad makrofitai trukdo turistinei veiklai.
7. ***Didinti suinteresuotųjų šalių informuotumą***. Scenarijų ekosisteminių paslaugų vertinimą rekomenduojama naudoti kaip informuotumo didinimo ir aplinkosauginio švietimo, t. y. mokymosi proceso, priemonę, remiančią suinteresuotųjų šalių dalyvavimą ir dialogą, ypač priimant sprendimus pakrančių zonose.
8. ***Internalizuoti netiesiogines sąnaudas***: vietos savivaldybės patiria dideles paplūdimių valymo išlaidas, kurias sukelia žmonių veikla, t. y. tarša ir šiukšlinimas. Todėl valdymo išlaidas rekomenduojama internalizuoti, pavyzdžiui, taikant principą „teršėjas moka“ – t. y. turizmo mokestį, arba „gamintojas moka“ – t. y. gamintojo mokestį.

9. CURRICULUM VITAE

Biography. Esther Robbe was born on 1990 August 7 in Ibbenbüren, Germany. In 2014, she graduated with Bachelor's Double Degree in International Business from University of Applied Sciences Dortmund in Germany and from the University ESAN in Lima, Peru. During this, she spent one semester in an international NGO on marine protection for an internship in Panama City, Panama. In 2014 she started her Master's in Integrated Natural Resources Management at the Humboldt University in Berlin, Germany (German state funded scholarship "Deutschlandstipendum") (Supervisor: Prof. Dr. Markus Hanisch, Prof. Dr. Gerald Schernewski). During this, she worked as a scientific assistant at the Department of Economics of Agricultural Cooperatives. After her Master's degree, she was a scientific assistant at the Leibniz Institute of Baltic Sea Research Warnemünde, Germany. In cooperation with this institute, she started PhD position at the Marine research institute of Klaipeda University in 2019 (Lithuanian state funded scholarship) (Supervisor: Dr. Jūratė Lesutienė; Advisor: Prof. Dr. Gerald Schernewski).

Research interests: Coastal and marine management, ecosystem services, marine litter, coastal ecology, macrophytes

Biografija. Esther Robbe gimė 1990 m. rugpjūčio 7 d. Ibbenbiurene, Vokietijoje. 2014 m. įgijo dvigubą tarptautinio verslo bakalauro laipsnį Dortmundo taikomųjų mokslų universitete Vokietijoje ir ESAN universitete Limoje (Peru). Studijų metu vieną semestrą atliko praktiką tarptautinėje jūrų apsaugos nevyriausybinėje organizacijoje Panamos mieste, Panamoje. 2014 m. pradėjo integruoto gamtos išteklių valdymo magistrantūros studijas Humboldtų universitete Berlyne, Vokietijoje (Vokietijos valstybės finansuojama stipendija „Deutschlandstipendum“) (vadovai: prof. dr. Markus Hanisch, prof. dr. Gerald Schernewski). Studijų metu ji dirbo moksline asistente Žemės ūkio kooperatyvų ekonomikos katedroje. Po magistrantūros studijų dirbo moksline asistente Leibnico Baltijos jūros tyrimų institute Varnemiundėje (Vokietija). Bendradarbiaudama su šiuo institutu, 2019 m. pradėjo doktorantūros studijas Klaipėdos universiteto Jūros tyrimų institute (Lietuvos valstybės finansuojama stipendija) (darbo vadovė – dr. Jūratė Lesutienė; konsultantas – prof. dr. Gerald Schernewski).

Moksliniai interesai: pakrančių ir jūrų valdymas, ekosisteminės paslaugos, jūros šiukšlės.

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Ecosystem Service Assessments in Water Policy Implementation: An Analysis in Urban and Rural Estuaries

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Coastal waters provide a wide range of ecosystem services (ES), but are under intensive human use, face fast degradation and are subject to increasing pressures and changes in near future. As consequence, European Union (EU) water policies try to protect, restore and manage coastal and marine systems in a sustainable way. The most important EU directive in this respect is the Water Framework Directive (WFD) (2000/60/EC). Objective is to reach a "good status" in EU waters, following a stepwise and guided process. Our major objective is to test how an ecosystem service assessment can support WFD implementation in practice. We use the Marine Ecosystem Service Assessment Tool (MESAT) that utilizes spatial definitions, reference conditions and the good status according to the WFD as well as data and information gained during the implementation process. The data-based tool allows comparative analyses between different ecological states and an evaluation of relative changes in ES provision. We apply MESAT to two contrasting systems in the German Baltic Sea region, the rural Schlei and the urban/industrialized Warnow Estuary. These data-based assessments show how the ES provision has changed between the historic, pre-industrial state around 1880 (reference conditions with high ecological status), the situation around 1960 (good ecological status), and today. The analysis separates the estuaries into water bodies. A complementary expert-based ES assessment compares the situation today with a future scenario "Warnow 2040" assuming a good ecological status as consequence of a successful WFD implementation. Strengths and weaknesses of the approaches and their utilization in the WFD are discussed. ES assessments can be regarded as suitable to support public relation activities and to increase the acceptance of measures. Further, they are promising tools in participation and stakeholder processes within the planning of measures. However an ES assessment not only supports the WFD implementation, but the WFD provides a frame for ES assessments larger scale assessments in seascapes, increases the acceptance of the ES approach and the readiness of stakeholders to get involved.

Keywords: Water Framework Directive, ecological status, reference conditions, Baltic, Warnow, Schlei, stakeholder involvement, expert assessment

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INTRODUCTION

Estuaries are highly dynamic, unique, and diverse ecosystems (Elliott and Whitfield, 2011). Already for centuries, these systems are subject to human impacts and utilization. As consequence, important species are largely depleted, ecologically valuable habitats are destroyed, water quality is degraded and alien species invasion is accelerated (Lotze et al., 2006). In many coastal ecosystems, the direct anthropogenic pressures are still increasing and ongoing environmental changes, like climate change and sea level rise, cause additional problems. Globally, an urgent need for a restoration and a sustainable management especially of estuaries still exists.

With respect to environmental quality and restoration of estuaries in the European Union (EU), the Water Framework Directive (European Union Water Framework Directive [EU-WFD], 2000) is the most important policy document. It aims to establish and/or maintain a "good ecological status" for all surface waters in the member states. To reach this objective, a comprehensive, integrated approach with a detailed implementation strategy was provided (European Commission [EC], 2003a). This directive is one of the most concrete and ambitious pieces of environmental legislation worldwide. However, nearly two decades after its adoption it did not reach its objectives and many problems and delays in its implementation are still obvious (e.g., Hering et al., 2010; Bouleau and Pont, 2015; Voulvoulis et al., 2017). Recently, the European Commission concluded that much remains to be done to fully achieve the objectives of the WFD (European Commission [EC], 2019).

Especially in estuarine ecosystems, the restoration and recovery is complex, follows different recovery patterns as well as rates and the restoration effectiveness differs between the ecosystems (Borja et al., 2010). The uncertainty how a system reacts to measures is a problem for WFD implementation and the public acceptance of these measures. Therefore, successful management requires integrating expertise and scientific information on one side with local knowledge and views, on the other, into a joint decision-making process. In this respect, ecosystem service (ES) assessments can be beneficial. Estimating the provision of ES under alternative management scenarios allows to link biogeophysical data, socioeconomic information, and stakeholder views in the policy and management process (Granek et al., 2010; Giakoumis and Voulvoulis, 2018).

The potential benefits of ecosystem service assessments for EU policies and WFD implementation are reflected by many studies (Bastian et al., 2012; Maes et al., 2012; Martin-Ortega, 2012; Reyjol et al., 2014). Hartje and Klaphake (2006) and Blancher et al. (2011) provide general academic and conceptual approaches on the relationship between ES assessment and the WFD. COWI (2014) compiled important potential benefits of ES assessments, e.g., to support the assessment and communication of the benefits of the directive, to encourage open communication of the impacts of the WFD implementation, to better understand changes caused by measures, to avoid unintended impacts of measures on other benefits or to obtain more information on who may benefit or lose from measures or non-action. However, these considerations about potential benefits require a proof in practice.

Grizzetti et al. (2016) explored how ecosystem services (ES) concepts are used in water management, especially in WFD river basin management plans, and provide several case studies. Vlachopoulou et al. (2014) and Giakoumis and Voulvoulis (2018) developed approaches that link ES and water management objectives. However, Heink et al. (2016) state that "Although the concept of ES has thrived over the last 10 years, its operationalization is still in its infancy." Further, these studies are focussed on river basins and comparable approaches and suitable assessment tools for coastal waters, meeting a concrete WFD demand, are largely lacking.

According to the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment [MEA], 2005), ES are defined as the benefits humans obtain from ecosystems and coastal ecosystems are among the systems with the highest monetary ES provision. Further, most public benefits are non-tradable and are outside the market values (de Groot et al., 2012). Jobstvogt et al. (2014) underline the cultural ES values of marine protected areas and a recent study provides an overview about the importance of ES and their relevance for human welfare and wellbeing in 32 world-wide coastal lagoons (Newton et al., 2018). Angradi et al. (2016) apply the ES concept to Great Lakes estuarine systems in the United States and Canada, and Luisetti et al. (2014) address comparable estuarine systems in England.

An awareness of benefits and potential relevance of coastal and marine ES exists, but this is still not adequately reflected in research. Publications on ES have increased exponentially during the last 15 years. However, Liquete et al. (2013) summarize in their review that most studies focus on terrestrial ecosystems and that a knowledge gap on marine and coastal ES still exists. This view is supported by Maes et al. (2012), who point out the need of additional research to cover marine ecosystems. Barbier et al. (2011) argue in the same direction and conclude that for coastal and estuarine ecosystems, the value for several services still has not been assessed properly. These shortages are especially true for estuarine ecosystems. According to Elliott and Whitfield (2011) the neglect of estuaries is a result of their inhomogeneity and transitional character, so that they were not perceived as one ecosystem for a long time.

While ES assessments in terrestrial urban systems have a long tradition (Luederitz et al., 2015) and the value of the concept is appreciated (Elmqvist et al., 2015), there are only single examples where an ES assessment took place in industrialized surface waters (Jacobs et al., 2015). The few existing assessment results hardly influenced urban planning and management (Piwowarczyk et al., 2013), but Jacobs et al. (2015) point out that they can be beneficial when engaging stakeholders or to inform policy on strategies for the sustainable use of ES, independently of the WFD.

For inner and outer coastal waters, the WFD provides a typology, spatially defines water bodies, defines reference conditions (high ecological status) and a good status. It provides comprehensive background and preparatory work, but it has to be explored, how this can be utilized as a basis for an ES assessment in practice. The ES assessment in the context of the WFD in estuaries in general and in industrialized, urban estuaries in particular, is an urgent task. For example, the WFD defines how a good status for coastal and marine habitats should look like from an ecological perspective. However, it is uncertain, what the consequences of this desired good status means for humans and for services provided by these ecosystems.

Objectives of this study are: (a) to apply and test a tool that builds upon the WFD typology and utilizes the European ES MAES standard; (b) to show how a data-based assessment can utilize and support major ideas of the WFD, for example by carrying out comparative relative ES assessments between different ecosystem states (present, good, high/reference conditions); (c) to provide comparisons between water bodies/sub-types within coastal estuaries as well as between urban and rural estuaries; (d) to test an expert-based future scenario assessment; and (e) to critically evaluate the practical use of ES assessment approaches for supporting WFD implementation on the local level.

MATERIALS AND METHODS

The Schlei Estuary

The rural Schlei Estuary is a brackish water body with a surface area of 52 km^2 and a total length of 43 km (**Figure 1**). The characteristic shape was formed by subglacial glacio-fluvival erosion processes during the Weichselian glaciation. It is surrounded by a hilly countryside, with altitudes up to 30 m above sea level. The climate is determined by westerly winds with a mean temperature of 8.6°C and a mean annual precipitation of 885 mm in Schleswig (1981–2010, DWD).

Already in the early medieval, Haithabu (near Schleswig) became a major trading center in the Baltic. During Christianization, population and agricultural areas further increased. With industrialization and the connection to the railroad network, fabrics and fish industry experienced economic upswing. In the 1960s and 70s land consolidation and intensification in agriculture changed the landform. In 2015, 53,366 people lived in the connected municipalities around the Schlei concentrated mainly in Schleswig and Kappeln (Statistisches Amt für Hamburg und Schleswig-Holstein, 2014b). Fishery lost its importance as an economic factor, but is still important as cultural heritage and therefore for tourism. However, Kappeln and Maasholm are still considered as important fishery harbors. Already in the 1960s, tourism was an important economic factor (Statistisches Landesamt Schleswig-Holstein, 1964). Nowadays, tourism is a major source of income. In 2014, 84,685 tourist arrivals were recorded (Statistisches Amt für Hamburg und Schleswig-Holstein, 2014a). Furthermore, the Schlei as well as the cities Schleswig and Kappeln are popular tourist destinations for day visitors.

The Schlei can be separated into the inner (near the city of Schleswig), middle and outer (close to the Baltic Sea) Schlei. It is classified as hypertrophic and one of the most eutrophied German Baltic coastal waters (Landesamt für Natur und Umwelt des Landes Schleswig-Holstein [LANU], 2001; Feibicke, 2005). Therefore, the Schlei is in a poor ecological state according to the European Union Water Framework Directive [EU-WFD] (2000). Major source of pollution is the river basin where agricultural causes high nutrient loads (Ohlendieck, 2008). The Schlei catchment covers an area of 667 km^2 and with 82% coverage, agriculture is the dominating land-use form. The average riverine water discharge into the Schlei is about 9.5 m^3/s. Today, in addition, the waterbody is facing an internal fertilization of phosphorous from accumulated sapropelic sediment layers, covering large areas of the inner and middle Schlei (Ripl, 1986).

High freshwater inflow and limited exchange with the Baltic Sea cause strong gradients. The littoral is dominated by reed belts. Other submerged vegetation, e.g., *Zostera marina*, can be found only in scattered patches limited to the outer Schlei. In the entire Schlei *Ulva intestinalis* and *Potamogeton pectinatus* occur (Meyer et al., 2005). Climate change and accelerated sea level rise cause threats for the historical area of Schleswig and the lowlands along the shore.

The Warnow Estuary

The urban, industrialized Warnow Estuary (including Breitling) is surrounded by the city of Rostock, covers an area of 12.6 km^2 and has a total length of 14.4 km (**Figure 2**). The estuary was formed during the Weichselian glaciation. The climate is characterized by its proximity to the Baltic Sea with a mean temperature of 9.2°C and a mean annual rainfall of 621 mm in Warnemünde (DWD, 1981–2010).

First human settlements date back to the 6th century. In the 12th century Rostock became a Hanseatic city with a peak in prosperity in the 15th century. Industrialization in the 19th century brought an economic upswing. In 1960, the overseas port was opened, leading to a further rise in population, economy and industry. Rostock was shaped by the centrally-planned social and economic system of GDR. After the German reunification in 1990, population and economy first decreased and later increased again. In 2015, Rostock had a population of 206,011 inhabitants and a population density of 1,137 inhabitants per km^2 (Hansestadt Rostock, 2016). Nowadays, Rostock functions as transport hub, industry and service centre. Seventy four percent of the Warnow Estuary shore is artificial. Harbor and shipping lanes occupy 37% of the water surface area. Tourism has an increasing economic importance for the region and it became a major Baltic cruise ship harbor. Another reason is that the growing seaside resort Warnemünde belongs to Rostock. In total, 5% of the city zone are nature and landscape protection areas. Fish landings decreased and lost its importance as economic factor. However, traditional small scale fisheries is maintained as a cultural heritage (Landesamt für Umwelt Naturschutz und Geologie Mecklenburg-Vorpommern [LUNG], 2007; Hansestadt Rostock, 2014).

The Warnow Estuary has a water volume is 49.6 million m^3 with a mean depth of 4.0 m and its deepest point at 14.5 m (shipping channel). It is highly eutrophied and in a poor ecological condition, according to the European Union Water Framework Directive [EU-WFD] (2000). Eutrophication is a result of high nutrient loads entering the system from the city

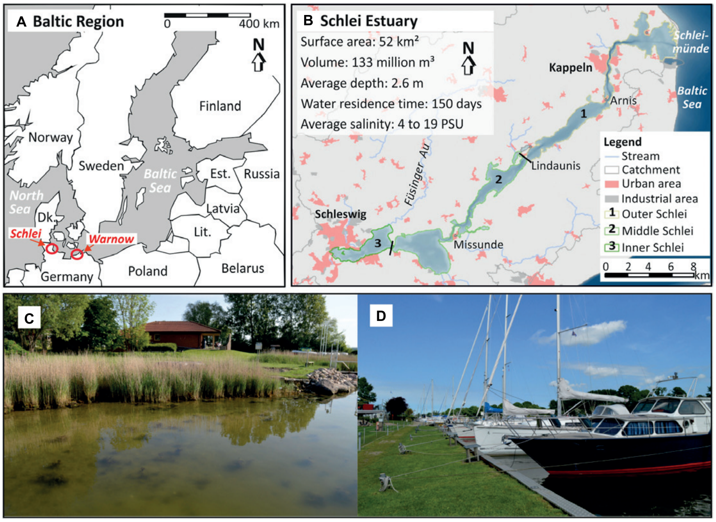

FIGURE 1 | (A) Location of the Schlei and the Warnow Estuary at the Baltic Sea coast of northern Germany, **(B)** basic geographical information about the rural surrounding of the Schlei Estuary and the boundaries of the inner, middle and outer Schlei, **(C)** the coastline of the shallow Schlei is accompanied by reed belts, and **(D)** today, especially water-related tourism determines the visual picture.

and especially with the Warnow River. The Warnow River drains a catchment of 3,222 km^2 and has a mean discharge of 16.5 m^3/s (1989–2009). The sediments in the estuary are sandy and about 10% silty (Müller and Heininger, 1999). The few natural parts of the coast are characterized by low herbaceous vegetation, show a high diversity in (protected) flora and fauna and are accompanied by reed belts and underwater vegetation. The estuary is an important resting and feeding ground for waterfowls and a spawning ground. Ongoing sea level rise together with a sinking coast accelerate coastal erosion (currently 35 cm/year) and increase the risk of storm surges.

Ecosystem Service Assessment Based on the EU Water Framework Directive

For several reasons, an ES assessment in coastal and marine waters is a special challenge compared to terrestrial ecosystems. Terrestrial ecosystems (e.g., forests, fields, urban area) have clearly defined and well visible boundaries, that are largely stable in time. Therefore, the landscape can be subdivided into subsystems. ES can be assessed for each subsystem and compared to each other. Most aquatic ecosystems, like mussel or seagrass beds, are not visible from outside, usually do not have distinct boundaries, and are spatially and temporally variable. Further, the availability of data usually is scarce. On the other hand, the ecology of a water body is relatively homogeneous and defined by major physico-chemical parameters, like depth, tidal range, salinity, temperature, turbidity, residence time, wave exposure and current velocities. In the WFD, these parameters are used for a characterization and classification of all coastal waters, referred to as typology (European Commission [EC], 2003c). The aim of typology is to subdivide the seascape into spatially defined ecological units with similar properties. Coastal waters of one type are subdivided into smaller units, the water bodies, according to pressures and resulting impacts. The water body is the management unit of the WFD. Altogether, the WFD provides a spatial sub-division of the seascape that is well suitable as basis for an ES assessment and forms one major basis for our approach.

Both assessed estuaries are micro-tidal (less than 0.2 m tidal range), have a natural water depth below 30 m and are sheltered with good to moderate water exchange. Therefore, both systems are mesohaline inner coastal waters (type B2) according to the Germany WFD typology (Schernewski et al., 2015). Because of the salinity gradients 5–18‰ (Warnow Estuary) resp. 4–19‰ (Schlei Estuary), both require a sub-division into the subtypes B2a (5–10‰ salinity) and B2b (10–18‰). Often these subtypes define the water bodies, as well. However, because of the complex morphometry, the Schlei Estuary is spatially subdivided into three water bodies (**Figure 1**). The Warnow Estuary, as heavily

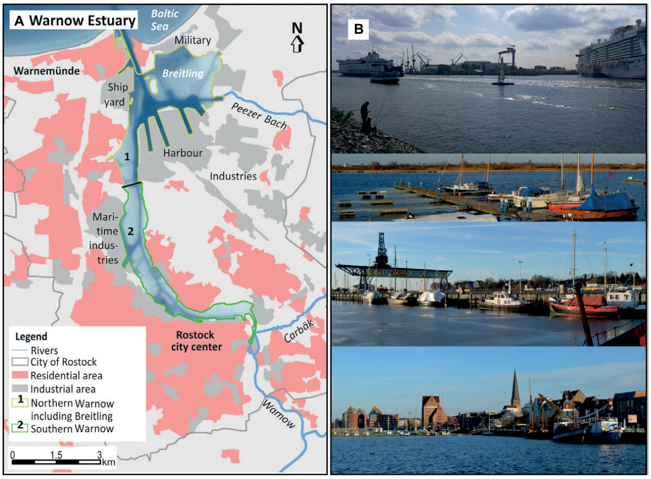

FIGURE 2 | (A) Basic geographical information about the industrial, urban Warnow Estuary and the boundary between northern, industrial and southern, urban Warnow water body, **(B)** the overseas harbor, a sport boat harbor, the city harbor and the city center of Rostock.

modified water body, officially has no further sub-division into water bodies, despite the fact that it covers two sub-types. To follow the WFD strictly, in our approach, we assumed a sub-division into two sub-types and two water bodies (**Figure 2**).

For each type, the WFD defines reference conditions, which describe the biological quality elements that would exist at high ecological status. It means with no, or very minor disturbance from human activities. Biological quality elements include phytoplankton, macro-algae, angiosperms, benthic invertebrate and fish fauna. If ecosystems with high ecological status do not exist, reference conditions can be defined based on historical data, modeling or expert judgment (European Commission [EC], 2003d). For the southern Baltic, it can be assumed that reference conditions indicating a high ecological status were present until the late 19th century (Schernewski et al., 2015). Objective of the WFD is achieving a good surface water status in the near future. The normative definition of the good status assumes that "the values of the biological quality elements for the surface water body type show low levels of distortion resulting from human activity, but deviate only slightly from those normally associated with the surface water body type under undisturbed conditions" (European Union Water Framework Directive [EU-WFD], 2000). The good status for each type is calculated based on the reference conditions. A pragmatic and commonly used approach, according to the WFD implementation guidelines (European Commission [EC], 2003d), is adding 50% to the reference nutrient concentrations to define the threshold for the good status. As consequence, the good status in the southern Baltic reflects a situation that, in most coastal waters, was still present in the early 1960s (Schernewski et al., 2015). In our ES assessments, we built upon these definitions. For WFD reference conditions, we refer to the period 1880–1900 and assume that a good status was still present in the early 1960s.

A major idea to adapt the WFD-typology for MESAT was, that coastal waters belonging to the same type show many similarities with respect to ecological properties, structures and processes. This is also true for the historic conditions. We assumed that the provision of several ES today is and in the past was largely similar in coastal waters belonging to the same type. In this case, once a coastal water has been assessed in detail, much of this information could be transferred to another coastal water belonging to the same type. This would make the assessment a lot less time consuming.

Ecosystem Service Assessment of Historic States

We adapted the Common International Classification on Ecosystem Services (CICES, version 4.3) (Haines-Young and Potschin, 2013) and partly updated it to CICES, version 5.1 (Haines-Young and Potschin, 2018). CICES sub-divides three sections, provisioning, regulating/maintenance and cultural ES. The ES in each section are further hierarchically sub-divided into divisions, groups and classes. We focus on the most detailed "class" level, to minimize the loss of information. Out of 48 ES classes we selected 31 in

MESAT resp. 30 in expert-based assessments to represent coastal water and marine ecosystems. According to Maes et al. (2016), each ES is represented by one or several indicators. Altogether we used 54 indicators (**Figure 4**). The ES assessment methodology is implemented in Microsoft EXCEL, including application guidelines, automated calculations, data aggregation and visualizations. It is called the Marine Ecosystem Services Assessment Tool (MESAT). More details and the tool itself are provided in Inácio et al. (2018).

The Warnow and the Schlei assessments were done independently by two Master students within a time-period of about 4 months. Both students had a suitable interdisciplinary background and were familiar with the locations. First step in the assessment was the search for suitable information and data for every indicator and the three periods in time: the present state, the years around 1960 and the late 19th century. The data was collected for every spatial sub-system, the WFD water body. In a second step, the data for different periods in time, the late 19th century and the early 1960s were compared with each other and with the present state. For the comparative assessment, we used a relative classification system. It allowed for comparing ES with different units directly and enabled a relatively fast application.

For assessing the quantity of changes, we defined eleven scoring classes. No changes (class zero) and five scoring classes each representing increasing and decreasing service provisions. The class boundaries are non-linear (**Figure 3**). For the calculation of the score, the indicator value of the present situation was divided by the value of the status of the earlier periods in time. The allocation into scoring classes means that a concrete value is often not needed, but just the expert judgment to which scoring class changes belong.

We used field, empirical or statistical data, reports and literature, information derived from models and expert knowledge. The data was categorized according to its reliability. These reliability scores were used in **Figure 7**, were the score of indicators were multiplied with factors describing data reliability in form of weighting factors. The higher the data quality the higher the weight and the influence of an indicator on the final ES class score. The reliability scores and factors for weighting were (1) very high (factor 2), (2) high (factor 1.5), (3) moderate (factor 0.75), and (4) low (factor 0.5). A definition of data reliability is provided in the **Appendix**.

Expert Based Assessments of a Future Scenario "Warnow 2040"

In a second application, we provided a future scenario for the year 2040 for the Warnow Estuary, called "Warnow 2040." Guiding question was how an ES assessment could support the practical implementation of the WFD. The scenario assumed a hypothetical implementation of the WFD including an improved, moderate ecological and a good hydrochemical status of the Warnow Estuary. In an internal background paper of the year 2015, the authorities responsible for WFD implementation (LUNG-MV, pers. com.) defined ecological targets for the Warnow Estuary, taking into account that the Warnow Estuary is a heavily modified water body and offers only limited possibilities for improvements. The suggested programme of measures included reduced external nutrient loads and a restoration of shoreline habitats. In our scenario, we assumed that negative eutrophication effects like algal blooms or hypoxia do not occur anymore in 2040 and that other environmental directives are implemented as well. Most important is the implementation of the EU Bathing Water Directive (European Union Bathing Water Directive [EU-BWD], 2006) that allows re-establishing bathing sites in the estuary.

"Warnow 2040" was sub-divided into one scenario spatially focusing on the northern, outer, industrial and the other on the southern, urban Warnow Estuary. We assumed that these scenarios are realistic and are enabled by WFD implementation and improved ecosystem quality. For the southern scenario, covering the old city harbor, we assumed an innovative, sustainable and maritime development offering a high quality of life. It included seaside housings, green spaces for recreation and public water access, including a beach. The city harbor scenario was based on internal plans of the city of Rostock. It further assumed an implementation of the plans for the national garden exhibition in 2025 and planned subsequent urban developments. For the northern, industrial part of the estuary, the scenario assumed that the deepening of the shipping canal and the harbor extension are realized leading to an increase of industry, construction (shipyard) and services. We assumed that near the seaside resort Warnemünde, maritime tourism and cruise shipping increased. This scenario was based on compiled internal plans of the city of Rostock and the Rostock Port company. The two scenarios were visualized with photographs and maps in a PowerPoint presentation.

The assessment involved 14 scientists with different background as well as 6 experts from different regional authorities, which are responsible or at least familiar with WFD implementation. The assessments were carried out within 4 meetings, face-to-face and via teleconferences. On average, the meetings lasted about 2 h and started with a short introduction including background and objectives, followed by the presentation of the "Warnow 2040" scenarios (altogether about 30 min). After an introduction into the ES assessment tool, the experts were asked to carry out an assessment individually on paper, which took about 35 min. The experts compared both scenarios with the present state of the estuary and scored, based on their perception of the changes, relative differences for each ES class separately using the scoring system shown in **Figure 3**.

For this assessment, a sub-set of 30 relevant ES classes were pre-selected by the authors, based on MESAT. After the individual assessment, the scores of each expert were entered into an EXCEL sheet. The following discussion gave the experts the possibility to raise questions, settle misunderstandings and, in case, to modify scores. Aim was not to unify the scores and views. Afterward the experts had the possibility to discuss the suitability of the ES and the indicators behind, the approach and the usability of the system within WFD implementation. The discussion on average took nearly 1 h.

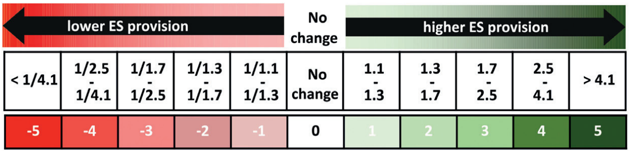

FIGURE 3 | The relative scoring system indicates changes between two different periods in time. For example, the score 1, indicating a slightly higher ES provision, is given when the increase in the present state is higher by a factor of 1.1–1.3 compared to a historic state.

Additionally all experts carried out a self-assessment in five classes, ranging from poor to excellent, with respect to geographical knowledge of the Warnow Estuary, knowledge about its ecological state and knowledge about the WFD.

RESULTS

Historic Development: Comparison of Schlei and Warnow

Altogether 31 ES classes were assessed based on 54 indicators. The assessments of the rural Schlei and the urban Warnow Estuary show many similarities. This is especially true for the provisioning and cultural services (**Figure 4**). The provisioning services in Schlei and Warnow are restricted to animal output, namely fisheries, and materials for processing, e.g., the use of eelgrass and reed, mainly for roofs. While the use of reed steadily declined during the last century in both systems, fishing shows a different development. In the Schlei, Nellen (1967) observed 16 limnic species and 7 marine species occupying habitats according to the salinity gradients. Commercially important fish species are Herring, Roach, Plaice, Cod, Flounder, Perch, European eel, and Sea trout. Using fishing techniques such as wires, eel-wires, gillnets for herring and flounder as well as seine fishing, the total landings were 236 t annually (2013–2015) compared to 109 t in the early 1960s (Nellen, 1963). Fisheries in the 1880s were much more intensive and important, and more fish species, even smaller and bony ones were used. While eutrophication caused an increase in fish landings during the last decades, the industrialization of the Warnow caused a steady decline. In 1880, several other provisioning services were reported for the Warnow, like the use of water for irrigation, the use of seaweed and reed in agriculture and small scale fish and mussel cultivation. Very likely, in 1880, similar uses existed in both systems, but were not documented for the Schlei. A recent new human activity in the Warnow are wind turbines for energy production and plans exist for the Schlei coast, as well. The use of animals or plants from coastal waters does not have a tradition in Germany or, at least, this tradition has been lost already a century ago. As consequence, provisioning services are of minor importance.

Similar in both systems is the strong increase in cultural services as result of steadily increasing tourism (**Figure 4**). Around the Schlei, nature-oriented tourism dominates, while in Rostock bathing and culture tourisms play an important role. Examples are the Hanse Sail and the Warnemünde Week, major sailing festivals in the Baltic region. However, the underlying indicators show serious weaknesses for our approach. The service aesthetic and entertainment both show a strong increase. The indicators "number of movies and broadcasts in the area" as well as "number of pictures" are also indicators for the technological development. For example, in the 1960s, only three public broadcast services (ARD, ZDF and regional programs "das Dritte") existed. The situation is similar with respect to number of pictures taken. In the 1960s, taking a photo was limited because only a few persons owned a camera. Further, most historic photos are not publicly accessible, while today, the popularity of a place can easily be assessed by its tags on e.g., Flickr.com. For the initial status postcards were considered, but this is problematic, because postcards at that time focused on technical and cultural developments rather than documenting the natural aesthetics of an area. The sense of aesthetics is based on individual subjective judgment and changed during the last century (Brook, 2013). In general, the score for cultural services and changes in time very much depend on whether the potential or the real demand is assessed.

Historic Development: The Schlei Estuary

Indicators related to the biological elements of the WFD, are mainly reflected within the regulating services. This is why they require special attention. Several regulating services are of high importance and show changes in time and between inner, middle and outer water bodies. The nutrient retention (R1) indicated by nitrogen fixation, burial, and denitrification mostly shows increases. With increasing eutrophication, the burial of nutrient and denitrification increased. These indicators reflect important ecosystem processes. It is questionable if increasing N-Fixation should be counted similarly, because different to the other processes, it adds nitrogen to the system. Therefore, we inverted the score for N-fixation. However, this process is negligible in the Schlei and did not change significantly in time.

Mass stabilization (R3) indicated by extent of emerged, submerged, and intertidal habitats shows a steep decrease between 1880 and today but an increase after 1960. Reason is that many habitats were lost by intensified human use of the Schlei until 1960. Afterward nature protection helped to increase the areas again. Flood protection (R5) covers shoreline erosion rate,

	Ecosytem Service classes	Warnow			Schlei				Indicators
			1960			1960			
		1880	Inner	Outer	1880	Inner	Middle	Outer	
Provisioning ES	P1. Plants outputs	-5	-1	-2	0	0	0	0	Harvest, Nº of Species
	P2. Animals outputs	-2	-3	-1	-2	3	3	3	Landings, key market species
	P3. Animals aquaculture	0	0	0	0	0	0	0	Harvest, Nº of Species
	P4. Plants aquaculture	0	0	0	0	0	0	0	Harvest, Nº of Species
	P5. Drinking water	0	0	0	0	0	0	0	Amount of water
	P6. Materials for processing	-5	0	0	-5	-5	-5	-5	Harvest
	P7. Materials for agriculture	-5	0	0	0	0	0	0	Harvest
	P8. Non-drinking water	-5	0	0	0	0	0	0	Amount of water
	P9. Energy from biota	0	0	0	0	0	0	0	Amount of plant and animal based resources
	P10. Physical energy	0	0	5	0	0	0	0	Amount of abiotic resources
Regulating ES	R1. Nutrient retention	5	2	3	1	3	2	2	N-fixation*, burial, denitrification
	R2. Pollutant dilution	5	5	5	0	0	0	0	Beach closures*
	R3. Mass stabilization	-5	-1	-4	-5	3	2	3	Habitat extension
	R4. Mass flows	-5	0	0	0	0	0	0	Sediment accumulation rate
	R5. Flood protection	-1	-1	-1	-1	0	1	1	Shoreline erosion rate*, wave height*, design-basis flood
	R6. Nursery grounds	-3	0	-1	-2	1	0	1	Habitat diversity, bottom oxygen*, Secchi depth, species distribution, nursery areas & protection
	R7. Pest control	-4	-2	0	-5	-1	-1	-1	Harmful algal blooms*, alien species*
	R8. Fixing processes	1	3	3	1	0	0	0	Nitrogen removal, water residence time
	R9. Chemical conditions	2	3	1	0	-1	-1	-1	Nutrient concentration*, salinity, oxygen concentration
	R10. Climate regulations	4	0	2	3	2	1	3	C stock & sequestration, pH, primary production
	R11. Regional regulation	-5	0	0	0	0	0	0	Evaporation rate
Cultural ES	C1. Experiental use	5	4	5	5	5	5	5	Participation in biota-related activities
	C2. Physical use	5	4	5	5	4	3	5	Tourists, ship berths, tourist boats
	C3. Scientific & educational	5	4	5	5	3	3	3	Scientific & educational publications, documentaries, exhibitions
	C4. Culture & heritage	5	5	5	5	5	5	5	Cultural and heritage sites
	C5. Ex-situ entertainment	5	5	5	5	5	5	5	Movies and broadcasts in the area
	C6. Aesthetic	5	4	5	5	5	5	5	Pictures
	C7. Symbolic	5	5	5	5	5	5	5	Red List and iconic species
	C8. Sacred & religious	-2	-3	-2	5	-3	0	4	Religious events
	C9. Existence & health	5	0	0	0	0	0	0	Health treatments & institutions
	C10. Bequest	0	0	0	5	5	5	5	Marine protected areas

FIGURE 4 | Ecosystem service (ES) classes and underlying indicators based on CICES (Haines-Young and Potschin, 2013, 2018) and MAES (Maes et al., 2016) and the assessment for Schlei and Warnow estuaries (Northern Germany). The assessments compare the ES provision between 1880 (high ecological status according to the WFD) and today for the entire estuary, as well as between 1960 (good ecological status according to the WFD) and today separated into the WFD water bodies. Positive scores indicate an increase in ES provision today (**Figure 3**). The asterisk (*) points out indicators where a decrease in the value was interpreted in the sense of an increase in ES provision.

maximum depth, needed for maximum wave height calculation, and the flood protection design basis. The Schlei is protected by regional dykes with slightly different heights, because a universal flood protection design basis does not exist. However, the height of dykes during the last decades steadily increased to deal with sea-level rise risks explaining the increase in ES provision.

Nursery grounds (R6) indicated by submerged and intertidal habitats diversity, occurrences of low oxygen concentrations (<6 mg/l), water transparency (Secchi depth), species distribution, nursery areas and total versus protected nursery areas. The changes in time and between the water bodies are limited, but this is a result of contradicting developments and indicator values. Between the 1960s and today Secchi depth declined, but nursery areas and their protection increased. Changes in chemical conditions are mainly a result of increasing eutrophication. As consequence, the phytoplankton primary production increased. This causes a higher score for climate regulations (R10) today compared to the past.

Lessons learnt from the Schlei assessment are that number, relevance and importance of indicators underlying an ES class differ very much. In some cases, indicator scores are opposing, and after averaging on ES class level, the contradictions result in no changes over time or between water bodies. As consequence, the reality is sometimes hidden. For some indicators, like beach closures, an assessment between two time periods is problematic since the legal framework

(European Union Bathing Water Directive [EU-BWD], 2006) and monitoring systems are recent (or have changed in time) and do not allow a historic assessment. Further, it is questionable if all ES classes are of similar and comparable importance.

Important questions were, whether an assessment on water body level makes sense and to what extent information from one water body can be transferred to another one, to save time and resources. **Figure 5** shows an averaged result for the entire Schlei compared to the assessment on water body level. It is obvious that the values between water bodies differ significantly, especially for several regulating services. The spatial separation into water bodies reduces the loss of information and provides a more comprehensive picture of a system. Consequently, we tried to apply MESAT on an even smaller spatial scale, the habitat level. We did choose a well defined submerged macrophyte area (Große Breite) and considered only 22 relevant indicators. However, for 10 indicators we did not find any data and the results provided only an incomplete picture. A higher spatial resolution strongly depends on a higher resolution of information and our approach seems not suitable on a habitat level.

Since water bodies are a subdivision of WFD coastal water types and share many properties, a lack of data in a water body largely could be compensated with data from another neighboring water body. Therefore, the spatial transfer of basic data and information is possible and reasonable, however, in detail water bodies within on type differ significantly.

The comparative assessment of two time periods, the 1880s compared to today and the early 1960s compared to today reveals significant differences and developments between the periods. The 1880s were supposed to reflect the reference state (high ecological state) and the early 1960s the good ecological status of the Schlei according the WFD. Especially the changes between the early 1960s and today give an indication on how the ES provision of an ecosystem could look like in future after the full and successful implementation of the WFD.

With respect to the Schlei, it is questionable whether in the early 1960s a good ecological status still existed. Already in the 1950s, the use of fertilizers in agriculture increased by almost 50%, from about 37 kg P (P_2O_5) kg ha^{-1} up to 60 kg P (P_2O_5) kg ha^{-1} (Ohle, 1965). Until 1956, the sewage water of approximately 35,000–40,000 inhabitants entered the Schlei without any treatment. Therefore, high total phosphor concentrations in rivers above >0.5 mg L^{-1} were observed (Nellen, 1967). Strong algal blooms in the Schlei were observed already in the 1960s (Nellen, 1967) and the loss of submerged macrophytes started already in the late 1930s (Hoffmann, 1937).

Shallow systems with a long coastline, a relatively large drainage basin and limited water exchange are sensitive to eutrophication. In northern Germany, several systems have to be considered as naturally eutrophic. As consequence, the "good status" according to the WFD is a eutrophic status. This is the case for the Schlei, as well. This limits the possibility for an improved human use of the Schlei, but does not violate our concept.

The quality of an ES assessment depends on availability and quality of data and information. To link the ES assessment to the WFD allows the usage of data that is collected in all EU countries within the WFD monitoring (e.g., Secchi depth, pH, salinity, oxygen, nutrients). Much recent and historic data has been prepared for the first steps in implementing the WFD, for example the development of a typology or the definition of reference conditions. This improves the conditions for an ES assessment. Further, several countries used ecological models for defining historic states and this spatial information on water

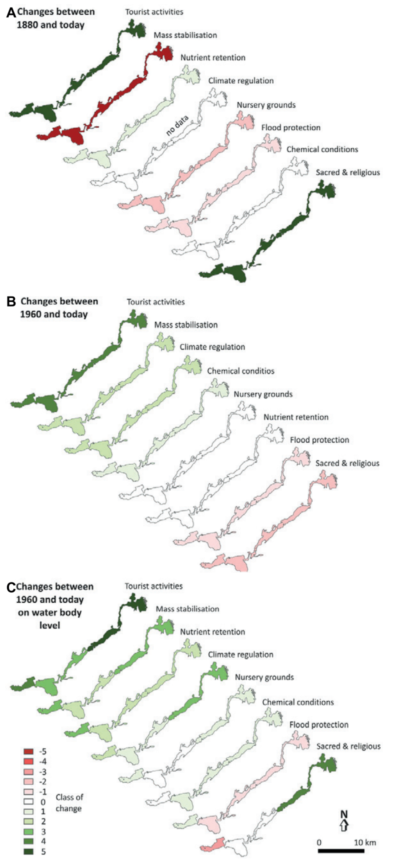

FIGURE 5 | Selected comparative ecosystem service assessments in the Schlei Estuary: **(A)** changes between 1880 (high ecological status of the WFD) and today, averaged over the estuary, **(B)** averaged changes between 1960 and today, averaged over the estuary, and **(C)** changes between 1960 and today on water body level.

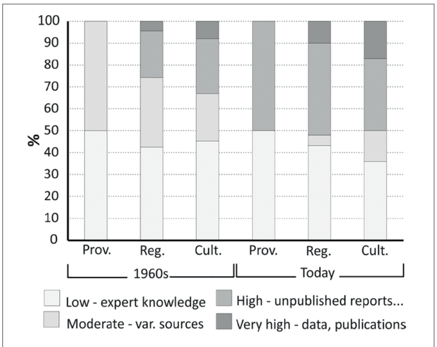

FIGURE 6 | Type and quality of information sources used in the ES assessment in the Schlei Estuary. The assessment includes the indicators of 22 ES classes. For indicators of 9 ES classes no data could be found.

body level is available, as well. Despite that, data availability and reliability is still a problem for several indicators and this problem increases when addressing the 1960s and especially the 1880s. Usually 35–50% of the information used in our assessment is based on assumptions or expert knowledge (**Figure 6**). It is considered to be of low reliability and this limits the reliability of our assessment results in general. Further, for 9 out of 31 ES classes no data could be found. The availability and quality of data for 1880 is even much worse and does not allow a separate assessment of single water bodies.

Historic Development: The Warnow Estuary

Already for centuries, the industrialized and urban Warnow Estuary was intensively used and modified by humans. As consequence, comprehensive monitoring datasets, detailed statistics, a large amount of planning documents and experts with specific knowledge exist. The availability and quality of data as basis for an ES assessment is much better compared to a natural system, like the Schlei Estuary. This is true for historic data, as well. Compared to the Schlei Estuary, much information about the state and situation around 1880–1900 is available. It means that from an information availability perspective, industrialized and urban systems are most suitable for an ES assessment. Despite that, serious information gaps for this historic period exist. Even in these systems, historic ES assessments and comparisons are based on a weak information basis and can hardly be regarded as reliable.

While natural systems are hardly affected by political and economic changes, this is different in urban and industrialized systems. After the Second World War until 1990, the Warnow Estuary belonged to the socialistic German Democratic Republic (GDR). During that time, a very specific development took place. Rostock was the only international harbor of the GDR and the most important location for shipbuilding industries. As consequence of the industrialisation, the population increased from about 70,000 after the Second World War to above 250,000 in 1990. During that time, the estuary was heavily modified. For example, the shipping channels were deepened and the coastline became largely artificial. As consequence, pollution increased and water quality declined.

One question is whether the political changes and associated developments are visible in our ES assessment? Some regulating ES classes, like mass stabilization, nursery grounds, fixing processes and chemical conditions, or the provisioning ES classes plant and animal outputs reflect these changes (**Figure 4**). The cultural ES classes show strong changes but do not reflect the specific situation in the Warnow Estuary. We can summarize that changes are visible in several ES classes. However, in general, these changes are not well visible and not reliable. The results of an ES assessment can hardly be used to visualize political and economic changes and their consequences on the ecosystem.

ES classes are based on one to several indicators. The indicators not only differ with respect to their quality as descriptor of an ES class, but also with respect to the data reliability. A question is, whether changes are possibly hidden by poor data quality. Another question is, whether inverse changes of indicators, describing one ES class, may cause no or only weak changes of ES classes and hide changes. A possible solution to these potential problems could be a weighting of indicators and/or ES classes, taking into account data quality. **Figure 7** shows the scores for ES classes calculated using two methods: averaging and weighted averaging of indicators. The weighted averaging takes into account data reliability, which was scored from very high (1) to low (4) by the experts during the evaluation process.

Only four ES classes show differences in scores, indicated by exclamation marks, between both methods: animal outputs, nursery grounds, pest control and climate regulation. Only with respect to ES class animal outputs the difference is above one unit and has significant impact on the result. Altogether, the advantage of taking data reliability into account has only negligible effects on the overall assessment and therefore is not beneficial in this study.

The ES classes in **Figure 7** show a CICES 5.1 sub-set with relevance for coastal waters. In a system like the Warnow Estuary additional ES classes like navigation, transportation, provision of cooling water, mediation of smell/noise/visual impacts make sense and would allow a more specific assessment. This has been taken into account in the assessment of the future scenario.

Assessing a Future State in the Warnow Estuary

Instead of carrying out an ES assessment for describing and visualizing historic changes, it can be applied to assess possible future states of a system using a tailor-made, expert based system. Usually industrial and urban estuaries, like the Warnow Estuary, are defined as heavily modified water bodies. According to the WFD, this allows defining less strict ecological quality objectives. In the Warnow Estuary, for example, only a moderate ecological state needs to be achieved. However, nearly two decades after

		Averaged score								Weighted score							
	Ecosytem service classes	Score	Indicator score 1	2	3	4	5	6		Score	Reliability score 1	2	3	4	5	6	Indicators
Provisioning ES	P1. Plants outputs	-2	-2	-						-2	3	-					Harvest, № of Species
	P2. Animals outputs	-2	-3	0					!	0	3	1					Landings, key market species
	P3. Animals aquaculture	0	0	-						0	3	-					Harvest, № of Species
	P4. Plants aquaculture	0	0	-						0	3	-					Harvest, № of Species
	P5. Drinking water	0	0							0	1						Amount of water
	P6. Materials for processing	0	0							0	3						Harvest
	P7. Materials for agriculture	0	0							0	3						Harvest
	P8. Non-drinking water	0	0							0	3						Amount of water
	P9. Energy from biota	0	0							0	3						Amount of plant and animal based resources
	P10. Physical energy	2	2							2	1						Amount of abiotic resources
Regulating ES	R1. Nutrient retention	0	-4	3	2					0	3	3	3				N-fixation*, burial, denitrification
	R2. Pollutant dilution	5	5							5	2						Beach closures*
	R3. Mass stabilization	-3	-2							-3	3						Habitat extension
	R4. Mass flows	0	0							0	3						Sediment accumulation rate*
	R5. Flood protection	-1	-	-2	0					-1	-	2	1				Shoreline erosion rate*, wave height*, design-basis flood
	R6. Nursery grounds	-1	0	-3	3	-	-3	-	!	0	1	3	2	-	3	-	Habitat div., bottom oxygen*, Secchi depth, species distrib., nursery areas
	R7. Pest control	1	4	-2					!	2	1	2					Harmful algal blooms*, alien species*
	R8. Fixing processes	1	2	0						1	3	3					Nitrogen removal, water residence time
	R9. Chemical conditions	2	4	2	1					2	2	2	2				Nutrient concentration*, salinity, oxygen concentration
	R10. Climate regulations	-1	-	-	0	-1			!	0	-	-	2	3			C stock & sequestration, pH, primary production
	R11. Regional regulation	-1	-1							-1	3						Evaporation rate
Cultural ES	C1. Experiental use	5	5							5	3						Participation in biota-related activities
	C2. Physical use	5	5	4	5					5	2	2	2				Tourists, ship berths, tourist boats
	C3. Scientific & educational	5	5	-						5	3	-					Scientific & educational publications, documentaries, exhibitions
	C4. Culture & heritage	5	5							5	2						Cultural and heritage sites
	C5. Ex-situ entertainment	5	5							5	3						Movies and broadcasts in the area
	C6. Aesthetic	5	5							5	3						Pictures
	C7. Symbolic	5	5							5	1						Red List and iconic species
	C8. Sacred & religious	-3	-3							-3	1						Religious events
	C9. Existence & health	0	0							0	1						Health treatments & institutions
	C10. Bequest	0	0							0	1						Marine protected areas

FIGURE 7 | Data based ES assessment for the entire Warnow Estuary provision. Shown are changes between 1960 (WFD good ecological status) and today. The scores for ES classes are calculated with two methods: by averaging and weighted averaging. The latter takes into account data reliability. Reliability scores indicate very high (1, weighting factor 2) to low (4, weighting factor 0.5) data quality. Positive ES class scores indicate an increase in ES provision today (**Figure 3**). The asterisk (*) points out indicators where a decrease in the value was interpreted in the sense of an increase in ES provision. The exclamation mark indicates ES classes where differences in scores exist.

WFD adoption its objectives usually have not been reached. This is true for the Warnow Estuary, but also for most coastal waters in Germany and all over Europe (Hering et al., 2010; Bouleau and Pont, 2015). As said before, one reason is that restoration and recovery is complex and takes time (Borja et al., 2010) and in some cases weaknesses in the approach and understanding of the system may be a reason (Voulvoulis et al., 2017). Possibly the most important reason for not reaching the good ecological status according the WFD is the lack of political will. Resistance of stakeholder groups against measures, high costs, or other policy priorities may serve as explanations for that. It seems that a healthy environment is perceived as not important enough or that the public is not aware of the benefits of a good ecological status. Consequently, incentives are needed to support the implementation of the WFD.

The question is whether an ES assessment can provide these incentives by visualizing the human benefits of a healthy coastal water. For this purpose, we developed a future scenario for the year 2040 for the Warnow Estuary and asked altogether 19 experts to compare it to the present state (**Figure 8**). This approach implements lessons learnt from the historic ES assessment. For example, the set of ES classes are tailor-made for this purpose and the focus is on extraction of knowledge and perceptions of a group of experts instead of using a weak database. On average, the assessors assume no significant overall changes in the ES provision for the northern, industrial, but an increase for the southern, urban water body.

The Warnow and Schlei Estuaries show that the importance of provisioning services is relatively low (**Figure 4**). By adding the ES classes "space for navigation and waterways" as well as "space for harbors and marine industries," the importance of provisioning ES increased and more completely reflected the situation in the Warnow Estuary. Further, it better reflects the changes that would result from the scenario "Warnow 2040"

a)	Northern, industrial water body	Authors (A)			Scientists (S)											Experts (E)					Average		
	Ecosystem Service	A1	A2	A3	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	E1	E2	E3	E4	E5	A	S	E
Provisioning ES	Wild plants outputs	0	0			0			0	2			0	2					1	0	0	1	1
	Wild animals outputs	0	-3	-1		-2	2		X	2		2	-3	-1	1	2	-4	x	3	0	-1	0	0
	Aquaculture	0	0				3		X				-1						1		0	1	1
	Water discharge	0	3	2	3	3	0	3	-1	2	0	2	2	1	3	0	2	x	0	2	2	2	1
	Water extraction	0	2	2	3	2	-2		0	3		0	-2	1				0	3	-3	1	1	0
	Materials for processing & agriculture	0	0			0			X	0			-1	1					1		0	0	1
	Physical & bio-energy	2	3	1	1		3		X	4		0	0	4	X			x	3	x	2	2	3
	Navigation & waterways	4	5	3	5	5	5	5	4	5	2	4	3	4	4	3	3	2	5	5	4	4	4
	Harbours & maritime industries	4	5	2	2	5	2	2	2	2	1	3	3	4	3	3	4	3	4	4	4	3	4
Regulating ES	Burial of nutrients & organic matter	-2	0	-2	-2	-2	-3	-3	-1	-3		-3	1	-3	-2	-3	2	-2	x	0	-1	-2	-1
	Nutrient removal	-2	X	X	-4	-2	-3	0	X	-2		x	-1	-3	X	-3	0	x	x	0	-2	-2	-1
	Primary productivity	-2	-2	-3	-4	-1	-3	0	X	-2		x	-1	1	-4	-1	0	-4	-4	-3	-2	-2	-2
	Water transparency	0	5	4	3	-3	5	0	X	0		-2	-1	1	1	2	0	0	4	3	3	0	2
	Matter transformation	-2	0	-2	X	-1	-2	-1	-2	-2	-1	x	0	-1	0	-1	-3		-3	0	-1	-1	-2
	Oxygen provision	0	0	-1	2	-2	-5	0	-3	0		x	0	2	5	2	-3	1	3	0	0	0	1
	Pest control	2	0	-2	2	2	3	2	X	1	3	1	0	-2	-4		0	-4	-3	-2	0	1	-2
	Nursery grounds	-1	-5	-2		-3	-3	-5	-1	-3		x	-2	-4	-4	-3	-3	-4	2	-1	-3	-3	-2
	Habitat diversity	-2	-2	-2	2	-3	-3	-2	-1	-3	0	-2	-1	-4	-4	-2	-5	-4	3	-2	-2	-2	-2
	Mass stabilization	-1	-5	-2	2	-3	2	-1	-2	1	0	-2	-2	-4	-2	-2	-5	-1	2	-1	-3	-1	-1
	Flood protection	0	-2	-1	1	-3	-3	0	-1	0		x	-2	-2	-3	-1	0	-2	1	3	-1	-1	0
	Local climate regulation	0	0	0	0	0			1			0	-2	-1	-2	0	0	-2	x	0	0	-1	-1
Cultural ES	Bathing & sun-bathing	-1	2	2	1	-2	-2	-3	0	1	1	2	2	0	1	0	0	2	1	0	1	0	1
	Recreation & water sports	-1	2	2	1	2	-5	0	-1	1	0	-1	-3	-1	1	0	-3	0	2	0	1	-1	0
	Aesthetic experience	-1	2	3		2	-3	0	2	4	2	2	-2	0	4	0	-4	5	2	0	1	1	1
	Attractiveness for seaside housing	-1	0	1	2	0	-2	-1	1	3	-1	0	-1	0	X	0	0	x	3	0	0	0	1
	Experiential use	-1	2	1	1	0	-5	-1	-2	3		0	-2	-1	0	-3	-4	0	2	0	1	-1	-1
	Scientific & educational		3	2	4	0	-2	0	X	4	3	0	0	-1	1	0	3	0	1	0	3	1	1
	Culture & heritage		5	3	2	0	-3	0	2	3	1		-1	0	1	0	0	1	0	1	4	1	0
	Health & recuperation	-1	0	0	2		-2		0	2		-1	-1		1	0	0	0	0	0	0	0	0
	Existence & bequest	0	-5	-2	2	-1	-2	0	X	2	0	2	-1	-2	-3	-3	-5	-2	4	-5	-2	0	-2
	Average	0	1	0	1	0	-1	0	0	1	1	0	-1	0	0	0	-1	-1	2	0			

b)	Southern, urban water body	Authors (A)			Scientists (S)											Experts (E)					Average		
	Ecosystem Service	A1	A2	A3	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	E1	E2	E3	E4	E5	A	S	E
Provisioning ES	Wild plants outputs	0	0			3			X	2			3						3	-2	0	3	1
	Wild animals outputs	0	1	2		3	2		X	3		2	2	0		2	0		3	-2	1	2	1
	Aquaculture	0	0		2				X			1	2						2		0	2	2
	Water discharge	0	2	0	3	1		2	-1	2	4	0	0	1	4	0	0	X	0	2	1	2	1
	Water extraction	0	0	1	3	2	5		0	3		0	0	1				4	2	0	0	2	2
	Materials for processing & agriculture	0	0			2	1		X	0			0						0		0	1	0
	Physical & bio-energy	0	3	1	1	2	4		X	4		0	0	4	2			3	3	x	1	2	3
	Navigation & waterways	-2	5	2	3	3	5	3	-1	3	4	2	-4	3	2	4	2	2	4	4	2	2	3
	Harbours & maritime industries	-2	0	0	1	2	0	0	2	1	3	0	-2	2		0	2		-1	1	-1	1	1
Regulating ES	Burial of nutrients & organic matter	1	0	-1	0	3	3	2	0	-1		0	0	0	1	0	0	X	X	0	0	1	0
	Nutrient removal	1	X	X	3	3	2	1	X	-2	1	X	2	2	2	0	0	4	X	0	1	2	1
	Primary productivity	-2	-2	-3	-3	-2	-3	0	X	-1		X	1	1	-4	0	0	-4	-5	-3	-2	-1	-2
	Water transparency	2	5	4	4	4	5	0	2	1	1	2	1	1	3	2	2	2	4	3	4	2	3
	Matter transformation	2	0	0	X	3	0	1	0	0		X	0	1	0	0	2	0	-2	0	1	1	0
	Oxygen provision	0	0	0	3	3	4	0	-1	0		X	1	0	5	2	-3	2	4	0	0	2	1
	Pest control	2	-2	-2		2	-3	0	X	2	2	1	0	-1	-4	0	0	-4	-4	-2	-1	0	-2
	Nursery grounds	2	5	2	3	3	3	1	-1	-3	2	2	1	2	1	0	0	4	4	-1	3	1	1
	Habitat diversity	2	2	2	4	3	2	2	-1	-2		3	2	2	2	0	-4	4	4	-2	2	2	0
	Mass stabilization	1	5	3	4	3	5	2	-2	2	2	2	1	2	3		-4	3	3	-1	3	2	0
	Flood protection	0	2	1	1	2		0	0	1		X	1	-1	0	0	0	0	3	3	1	1	1
	Local climate regulation	0	0	0	2	1			0			1	1	1	1	0	0	X	X	0	0	1	0
Cultural ES	Bathing & sun-bathing	4	5	4	4	4	5	3	4	4	4	4	4	2	5	3	3	5	4	1	4	4	3
	Recreation & water sports	3	5	4	4	5	0	3	1	5	4	2	3	3	4	3	3	4	4	2	4	3	3
	Aesthetic experience	5	5	4	4	3	5	5	2	4	3	3	3	4	4	3	4	4	4	x	5	4	4
	Attractiveness for seaside housing	4	5	4	4	4	5	3	1	4	3	3	4	2	4	3	3	4	4	2	4	3	3
	Experiential use	1	5	1	3	3	-4	3	0	3		2	1	2	1	0	-3	3	3	-1	2	1	0
	Scientific & educational	3	5	2	4	3	2	1	X	4	3	3	1	3	1	2	3	2	4	1	3	3	2
	Culture & heritage	4	5	4	4	2	5	3	4	4	4	2	2	3	2	0	3	2	0	3	4	3	2
	Health & recuperation	2	0	0	4		2		3	5		2	2	1	X	0	0	X	3	0	1	3	1
	Existence & bequest	1	5	3	3	3	3	2	X	4	2	2	2	1	4	2	-4	5	4	-5	3	3	0
	Average	1	2	1	3	3	2	2	1	2	3	2	1	2	2	1	0	2	2	0			

FIGURE 8 | Ecosystem service (ES) classes used in expert-based assessment for the Warnow Estuary. The authors, 11 scientists and 5 experts (persons working at water authorities on the WFD implementation) scored the changes between today and the future scenario "Warnow 2040." The assessment is separated into two water bodies, the northern industrial (see **a**) and the southern, urban (see **b**) part of the estuary. Positive scores indicate that an increase in ES provision in future was assumed (**Figure 3**). Gray cells indicate that the expert assumed the ES as not relevant. Gray cells with x indicate a lacking answer.

implementation (**Figure 8**). On average, the experts expected that the scenario would increase the provisioning ES in the northern and in the southern water body. Moreover, they expected a decrease of regulating ES in the northern water body and an increase in the south.

Even a strong increase in the provision of provisioning services because of a good ecological status alone would hardly give a convincing justification for improving environmental quality and the required investments. Cultural services and changes in their provision have a most direct impact and relevance to a broad public, especially in urban systems. The ES assessments of cultural services show a slight increase in the industrial, northern and a strong increase in the urban, southern water body (**Figure 8**). Especially for the urban, southern water body this increase, together with the overall increase in ES provision, can be regarded as a relevant incentive to improve the ecological quality and could support the WFD implementation.

A systematic difference in the perception of changes that would result from an implementation of the scenario "Warnow 2040" between the separately assessed groups of authors, scientists (working at scientific institutions) and experts (working at authorities) is not visible. However, the perception between individual persons differs strongly, even within the three groups. For example, while persons E2 and E5 do not expect an overall increase of ES for the urban water body, persons S1, S2, and S7 expect a strong increase. Some scientists seem to be more positive about the scenario, while some persons working at authorities seem more skeptical.

With respect to single ES classes there are many strong differences and contradicting scores among the assessors. For example, with respect to changes in cultural service provision in the urban water body, namely experiential use and existence and bequest, the majority of persons expects increases, but single persons perceive the change differently and expect strong decreases. These differences point out ES where different perceptions, world-views, understandings or knowledge exist.

On average, the knowledge between the group of scientists and the authority experts did not differ. Based on a self-assessment and with respect to geographical knowledge it was considered good to very good and about the ecological status of the Warnow Estuary medium to good. The authority experts indicated a good to very good knowledge about the WFD and its implementation while the scientists indicated only a medium to good knowledge. Some experts stated only little or moderate knowledge about one of the topics. Either, they only moved recently to the area, or were not professionally dealing with the ecological status of the Warnow Estuary. The group of scientists (including the authors) showed strong differences when asked about their knowledge about the WFD, ranging from little to excellent. However, comparing experts with excellent knowledge (A1, A2, and S3) with the one that indicated little/moderate knowledge (S4, S5, S6, S10), does not show systematic difference in the assessment results (**Figure 8**). In general, differences in knowledge seem to have no important influence on the result, but it seems that experts with less knowledge are more cautious and hardly ever give very high or very low scores.

The feedback discussions with the involved experts addressed benefits and weaknesses of the approach. The experts saw the need to further improve the definition of several indicators and suggested a narrower scoring system between −3 and 3. They were concerned that the indicators only partly reflect the biological elements of the WFD, about the subjectivity of the individual scoring, limitations of the provided background information or simplifications in the scenario. Further that the scenario goes much beyond the focus of the WFD and the subjective influence resulting from visualization and presentation of the scenario. Especially in the Warnow Estuary, experts were concerned that the potential for improvements in the ecological status is limited and spatially restricted to smaller areas or that improvements resulting from the WFD water quality improvements require measures in the river basin. It means that costs, possible disadvantages and benefits are separated spatially. One expert saw the risk that in other cases a good ecological status may not increase the overall ES provision. Another concern was the possible conflict between harbor development and water quality improvement.

The vast majority of experts saw the potential benefits of an application within the WFD in the possibility to better involve stakeholders in planning of measures and in transferring aims and benefits of the WFD and its implementation to a broader public, and thus increase its acceptance.

DISCUSSION

Previous studies show that an absolute assessment of ES is problematic. This is especially true for monetary assessments, for example ES classes addressing coastal aesthetics. Different approaches for valuation need to be used for different ES and make results difficult to compare. As consequence, Newton et al. (2018) recommended non-monetary evaluation methods and their standardization to ensure that results can be compared. Our ES assessment methodology meets this demand. It does not assess the absolute value of ES, but focusses on classified relative changes between two assessed time periods or alternative situations. This can be done data-based by one assessor or based on experience and knowledge of a group of experts. This approach allows a direct comparison of ES classes with different units, is spatially expandable and transferable, and enables a relatively fast assessment.

Our approach to utilize major elements of the WFD for an ES assessment turned out to be beneficial, because we used a politically and societally accepted normative system as framework, were able to adapt a generally accepted spatial seascape subdivision and were able to utilize large amounts of data that were raised and compiled for the WFD implementation. Another advantage was that it enabled us to involve a defined group of experienced and interested experts in the ES assessment. Therefore, the practical benefit of the WFD approach for an ES assessment in coastal waters goes beyond the conceptual links and synergies compiled by Hartje and Klaphake (2006) or COWI (2014).

An advantage of the data-based comparative assessment between two periods in time is a reduced subjectivity. However, the data basis for the reference (high ecological) state according to the WFD (years around 1880) or the good ecological state (around 1960) is partly weak. Comparisons to the present state are hardly reliable in detail. Comparative historic assessments show general trends and give an idea, how intensified human uses and eutrophication have changed the provision of a broad spectrum of ES in water bodies. Further, these comparisons give an insight in potential benefits (usually increased ES provisions) that may be provided when coastal waters are in a good ecological state again, as result of a full WFD implementation.

The two assessed coastal water systems, the rural Schlei and the urban/industrialized Warnow Estuary can, with respect to structure, problems and challenges for WFD implementation be regarded as representative for a large spectrum of coastal water systems, at least at the southern Baltic Sea. Therefore, major aspects of the approach can be transferred to and applied in other coastal waters. In case of urbanized/industrial estuaries, for example, to Kiel, Lübeck, Flensburg, or Szczecin.

Hering et al. (2010) complained that the WFD monitoring focusses on biological structures, not on functions or ES. Further, that it is not well understood how stressors and biological structure affect ES provision. Both aspects remain problems. Neither the existing monitoring data nor indicators and ES classes according to CICES 5.1 (Haines-Young and Potschin, 2018) are optimal for representing overall state and changes in ES provision. This is especially true for urban/industrial water bodies. In these systems, tailor-made sets of indicators and ES classes, representing the specific features and uses, are recommendable. Further, they have to be tailor-made for the purpose of the assessment, for example the scenarios that shall be compared.

Another aspect is that commonly used ES classes and indicators, like CICES 5.1 (Haines-Young and Potschin, 2018) were mainly developed for and applied to terrestrial and natural systems. They are not optimal for urbanized/industrial systems and coastal waters. In a system like the Warnow Estuary, additional ES classes like navigation, transportation, provision of cooling water, mediation of smell/noise/visual impacts make sense and could allow a more specific assessment. Further, non-optimal ES classes may cause an under-valuation of coastal water systems compared to terrestrial systems. Additionally or alternatively, a weighting of the scores on ES class level according to their relevance for the objective of an assessment could make sense. It would allow to tailor-made the assessment to specific systems and purposes. The choice of additional ES classes, modifications of ES classes or a weighting would have to be done by experts. This would add subjectivity to the results and reduce the possibility of inter-comparisons between systems, but this may make sense for applications within the WFD.

According to European Commission [EC] (2003b) water bodies are coherent units to which the environmental objectives of the directive must apply. They shall enable an accurate description of the status compared to environmental objectives. Against this background, two separate water bodies that subdivide the Warnow Estuary are not necessary. Water retention time may serve as suitable indicator to separate water bodies and assessment units. However, for future scenario assessments, where the good ecological status becomes part of a comprehensive development scenario, sub-divisions are reasonable. In case of the Warnow Estuary, the sub-division of water bodies is necessary because both show a very different utilization and likely, a very different future development. This sub-division is in agreement with the view in the official WFD implementation guideline. European Commission [EC] (2003f) recommends that planning of water management should keep links with other planning processes and that both should support each other. This means that if a sub-division of water bodies into smaller units would be beneficial for planning, it could be done.

The spatial size of a system has strong effects on its accessibility, on the visible details and the overall result. Size-limitations result from availability and spatial resolution of data. What we learnt from our study is that historic assessments need larger spatial units. They should be carried out on estuary level, because of data availability. For expert based assessments, smaller spatial units are preferable, like water bodies that sub-divide an estuary. Smaller, more homogeneous spatial units are more tangible and concrete for the involved external experts and allow a more reliable scoring. Further, smaller spatial units allow more concrete definitions and visualizations of future scenarios.

Relatively low values for provisional ES are not specific for German waters or only observed in industrialized coastal water systems, but are common for most coastal waters world-wide (Jacobs et al., 2015; Newton et al., 2018). Therefore, the monetary value of provisioning services or strong negative changes in provisioning services alone hardly provide a convincing public justification for costly measures aiming at achieving a good ecological status in coastal waters. In coastal water systems, regulating and cultural services are much more important (Jacobs et al., 2015; Newton et al., 2018) and provide a better justification for the implementation of WFD measures.

ES assessments do not provide crisp and reliable data and results. They rather indicate ongoing changes and allow visualizing changes and possible benefits for humans, resulting from an improved ecological status. Especially cultural services have a direct relevance for the local population and changes are directly perceivable. As indicated by our involved experts, ES assessments may play a role in WFD public relations and information.

The WFD integrates economics into water management and water policy decision-making (European Commission [EC], 2003b). To achieve the environmental objectives, the WFD calls for the application of economic principles, approaches, tools and instruments. Economic analyses shall help understanding the economic issues and trade-offs of restoring water quality. For example, water bodies with less stringent environmental objectives can be defined, to account for economic and social impacts (European Commission [EC], 2003b). An ES assessment broadens the view on environmental quality. It adds a human dimension and establishes links to economic aspects. It can be regarded as a complementing "economic" tool in this respect and supports the demanded "search for overall sustainability" (European Commission [EC], 2003b). Especially a more comprehensive view on environmental quality, threats and dependencies became among the involved experts was one benefit. This underlines observations from river basin case studies (e.g., Grizzetti et al., 2016; Giakoumis and Voulvoulis, 2018) and supports assumptions by COWI (2014).

The WFD, Article 14, specifies that European Union member states shall encourage the active involvement of all interested parties in the implementation of the WFD (European Commission [EC], 2003e). Public participation includes information supply, consultation, and active involvement. Active involvement implies that "stakeholders are invited to contribute actively to the planning process by discussing issues and contributing to their solution" (European Commission [EC], 2003e). Most of our involved experts perceived an ES assessment as a suitable approach to involve stakeholders in a guided, coordinated process. Our ES scenario assessment shows that it can serve as a tool to catch the views of experts, can extract disagreements between expert opinions and allows settling misunderstandings in subsequent discussions. Similar to our Warnow 2040 scenario, our assessment approach could be applied to concrete WFD measure plans. ES assessments can help structuring and preparing follow-up participatory meetings and may support and accompany the measure implementation. Similar observations are reported for river basins (e.g., Blancher et al., 2011; Grizzetti et al., 2016; Giakoumis and Voulvoulis, 2018).

Planning within the WFD usually includes current and foreseen scenario assessments, target setting as well as development and implementation of alternative programmes of measures (European Commission [EC], 2003f). Important aspects in this process are, to facilitate the interaction and discussion among managers and stakeholders by providing tools for conflict resolution, knowledge and information management as well as capacity building. Knowledge and information are regarded as the foundation for effective management (European Commission [EC], 2003f). An ES assessment facilitates the interaction between actors, initiates a social learning process as well as supports gathering knowledge and competence beyond the own field of expertise. It can serve as a supporting tool in planning and decision-making (Schernewski et al., 2018).

CONCLUSION

Our ES assessment approaches turned out to be suitable for the historic and future scenario applications. It utilizes major elements of the WFD for the ES assessment, like the spatial seascape subdivision, allows for a direct comparison of ES classes with different units, is spatially expandable and transferable and enables a relatively fast assessment. The two assessed coastal water systems, the rural Schlei and the urban/industrialized Warnow Estuary share many similarities with other southern Baltic Sea estuaries (historic development, morphogenesis, hydrological conditions) and to a certain degree, the results can be regarded as representative for other Baltic coastal water systems.

In the European WFD implementation, ES assessments can serve as a complementary approach to support the economic analysis of measure programs as well as planning and implementation processes. However, an ES assessment not only supports the WFD implementation, but the WFD provides a frame for larger scale ES assessments in seascapes, increases the acceptance of the ES approach and the readiness of stakeholders to get involved.

Data-based comparative ES assessments of different time periods allow visualizing changes that happened in coastal waters during the last decades and consequences for human uses. They can also visualize potential benefits and costs resulting from urban development plans (Warnow 2040). Expert-based ES assessments allow for comparing sets of measures or scenarios and can serve as a tool in public participation and stakeholder involvement processes. Independently of the approach, ES assessment results hardly can be regarded as reliable information. Strengths are that they facilitate communication processes, broaden the view and the knowledge and support social learning processes. Our study in practice proves that the conceptual considerations by COWI (2014), which are mainly focussed on river basins, are true for coastal waters, as well. ES assessments can support the assessment and communication of the benefits of the directive, can encourage open communication of the impacts of the WFD implementation and can help to better understand changes caused by measures.

ETHICS STATEMENT

All experts involved in the assessment were informed about the intention to publish the assessment results and orally agreed to it. They had the possibility to review and comment the results.

AUTHOR CONTRIBUTIONS

GS, the project leader, developed the manuscript concept, took care of the data analyses and did the manuscript writing. MI provided the assessment tool and graphical visualizations. PP carried out the ES assessment in the Schlei and ER in the Warnow. ER and JS prepared the scenario "Warnow 2040," largely moderated the meetings with stakeholders and took minutes.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00183/full#supplementary-material

APPENDIX | Data sources and definition of data quality.

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PAPER II

Environmental Management
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An Impact Assessment of Beach Wrack and Litter on Beach Ecosystem Services to Support Coastal Management at the Baltic Sea

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Abstract
As accumulation zones, sandy beaches are temporal sinks for beach wrack and litter, both often seen as nuisances to tourists. Consequently, there is a need for beach management and an enhanced political interest to evaluate their ecosystem services. We applied a new online multidisciplinary assessment approach differentiating between the provision, potential, and flow at German and Lithuanian beaches (Southern Baltic Sea). We selected a set of services and assessed four beach scenarios developed accordingly to common management measures (different beach wrack and litter accumulations). We conducted comparative assessments involving 39 external experts using spread-sheets and workshops, an online survey as well as a combined data-based approach. Results indicated the relative importance of cultural (52.2%), regulating and maintenance (37.4%), and provisioning services (10.4%). Assessed impact scores showed that the removal of beach wrack is not favorable with regard to the overall ecosystem service provision. Contrarily, the removal of litter can increase the service flow significantly. When removing beach wrack, synergies between services should be used, i.e., use of biomass as material or further processing. However, trade-offs prevail between cultural services and the overall provision of beach ecosystem services (i.e., coastal protection and biodiversity). We recommend developing new and innovative beach cleaning techniques and procedures, i.e., different spatio-temporal patterns, e.g., mechanical vs. manually, daily vs. on-demand, whole beach width vs. patches. Our fast and easy-to-apply assessment approach can support decision-making processes within sustainable coastal management allowing us to show and compare the impacts of measures from a holistic ecosystem services perspective.

Keywords Beach cleaning · Marine litter · Beach cast · Expert-based · Stakeholder participation · Online assessment

Introduction

Increasing human activities on beaches and developments in the surrounding area have led to the endangerment and often destruction of the typical flora and fauna in recent decades and even centuries (Davenport and Davenport 2006). At first glance, sandy beaches seem almost devoid of faunal life, as animals are often too small to be seen by the naked eye (Radziejewska et al. 2017). Thus often neglected, sandy beaches are important habitats that support a variety of life ranging from microbes to invertebrates and shorebirds (Dahl 1952; McLachlan 1983; Little 2000). Similarly, given the low species diversity of sandy beach vegetation, they harbor a disproportionate amount of rare and endangered species that are adapted to stressful habitat conditions (García-Mora et al. 1999; Acosta et al. 2009). However, Baltic coasts, especially sandy shores, are mainly related to

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tourism and recreation and face several human pressures. While beach tourism increased Baltic-wide by 10.4% or 88 million tourist arrivals between 2014 and 2016 (BSTC 2018), large sections of the Baltic coasts account for an annual coastal erosion of 0.2–0.3 m/year on average with the highest loss rates up to 1.5 m/year (Jensen and Schwartzer 2013). Increasing policy relevance and demand for nature protection areas (e.g., Natura 2000), as well as a tourism-driven requirement for beach cleaning, lead to trade-offs between nature conservation and tourism interests. Although many far-reaching impacts of human activity on the beach ecosystem are assumed, sufficient ecological studies which explicitly address this complex topic for the Baltic Sea coast are lacking (Mossbauer et al. 2012; Chubarenko et al. 2021). Spatial conflicts and trade-offs call for consensus-building and decision-making, and thus for coastal management that more holistically integrates human and environmental interests.

A major issue for beach management performed seasonally by the municipalities/resorts at sandy beaches is the accumulation of beach wrack and litter, as they represent nuisances to beach goers (Corraini et al. 2018). As there is no common international definition nor terminology of beach wrack, we defined it as seaborne organic material including seaweed debris (seagrass, macroalgae), remains of dead animals like crabs, and seashells washed ashore. Other terms used in literature include "beach cast", "beach debris", and "flotsam" (Liu et al. 2019), or further divided into "terrestrial debris" (Chubarenko et al. 2021). In the Baltic, beach wrack mainly consists of seagrass and macroalgae with only a little amount of shells (Chubarenko et al. 2021). The Køge Municipality in Denmark removed 14,000 t beach wrack year $^{-1}$, while on average it sums up to 1,400–2,800 t year^{-1} (Chubarenko et al. 2021). In Southern Sweden, they determined 57,000–61,000 t, in Solrød municipality (Køge Bight, Denmark) 13,000–24,000 t, and in Sopot Municipality (Gulf of Gdansk, Poland) 160–800 t year^{-1} (Schultz-Zehden and Matczak 2012). Composition and amounts of beach wrack differ highly among coasts due to different hydrodynamics (e.g., currents, wind-driven transport) and offshore vegetation (e.g., seagrass meadows) as well as among season, years, and countries. Despite lacking data on concrete numbers, it still identifies beach wrack as a major problem for local municipalities and their beach management.

In addition, marine litter further intensifies the management problem and complicates the handling of collected material during cleanings by its entanglement within beach wrack. Marine litter is defined as "any persistent, manufactured or processed solid material which has been deliberately discarded, or unintentionally lost onshore or at sea" including plastics as evidently the most dominant group (OSPAR Commission 2010). Others also include feces and organic material, like food waste. Here, we defined litter as a material with anthropogenic origin washed ashore from the sea as well as litter from human activities from the beach, sea-based and land-based sources; we considered only meso (5–25 mm) and macro litter (>25 mm) (Hartmann et al. 2019). Litter pollution is a common problem at sandy beaches, ranging from 0.09 items m^{-2} to 0.61 items m^{-1} and 0.91 items m^{-2} in the Mediterranean mainly composing of plastics (Silc et al. 2018; Asensio-Montesinos et al. 2020; Prevenios et al. 2018) while showing a mean value of 47 to 222 items 100 m^{-1} in the Baltic (Schernewski et al. 2017). For decades, marine litter has been a prevailing and ubiquitous topic within political agendas. Several initiatives and programs included marine litter, for example, the United Nations Environmental Program to achieve their "Sustainable Development Goals". The European Union defined marine litter as one out of 11 descriptors of the aimed "Good Environmental Status" by the Marine Strategy Framework Directive. For the Baltic Sea, the Helsinki Commission (HELCOM) included marine litter in its "Baltic Sea Action Plan". Despite its relevance, local municipalities are still missing clear regulations and recommendations for tackling mixed beach wrack with litter, demanding clear thresholds, reduction, and mitigation measures to fight marine litter pollution.

Scarce studies indicated high costs for beach cleanings as an important problem for local municipalities in the Baltic Sea Region (Hofmann and Banovec 2021; Mossbauer et al. 2012; Weinberger et al. 2020). For example, according to Chubarenko et al. (2021), the small municipality of the Island of Poel (Germany) with ca. 2,500 inhabitants treated an average of 3,000 m^3 of beach wrack per year, resulting in annual costs of 200,000 €. The bigger municipality of Greve (Denmark) with ca. 50,000 inhabitants has paid 268,000 € in 2017 for beach clean-up. However, studies on the beach management costs in the Baltic Sea region, especially on the international level, are rare. Besides, numbers are also hardly comparable, as municipalities face different cleaning conditions in terms of cleaning technique, labor intensity, personnel costs, infrastructure, machinery, tourism density, and amounts of wrack. According to a recent beach wrack study by Hofmann and Banovec (2021), municipalities and private beach operators invest between 20€ and 40€ per m of beach length annually in beach cleaning efforts. However, there is also the loss of income in tourism caused by beach wrack and litter presence (Zielinski et al. 2019), also called the social costs (Brouwer et al. 2017). As the preference of beachgoers for a "clean beach" are usually the main reason for beach cleanings, environmental education and awareness-raising are central issues for the acceptance of beach management measures (Zielinski et al. 2019; Kataržytė et al. 2020). There is another aspect hindering their management procedure that beach wrack is often not yet included in international policies. Sometimes beach wrack is only covered as a side aspect by national or local regulations, e.g., for handling and recycling. Thus, problems of local municipalities range from losses of income to increasing costs and restrictions on handling collected material (Chubarenko et al. 2021). Despite its relevance in research and policies for decades, there is still a lack of a harmonized beach management and policy implementation within the Baltic Sea Region addressing sandy beaches adequately.

Consequently, beach management from a holistic perspective is needed which can be given by ecosystem service assessments that are explicitly anthropocentric. Ecosystem services (ES) are defined as the benefits humans obtain from ecosystems directly or indirectly (Costanza et al. 1997). The Common International Classification on Ecosystem Services (CICES V5.1) according to Haines-Young and Potschin (2018) and Maes et al. (2015) distinguishes the three main categories: provisioning, regulating and maintenance, and cultural ecosystem services. Due to the difficulty in assessing the value or the monetary background, "pure" ecosystem functions without direct or indirect benefits to humans are often neglected by the public. Studies include this aspect by adding a fourth category of supporting services (Millennium Ecosystem Assessment 2005) or the "ecosystem integrity" (Müller et al. 2020; Müller and Burkhard 2012). Widely accepted ecosystem service terminology differentiates between the potential (stock or potential supply), flow (actual use or real supply), and demand for ecosystem services (Burkhard et al. 2014; Müller et al. 2020). Scientific and political interest and relevance of ecosystem services increased exponentially during the last decades (Chaudhary et al. 2015; Bouwma et al. 2018). A vast range of assessment methods for modeling, mapping, and evaluation of ecosystem services exist based on biophysical, socio-cultural, and monetary values. A decision tree was developed by Harrison et al. (2018) to support the selection of appropriate methods depending on the purpose and available data input. Consequently, for management issues ecosystem service assessments can provide an integrated view that is needed to include stakeholders' perspectives combined with biophysical data as well as economic consequences of measures.

Despite the often recreational focus at sandy beaches, they provide a wide range of ecosystem services. With regard to provisioning services, Emadodin et al. (2020) assessed the potential of beach wrack as agricultural fertilizer. Other studies on maintenance and regulating services range from coastal protection by wave attenuation (Defeo et al. 2009) to its potential as carbon sinks (Beaumont et al. 2014). Most studies focus on cultural services, for example evaluating the willingness to pay for beach ecosystem services (Enriquez-Acevedo et al. 2018) and the impact of beach wrack on tourism and bathing quality (Quilliam et al. 2015). Nevertheless, a holistic ecosystem service assessment of the overall provision of beach wrack and beach ecosystems is still lacking.

The prevailing question of this study is how marine litter and beach wrack affect Baltic sandy beach ecosystem services. As representative areas for high impacted beaches, we focused on sandy beaches in Germany and Lithuania. They exhibit different hydrodynamics (e.g., exposition, fetch), socioeconomic characteristics (e.g., population, uses, hinterland), and environmental conditions (e.g., seagrass meadows in front of the shore). The aims of this study were (1) to identify and assess the importance of ecosystem services for the overall provision at sandy Baltic beaches, (2) to develop beach scenarios that are representative of common Baltic beach management, (3) to assess the impact of beach wrack and litter on beach ecosystem services using two new remote and multidisciplinary expert-based assessment approaches, (4) to further differentiate between ecosystem service potential and flow by a combined data-based assessment approach, (5) to show trade-offs and synergies between beach management measures and give recommendations for improved beach management by showing its practical relevance, (6) to show applicability and opportunities of ES assessments within international coastal and marine policy implementation.

Management of Sandy Baltic Beaches in Germany and Lithuania

In the Baltic, Germany has by far the highest pressure from coastal tourism with 77.29 million overnight stays yearly (Eurostat 2019) (Fig. 1). The German Baltic outer coast has a length of 720 km including 450 km of sandy beaches (Kliewe and Sterr 1995), that are mainly of dissipative character due to hydrodynamic conditions as low water depth, low wave exposition, short fetches, and little slope (Froehle and Fittschen 1998). Only 22 km of the coastline is under nature protection including several Natura 2000 habitats and two national parks (Vorpommersche Boddenlandschaft and Jasmund) (Schumacher 2008). Due to dense populations of seaweed, beach wrack washed ashore mainly consists of eelgrass (mainly of *Zostera marina L.*, rare *Zostera noltii Hornem.*) and brown algae (e.g., *Fucus vesiculosus L.*) (Chubarenko et al. 2021). Comparatively high amounts of up to 1,000 kg/m year^{-1} with an average of 269 kg/m of beach wrack (in total 4,900 t) are projected to accumulate annually (Mossbauer et al. 2012). Accumulation hot spots are more common at western beaches (e.g., Island of Poel or Boltenhagen), but also at piers or bights after storm events, for example at Hohe Düne with amounts of up to 20 kg/m per event (Fig. 2), or at the Island of Rügen with up to 1,000–2,000 t/ year^{-1} (Chubarenko et al. 2021). Beach litter pollution compose mainly of cigarette butts and

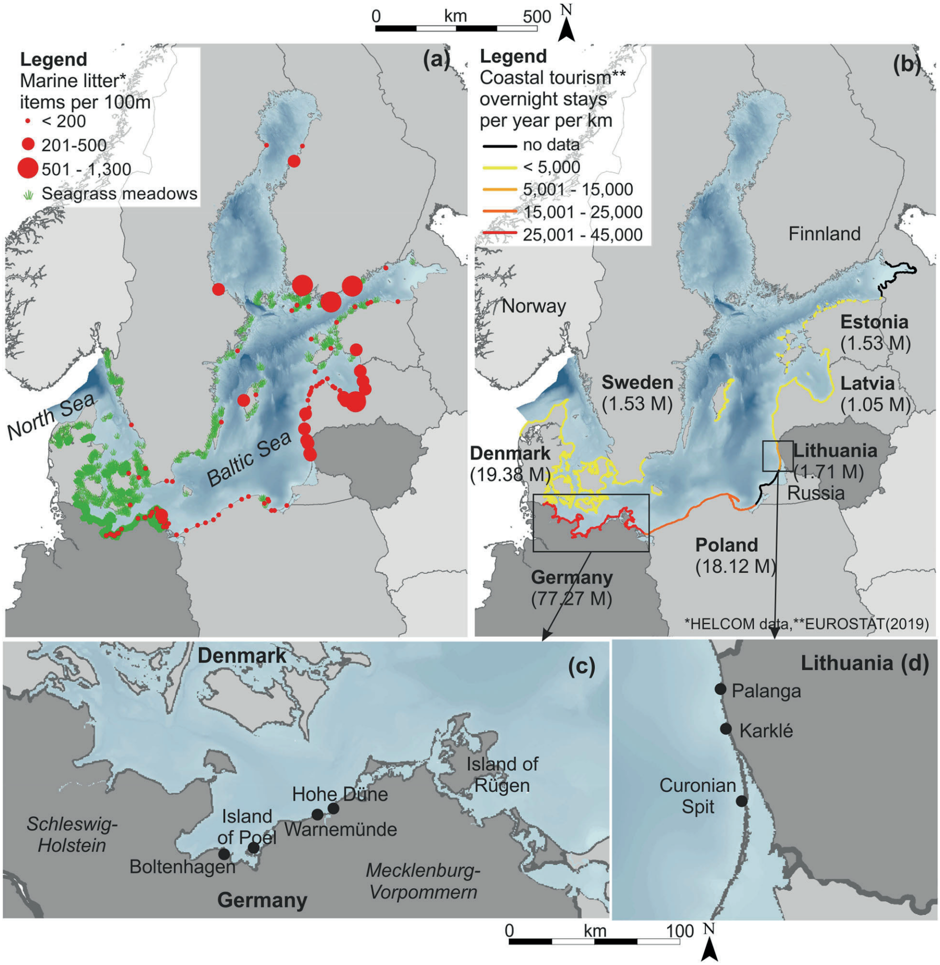

Fig. 1 Map of the Baltic Sea indicating (**a**) marine litter distribution and seagrass meadows (HELCOM data), (**b**) coastal tourism in overnight stays in 2019 per km and in total (in brackets) (Eurostat 2019), (**c**) the German Baltic coast and (**d**) the Lithuanian coast with study sites

plastics items (Haseler et al. 2017) showing a relatively low median value of 47 items per 100 m (OSPAR method) varying from 7 to 404 items (Schernewski et al. 2017) compared to Lithuanian beaches. During the summer season, beaches were cleaned mechanically and daily at beachside resorts (e.g., Warnemünde). Removed material amounted up to 269 kg/m on average beach wrack mixed with sand (Mossbauer et al. 2012). Beyond that, seasonal cleaning takes place when certain amounts of biomass accumulated, e.g., after winter storms (e.g., January 2019 Hohe Düne, Fig. 2). Costs sum up to annually 38€ per meter managed beach (Mossbauer et al. 2012), showing annual costs from 7.6–253€/m³, with the highest values in Scharbeutz of up to 140,000€ (Jensen 2017). Regarding legal aspects of handling and recycling opportunities, according to the German federal law (KrW-/AbfG section 3 part 1–circular economy/waste law), beach wrack that is accumulated on beaches is defined as organic waste, while also further direct use as fertilizer is strictly regulated.

Fig. 2 Sandy beaches in Lithuania (LT) and Germany (GER): (**a**) remote Karklė beach in the regional park (protected) in May 2019 (LT), (**b**) summer season in Warnemünde in 2020 (GER) not cleaned, (**c**) decomposing beach wrack in Palanga (LT) in October 2020, (**d**) beach wrack accumulation after a storm in January 2019 in Hohe Düne (GER), (**e**) a mechanical beach cleaning of beach wrack at Hohe Düne January 2019, (**f**, **g**) beach wrack mixed with marine litter, and (**h**) piece of paraffin wax at a beach of Curonian Spit (LT)

With a length of 90.6 km, the Lithuanian coast is separated into the outer coast of Curonian Spit (50.0 km) mainly consisting of sandy beaches, and the mainland including beaches (38.4 km), moraine and sand cliffs (5.6 km), and natural coastal dunes (3.7 km) (Jarmalavičius et al. 2012). The coastline is highly exposed with long fetches. Coastal tourism in Lithuania counted up to 1.71 million overnight stays yearly (Eurostat 2019) (Fig. 1). As data on beach wrack composition is lacking, we assume the main composition of beach wrack is based on the described macroalgae communities such as *Polysiphonia spp*. (red algae), *Furcellaria lumbricalis* (red), *Cladophora spp*. (green) and a low amount of *Fucus vesiculosus* (brown) (according to studies of Labanauskas (1998), Bučas et al. (2007), and Bučas et al. (2009)). Comparatively low amounts of beach wrack at the beachside resort Palanga sum up to 400 t (Schultz-Zehden and Matczak 2012). Marine litter compositions show high amounts of paraffin wax (Fig. 2) also commonly accompanied by amber (Esiukova 2017; Haseler et al. 2017) with comparatively high mean values of 222 items per 100 m varying from 138 to 340 items

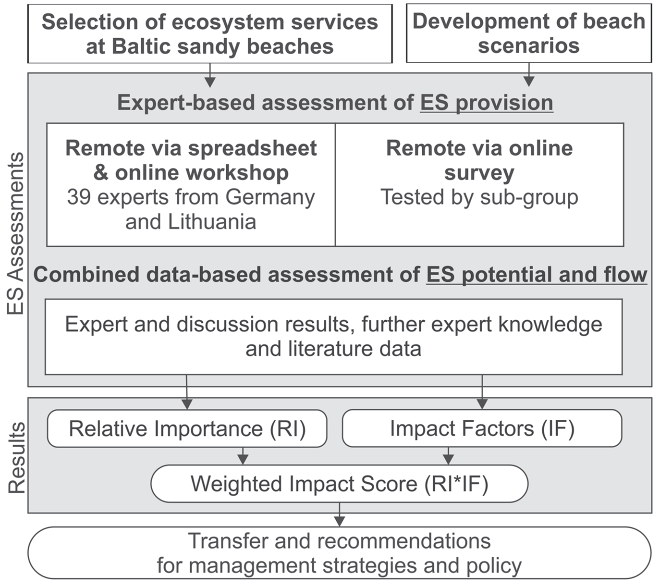

Fig. 3 Flow diagram of study methods and assessment design

(Schernewski et al. 2017). Beach wrack and marine litter management along the Lithuanian coast differ depending on the use and level of protection of the coast. In some sections, where it is a part of protected territory, especially in Seaside Regional Park, beach wrack and marine litter it is not removed and left to its natural conditions. At public beaches or recreational sections of the coast, beach wrack and marine litter is being managed based on municipality and public area cleaning company contracts, to ensure an attractive and clean environment for tourists. Around 45% of the coast is not managed due to the remoteness and no public use interest, mostly along the Curonian spit (~32 km). At the main beachside resort Palanga (Fig. 2), since 2019 daily mechanical beach cleaning takes place during tourism season from 15th of May to 15th of September (~40 moto-hours/month), while done before only manually or semi-manually. In 2019, a total of 1.49 t per 35 ha beach wrack and litter were collected. This resulted in an estimated cost of 32 €/m^2 for beach wrack and litter removal.

Methods

We first followed a two-steps preparation phase (Fig. 3). After selecting a set of ecosystem services explicitly for assessing southern Baltic sandy beaches, we developed four representative beach scenarios for the study area and their beach management. Based on these, two expert-based ecosystem service assessments were carried out to assess the relevance of beach ecosystem services as well as the impact of beach wrack and litter on such provision. Complemented by a combined data-based assessment we further differentiated between the general service provision, potential (stock or potential supply), and flow (actual use or real supply) to give recommendations for practical beach management and policy implementation.

Selection of Ecosystem Services and Scenario Development

We selected a set of 21 services relevant for local management and policy specifically for Baltic sandy beach ecosystems (Table 1). These are based on the Common International Classification of Ecosystem Services (CICES V.5.1) according to Haines-Young and Potschin (2018), adapted from Müller et al. (2020) and Barbier et al. (2011). Description and examples are specified to the study area, southern Baltic sandy beach ecosystems, while services on the class level are generally valid for sandy beaches globally (Defeo et al. 2009).

Four realistic beach scenarios were developed representative for common management measures in the Baltic as the basis for a comparative ecosystem services assessment (Fig. 4). The scenarios include different states of beach wrack and litter accumulations (excluding micro litter).

Table 1 Selected beach ecosystem services for the assessment of Baltic sandy beaches (derived from own data and based on CICES V. 5.1 according to Haines-Young and Potschin (2018), Müller et al. (2020), and Barbier et al. (2011))

		Ecosystem service classes	Description and examples
Provisioning (P)	1	Wild plants for materials (further processing)	Eelgrass for insulating material (e.g., in the construction and building sector)
			Eelgrass for stuffing material (e.g., pillows, mattress)
			Beach wrack as soil improver (e.g., in gardening and agriculture)
			Beach wrack as coastal protection (e.g., dune restoration)
	2	Biomass as an energy source	Beach wrack for energy conversion (e.g., bio gas or fuel, biochar)
	3	Extraction of minerals	Extraction of nutrients from beach wrack (e.g., as fertilizer)
			Sand extraction
	4	Timber/Driftwood	Driftwood used for further processing (e.g., handicrafts, arts)
	5	Natural ornaments	Collection of natural ornaments (e.g., seashells) washed ashore for arts, jewelry, and souvenirs
Regulating and Maintenance (RM)	1	Sediment storage and transport	Beaches as sand storage and transport for natural coastal dynamics
	2	Coastal Protection/Flood control	Attenuation of wave energy and flood prevention (e.g., beach width, inclination, vegetation, or beach wrack)
	3	Biodiversity and habitats	Beaches and their ecosystem providing suitable habitats and nursery grounds
	4	Pest and disease control	Beaches and their ecosystem as the provider of habitat for native pest and control agents (to keep the system´s resilience)
	5	Water purification	Regulation of the chemical condition of salt waters by living processes (e.g., algae, sea grass)
	6	Groundwater regulation	Maintaining of water cycle features (e.g., water storage and buffer, natural drainage, irrigation, and drought prevention)
	7	Carbon sequestration	Regulation of chemical composition of atmosphere and oceans by sequestration of carbon
	8	Nutrient regulation	The capacity of an ecosystem to store and recycle nutrients (e.g., nitrogen and phosphorus for beach soil and dune vegetation)
	9	Seed dispersal	Dispersal of seeds and the reproduction of lots of plants e.g., resuspension by beach wrack and natural coastal dynamics
Cultural (C)	1	Recreation & tourism (active)	Beach as recreational, touristic area (hiking, swimming sunbathing) and sports spots
	2	Recreation & mental health (observational)	Beach for wildlife watching and nature observation
	3	Knowledge systems	Education: Beach ecosystem as a site to educate about nature conservation and human-nature conflicts
			Research: topic and study object of interest
	4	Culture and heritage	Beaches and their ecosystems as part of cultural heritage, thus historically important (e.g., history of sailors and fishermen, seaside festivals)
	5	Regional identity	Elements or processes of ecosystems that contribute to a person’s individual identity (sense of belonging) or strengthen people’s group identity
	6	Landscape esthetic	Inspirational experiences at beaches and their ecosystems for enjoyment of nature (natural beauty)
	7	Natural heritage	The existence value or non-use of nature and species themselves, preservation for future generations

Fig. 4 Visualization of four beach scenarios developed showing different states of beach wrack and litter accumulations

- *Baseline scenario*: shows a common Baltic sandy beach without accumulations of beach wrack nor marine litter. Thus, it is representative of beaches that look alike naturally with little to no wrack accumulation. Furthermore, it describes the state of art and most common management practice after cleanings (mechanically, manually by hand, or both) at beaches used for tourism.
- *Scenario 1*: shows marine litter accumulations from both the sea and land without beach wrack. It is defined by moderate to high amounts of marine and beach litter with around 300 macro litter items per 100 m beach length. It describes commonly polluted beaches in the vicinity of cities and human settlements.
- *Scenario 2*: shows beach wrack accumulations without marine litter. We defined a 35% coverage of beach wrack within 10 m from the swash zone to the beach (beach width). It describes near-natural beaches without cleaning measures, usually in remote areas without direct access or parking lots.
- *Scenario 3*: shows accumulations of both beach wrack (35% coverage within 10 m from the swash zone to the beach) and marine litter (~300 items). It describes beaches that are not regularly managed nor cleaned, for example, remote beaches, but also beaches after storm events.

Ecosystem Service Assessments

We applied a multidisciplinary comparative ecosystem service assessment approach comprising three steps: (1) remote expert-based assessments via spreadsheets individually and

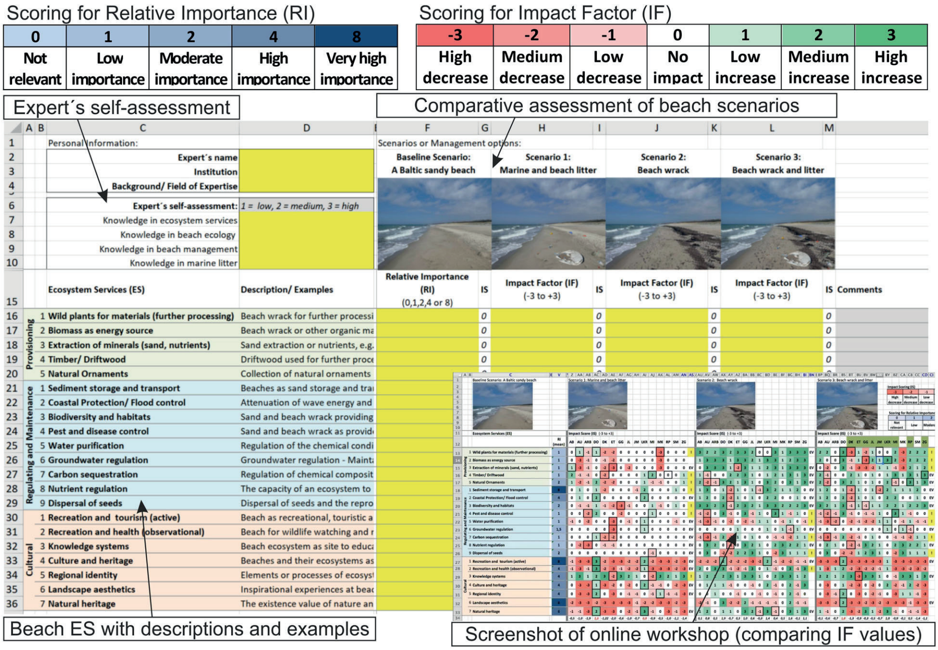

Fig. 5 Design of expert-based assessment via spreadsheet including scoring for assessment and an exemplary screenshot of an online workshop

online workshops in groups, (2) remote expert-based assessments via an online survey for a methodological test, and (3) a combined data-based assessment integrating expert values and discussion results, further expert knowledge and literature data (Fig. 3).

First, remote expert-based assessments via spreadsheets were carried out, based on an already tested comparative expert-based approach for coastal and marine ecosystem services (Inácio et al. 2018). We collected data through rating ecosystem services and assessing impacts by the developed beach scenarios. Assessment results showed perceptions, knowledge, and values of ecosystem services from different experts. A total of 39 experts replied to this spreadsheet-based assessment within a time span of 10 days, individually and remotely, supported by a guideline including detailed scenario description and edited photos accordingly (Fig. 5).

Experts assessed empirically the “Relative Importance” (RI) of each ecosystem service for the total provision at a Baltic sandy beach in general and independent from any scenario (Fig. 5). We used a non-linear scoring (0, 1, 2, 4, 8) to highlight extreme values in perceptions, for more robust and clear results, and to better differentiate between services. Furthermore, the suitability and handiness of the scaling and tool should support the experts during the assessment. Afterward, the experts rated the “Impact Factor” (IF) indicating the relative change or impact of each scenario compared to the baseline scenario. We used a scaling from high decrease (−3) to high increase (+3) in service provision based on experiences from former assessments (Schernewski et al. 2017).

During three online workshops on 4 June 2020, 19 June 2020, and 2 July 2020 experts discussed argued their given values and could modify them in case of misunderstandings (29 experts were present). Each workshop took around 90 min including an introduction, a presentation of preliminary results, and a structured discussion that was recorded (Fig. 5). The aims of the workshops were to discuss extreme values and outliers going through all services and scenarios addressing experts directly, to compile different argumentations and views, and to identify possible misunderstandings. Afterward, experts that could not attend were interviewed in additional and individual online meetings.

Experts were mainly scientists (31) from seven different universities and institutes, but also from non-governmental organizations and initiatives (7), other governmental institutions (1), and state authorities (1). Experts had different university degrees (bachelor, master, Ph.D., professor) from

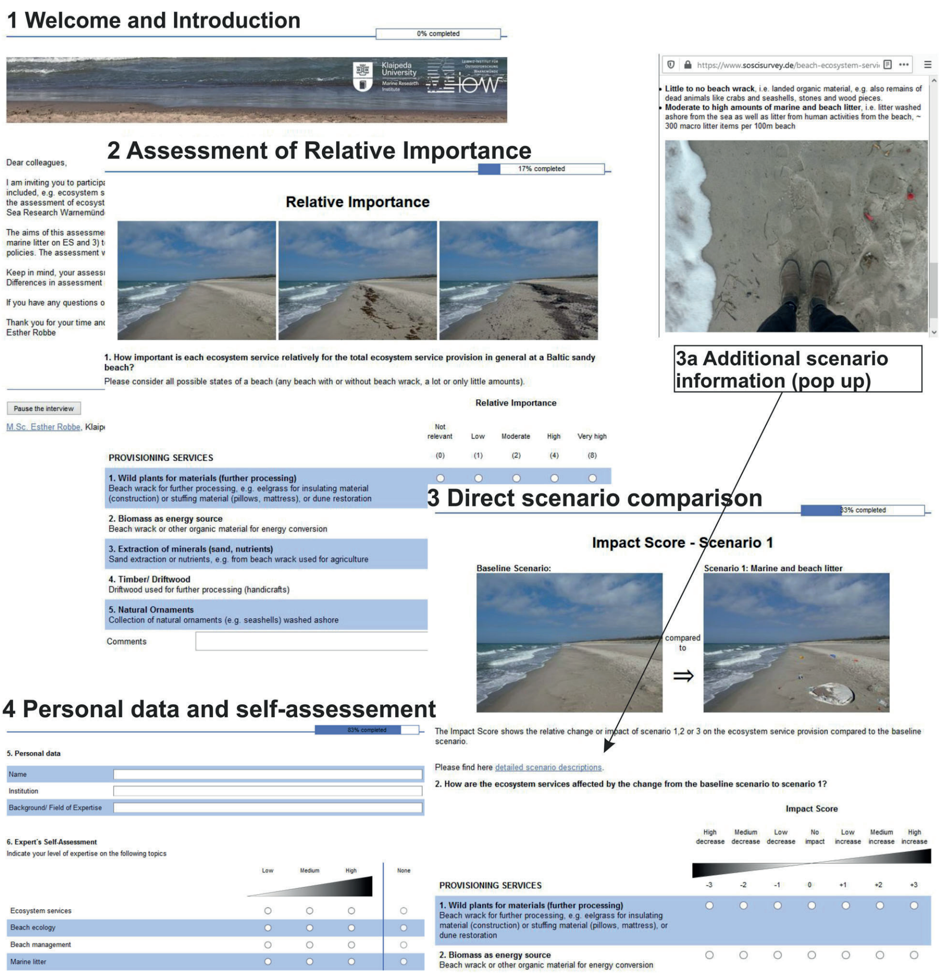

Fig. 6 Design of expert-based assessment via online survey showing exemplary webpages

diverse disciplines (biology, ecology, geography, engineering, geoinformatics, numerical modeling, oceanography, coastal and marine management). In addition, we divided the experts into groups according to their institutional nationality: Lithuania (14) and Germany (25) and their level and field of expertise: ecosystem services (12), marine litter (13), ecology (14) based on their self-assessment and the authors' estimate.

As a common method for uncertainty analysis, the Monte Carlo simulation test allowed us to compute randomly repeated samples of data to assess its patterns and diminish errors in sampled data (Carsey and Harden 2013). Computing random samples repeated certain times (10, 20, 30, 40, 100, 1000), we identified the number of experts to be at least 30 to achieve robust sampling data.

Secondly, for a methodological test and comparison, we applied the same approach via an online survey (www.soscisurvey.de) (Fig. 6). We tested and compared the applicability for the interviewer and the usability for the interviewees deducting strengths and weaknesses for both the spreadsheet-based assessment and online survey based on pre-defined indicators. These included technical setup and data analysis (interviewer) and comprehensibility, practicability, technical usability, and time requirements (interviewee). Five experts from the first group were asked to carry out the same assessment also via the online survey. Here we aimed to compare both methods and to give recommendations when and why to use which methodological implementation.

Thirdly, the main aims of the combined data-based assessment approach were to reduce subjectivity and bias of expert results, to fill knowledge gaps and clarify misunderstandings among experts, to confirm and compare experts' and literature data (if existent). This assessment was carried out by the authors of this paper using expert values and discussion results, further expert knowledge, and literature data (Fig. 3). We also further differentiated between the potential supply or stock (here only referred to as "potential") and real supply or actual use (here only referred to as "flow") of beach ecosystem services for a more detailed view and possible use within coastal management. Furthermore, we combined all relative importance (RI) values with the impact factors (IF) calculating a weighted impact score (IS) by simple multiplication for comparison and the final assessment of both the expert-based and data-based results (Table 2).

Results

Relative Importance (RI) of Beach Ecosystems Services—Expert-Based

The most relevant category with 52.2% were the cultural services, showing high (4) to very high importance (8) for all services (Fig. 7). Three services of the regulating and maintenance category (37.4%) are of high importance (8) (RM1, RM2, RM3), while all provisioning services (10.4%) indicated only low (1) to moderate (2) importance.

The highest agreement among experts accompanied by the lowest standard deviation (SD) was calculated for cultural services (0.64) while provisioning (0.88) and regulating and maintenance services (0.97) represented a higher dispersion. Excluding two NVs (no value), the relatively spontaneous assignment of values was sustainably changed by subsequent discussions in the workshops: 14 from 39 experts changed 67 out of 817 values (8.2%) (in detail see Supplementary Information).

Only 6 out of 21 services (29 %) differed across institutional nationality. More differences were seen across fields of expertise, 10 out of 21 services (48%), mainly among "Ecology" and "Marine litter" groups (9 services). However, the largest difference is only one class of change (e.g., low to moderate). With regard to the respective expertise level (bachelor, master, Ph.D., prof) only the value estimation for one service, biodiversity, and habitats (RM3), differed significantly. Thus, the variability of assessment values among expert groups based on institutional nationality, field, and level of expertise was low.

Perceptions on the importance of provisioning services (=P) were partly based on different interpretations of ES terminology (potential vs. flow) as well as of definitions and descriptions (Fig. 7). High values for wild plants were stated due to the interpreted potential for the further economical processing of the material (P1). Instead, historic flows were the primary reason behind low values. Similarly, biomass as an energy source (P2) was assessed of high importance due to its potential, but limited by high energy loss and economic costs in material managing. Low values for mineral extraction (P3) from the collected material likely stated a lack of such practices at our study sites. Mineral collection in Germany and Lithuania takes place either offshore or from inland deposits. A historic potential of amber included as a mineral by some experts may be a reason behind higher values. Driftwood (P4) was sometimes understood as marine litter, while others did not consider it as a beach wrack component nor marine litter (despite guideline definition). Experts mainly mentioned amber and seashells for collecting natural ornaments (P5). Nevertheless, experts emphasized that in Germany and Lithuania it is legally forbidden to take natural resources from the beach if it is not for personal use.

Background for different perceptions on the importance of regulating and maintenance services (=RM) was also partly interpretations of ES terminology (supply and demand). The services sediment storage and transport (RM1) and coastal protection (RM2) became more relevant with increasing demand, which highly depends on beach exposure and location. The low value for a variety of species at sandy beaches resulted from the experts' lack of knowledge and comparison to other habitats (e.g., forests or meadows). Compared to the otherwise relatively species-poor sand areas of beach ecosystems, beach wrack and the drift line were seen as biodiversity hotspots, representing pristine and unique habitat characteristics (RM3). Results indicated low importance for pest and disease control (RM4). However, experts' interpretations ranged from threats to human health to ecosystem level, e.g., including the fact that sometimes beach wrack is enriched with aggregated filaments of drifting harmful microalgal blooms. The capacity of sand as a filter for water purification (RM5) was considered mostly irrelevant, as there is only retention of coarse and solid material, and sand only contains small amounts of organic matter. Due to the high porosity of sand grains and consequently a lacking water storage capacity, some experts pointed out a possible enhancement of salt-water intrusion of groundwater (RM6). Low values for carbon sequestration (RM7) were estimated due to the low

Table 2 Results of expert-based (service provision) and combined data-based assessments (service potential and flow) showing Relative Importance (RI), Impact factors (IF), and the weighted Impact Scores (RI in % × IF = IS) for all three scenarios

Ecosystem services	Relative importance				1: Marine litter						2: Beach wrack						3: Beach wrack and litter					
					Impact factor			Impact score			Impact factor			Impact score			Impact factor			Impact score		
	Data	Experts	Data (%)	Exp. (%)	Potential	Flow	Provision	Potential	Flow	Provision	Potential	Flow	Provision	Potential	Flow	Provision	Potential	Flow	Provision	Potential	Flow	Provision
P1	1	1	1.3	1.5	0	0	0	0.0	0.0	0.0	3	2	3	4.0	2.7	4.4	3	1	1	4.0	1.3	1.5
P2	1	1	1.3	1.5	1	0	0	1.3	0.0	0.0	2	1	3	2.7	1.3	4.4	3	1	1	4.0	1.3	1.5
P3a	1	1	1.3	1.5	0	0	−1	0.0	0.0	−1.5	2	1	2	2.7	1.3	2.9	2	0.5	−1	2.7	0.7	−1.5
P3b	1		1.3		0	−1		0.0	−1.3	0.0	0	−1		0.0	−1.3	0.0	0	−1		0.0	−1.3	0.0
P4	1	1	1.3	1.5	0	−1	0	0.0	−1.3	0.0	0	−1	1	0.0	−1.3	1.5	0	−1	1	0.0	−1.3	1.5
P5	2	2	2.7	2.9	1	0.5	0	2.7	1.3	0.0	3	2	2	8.0	5.3	5.8	3	1.5	1	8.0	4.0	2.9
RM1	8	8	10.7	11.7	0.5	0.5	0	5.3	5.3	0.0	1	1	1	10.7	10.7	11.7	1.5	1.5	1	16.0	16.0	11.7
RM2	8	8	10.7	11.7	0	0	0	0.0	0.0	0.0	3	3	1	**32.0**	**32.0**	11.7	3	3	1	**32.0**	**32.0**	11.7
RM3	8	4	10.7	5.8	1	−1	−1	**10.7**	−10.7	−5.8	3	3	3	**32.0**	**32.0**	**17.5**	3	2	1	**32.0**	21.3	5.8
RM4	1	1	1.3	1.5	−1	1	0	−1.3	1.3	0.0	2	2	0.5	2.7	2.7	0.7	2	2	0	2.7	2.7	0.0
RM5	1	1	1.3	1.5	−1	1	0	−1.3	1.3	0.0	2	2	0	2.7	2.7	0.0	1	1	0	1.3	1.3	0.0
RM6	1	1.5	1.3	2.2	0	1	0	0.0	1.3	0.0	0	2	0	0.0	2.7	0.0	0	2	0	0.0	2.7	0.0
RM7	1	1	1.3	1.5	0	0	0	0.0	0.0	0.0	−1	−1	0	−1.3	−1.3	0.0	0	0	0	0.0	0.0	0.0
RM8	4	1	5.3	1.5	−2	−2	0	**−10.7**	−10.7	0.0	3	3	2	16.0	16.0	2.9	3	1	1	16.0	5.3	1.5
RM9	1	2	1.3	2.9	1	−1	0	1.3	−1.3	0.0	2	2	2	2.7	2.7	5.8	2	1	1	2.7	1.3	2.9
C1	8	8	10.7	11.7	0	−2	−2	0.0	**−21.3**	**−23.4**	0	−2	−2	0.0	**−21.3**	**−23.4**	0	−3	−3	0.0	**−32.0**	**−35.0**
C2	8	4	10.7	5.8	0	−1	−2	0.0	−10.7	−11.7	3	2	2	**32.0**	**21.3**	11.7	3	1	−1	**32.0**	10.7	−5.8
C3	2	4	2.7	5.8	1	1	1	2.7	2.7	5.8	1	1	2	2.7	2.7	11.7	1	1	2	2.7	2.7	11.7
C4	4	4	5.3	5.8	0	−2	−1	0.0	−10.7	−5.8	0	2	0	0.0	10.7	0.0	0	−1	−1	0.0	−5.3	−5.8
C5	2	4	2.7	5.8	0	−2	−1	0.0	−5.3	−5.8	0	1	0	0.0	2.7	0.0	0	−1	−1	0.0	−2.7	−5.8
C6	8	8	10.7	11.7	0	−2	−3	0.0	**−21.3**	**−35.0**	0	−1	0	0.0	−10.7	0.0	0	−3	−3	0.0	**−32.0**	**−35.0**
C7	4	4	5.3	5.8	0	−2	−2	0.0	−10.7	−11.7	0	2	1	0.0	10.7	5.8	0	1	−1	0.0	5.3	−5.8
Sum					2	−12	−12	11	−92	−95	29	26	24	149	124	75	31	11	0	156	34	−42

Bold values show the highest impact scores for each scenario, indicating also the main trade offs between services (positive and negative values in bold)

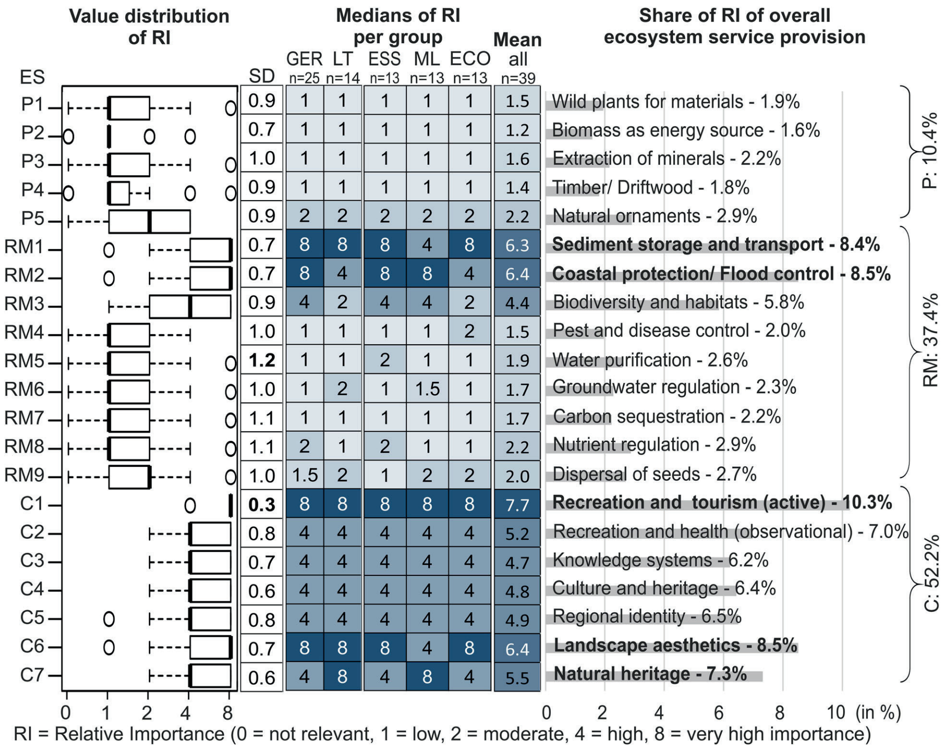

Fig. 7 Expert-based results on the Relative Importance (RI) for provisioning (P), regulating and maintenance (RM) and cultural (C) services [standard deviations (SD); institutional nationality (GER Germany, LT Lithuania); field of expertise (ESS ecosystem services, ML marine litter, ECO ecology)]

binding of carbon to a corresponding matrix, e.g., plants. An exception is the dunes, which have a higher potential to store carbon by their vegetation. The carbon content in beach wrack was indicated to be relevant only with regard to further storage or processing by management activities. Experts evaluated nutrient regulation (RM8) to be of low to moderate importance when removed beach wrack biomass was assumed to be further processed on land, e.g., as compost. Furthermore, the same importance was given for the beach wrack biomass when left at the beach (within or across habitat level). The dispersal of seeds (RM9) was assessed as not relevant seawards and at more exposed beaches, but of low importance when considering their dispersal onshore via sand movement (from shore to dunes).

Recreation and tourism (C1) and recreation and health (C2), mentioned here as cultural services (=C), are very common (e.g., sunbathing, sports), popular, and an important economic factor in the Baltic region. Furthermore, beaches are also used for education and science (C3) with their diverse ecosystem characteristics and issues. A similar important is culture and heritage (C4), which includes for example public sea-side festivals and sailors' tales. Regional identity (C5) is explained as the feeling of belonging or being at home in a particular region or desire to live next to the sea and coast. Landscape esthetics (C6) as a personal perception of beauty is regarded as a prerequisite for most of the cultural services. As a natural heritage (C7), people want to preserve beach ecosystems for future generations.

Impact Factor (IF) of Beach Scenarios on Service Provision—Expert-Based

Litter affected all cultural services negatively but one (C3), while the remaining services only showed low to no impact in service provision by litter only (scenario 1) (Fig. 8). Contrarily, beach wrack affected all provisioning, regulating, and maintenance services positively apart from one

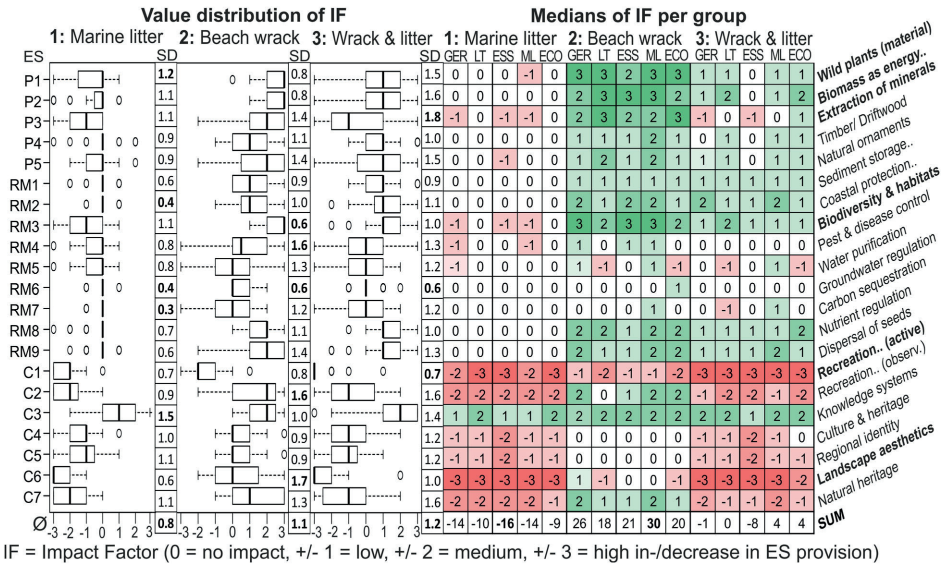

Fig. 8 Expert-based results on Impact Factors (IF) of scenarios for provisioning (P), regulating and maintenance (RM) and cultural (C) services [standard deviations (SD); institutional nationality (GER Germany, LT Lithuania); field of expertise (ESS ecosystem services, ML marine litter, ECO ecology)]

service (RM5), while results for cultural services are inconsistent including both positive and negative impacts. Among all services, only one cultural service (C1) was affected negatively. Other cultural services indicated no to moderate positive impacts except from one (C6) showing inconsistent values. Litter added to beach wrack (scenario 3) had the most negative impact when compared to scenario 2 and scenario 1 for all provisioning, regulating, and maintenance services (mainly P1-3, RM3). However, within mixed compositions, the negative impact of litter prevails for most cultural services, while the positive impact of beach wrack prevailed for most provisioning, regulating, and maintenance services.

Experts revealed the highest agreement, or lowest standard deviation (SD = 0.8), for the addition of litter as a clear negative impact trend on service provision. Most disagreement among experts is shown for both beach wrack scenarios 2 (SD = 1.1) and 3 (SD = 1.2). From 2457 IFs excluding six NVs (no value), 16 experts decided to change 186 values after discussion (7.6%) (in detail see Supplementary Information). This indicates that results are robust and valid also without discussions. Only two services exhibited inconsistent results including positive and negative IFs (RM5, C6). As only a few services indicated two classes of change, mainly on expertise level, differences among expert groups are very low.

Main reasons for the dispersion of RI and IF values are based on different interpretations regarding (1) ecosystem service terminology (i.e., potential or actual use, supply, and demand), (2) definition and description of services (sand and nutrients as minerals), (3) reference frame (within or across habitats, long or short-term perspective, size classes of litter, sea or land), and (4) due to misunderstandings and lack of knowledge (scenario descriptions, driftwood as marine litter, pests as risk for human health), and additionally (5) subjectivity (mainly cultural services), and (6) field of expertise and institutional nationality.

Scenario 1—Marine litter accumulated at the beach

Different perceptions about litter accumulations at the beach are partly based on misunderstandings, assuming for example beach wrack presence or dune vegetation used as biomass for further economical processing (P1) (Fig. 8). Experts argued that litter could serve as additional energy input within incineration plants (P2). They expected that the use and processing of sand (P3) and of collected driftwood (P4) were more challenging when contaminated with litter, e.g., due to necessary separation before use. Some experts assumed similar drifting characteristics of litter and driftwood, thus a correlation of landed material, which explains the positive outlier and values. Tourists would be discouraged by a high percentage of litter in their collection of natural material and would prefer cleaning activities (P5). Others assessed the potential that would not change or even increase when considering litter also as natural ornaments (e.g., art projects or collecting sea glass).

Experts identified litter (especially bigger items) to serve as an erosion catalyst, or as additional physical barriers to trap sand within a small scale and short-term perspective (RM1-2). Others argued that there was no impact at all, as the amount of sand remained the same and litter presence is too low. Regardless of its texture, experts stated that litter as a hard substrate added to the ecosystem can serve as additional habitat for organisms, e.g., crabs using litter as a refuge or epiphytes for fixation (RM3). They also assumed that litter poses a danger to wildlife by simple entanglement or as nesting material of birds. More severe pollution was expected by an increased accumulation and breakdown of litter in smaller fragments over time. Litter was also seen as a carrier or habitat for pathogens, pests, or invasive species (RM4). Consequently, experts expected an increased demand for pest and disease control which will be correlated with litter amounts. Possible harmful pollutants out of litter could be released within ambient water. However, experts assumed a higher impact on the ecosystem, when the material is defragmented into micro up to nano-size level because this increases the uptake by organisms as well as the surface area for colonization (RM5-6). Only a few experts considered litter as possible carbon sequestration or as a release of carbon via decomposition processes (RM7). Most experts expected that litter does not affect the recycling of nutrients, unless if higher concentrations of pollutants are introduced into the system (RM8). For the dispersal of seeds and similar to RM4, some experts regarded litter as an additional hard substrate. It could serve as a carrier for seeds and seedlings as also for bacteria and viruses considering different terrestrial and aquatic-influenced transmission paths in water and air (RM9). Litter may also hamper seeds in germination and growth, from dispersal (e.g., trapped in a bottle) or avoid growth by covering areas (i.e., obstacles to wind or wave-driven dispersal).

Perceptions of litter impact on cultural services differed mostly due to subjectivity and the experts' perspective—their own or as common tourist. Litter is a clear nuisance to beach tourism (C1-2), that is impacted as soon as the esthetic sentience is affected. They assumed litter to have a negative impact on beach goers' sensitivity to uncleanliness in particular (C2). Litter was expected to increase the visibility of human-nature conflicts which is being used for educational and scientific purposes and awareness-raising (C3). As an additional parameter, as a manmade problem, litter within the ecosystem does not reflect pristine natural conditions, thus changes research discussion and experimental designs by altering the study of natural ecosystem processes and functions. Litter might cause a decrease in the sense of personal identity by shame and embarrassment (C4-5). However, litter can present historical conditions for later archeological research about our current lifestyle or serve as inspiration for art projects. Experts also argued that pollution could lead to a strengthening of group identity via activism and personal engagement (e.g., "clean up" activities). Litter is a strong visual nuisance for enjoyment and perception of a pristine nature (C6). Higher litter amounts increase the desire to keep the environment intact and conserve it for future generations, even though some argued that marine litter does not impact the actual value of nature significantly (C7).

Scenario 2—Beach wrack accumulated at the beach

Perceptions on organic biomass amounts at the beach (beach wrack) differed mostly based on interpretations of ES terminology (Fig. 8). For example, the actual use (or flow) of wild plants for further processing, e.g., of respective species like eelgrass or brown algae (P1) or as biomass for energy production (P2) was assessed as very limited or unknown. However, since there is currently an increase in public environmental awareness, the economic potential as a resource for e.g., building insulation or as an initial biomass supplement for biochar/biogas was expected to increase in the future. For sand extraction (P3) the moisture level and the amount/composition of biomass were considered as challenges for further use, as the meshes of sieves of the machines were clogged with the sand-biomass mixture. Regarding the use of beach wrack for soil improvement and fertilizing, e.g., for gardening/agricultural purposes, a higher proportion of organic biomass is a prerequisite. Amber also catches far better in stranded seaweed thus more amber can be found here. Consequently, due to a better trap function and similar buoyancy (thus drifting characteristics), most experts expected a positive correlation between amounts of beach wrack and driftwood (P4) as well as natural ornaments (P5). However, beach wrack might also cover or entangle driftwood and natural ornaments, causing higher efforts to collect.

Most experts emphasized that higher beach wrack accumulations reduce erosion even in front of the beach, as they attenuate wave energy and contribute to sand trapping. The accumulation zone at the beach can serve as a further sand trap for wind-driven particles both from sea and land and might broaden the beach area (RM1-2). However, in relation to the larger scaled sediment transport along the coastline and its physical processes, beach wrack was mentioned as a minor impact. Experts assessed beach wrack as an important habitat and consequently hot spot for biodiversity, e.g., microbiological processes (e.g., bacteria) and organisms like invertebrates, insects, and birds (RM3) (cf. "Selection of Ecosystem Services and Scenario Development"). Some indicated the possible occurrence of potentially toxic microorganisms and pathogens within beach wrack, while others mentioned the disease-reducing function as a habitat for native pest control agents (RM4). When pest probability is increasing, some experts assumed that biotic interaction or feedback and thus the capacity of pest control also increases accompanied by higher demand for this service. Due to leaching, a release of nutrients and potential pollutants out of beach wrack were expected to enter the water (RM5), which could enhance eutrophication. Experts suspected that wet beach wrack close to the water line is releasing higher concentrations of nutrients and possibly harmful substances than dried beach wrack at the upper beach area close to the dunes. The decomposition of organic material emits greenhouse gases like carbon dioxide and methane (RM7). Consequently, experts indicated that the removal and further processing of beach wrack could reduce these emissions and thus improve carbon storage capacities. Beach wrack as a major nutrient source for the ecosystem was identified as the basis of life at beaches (RM8). Organic matter is an important nutrient source (i.e., phosphorus and nitrogen) for the early stages of soil formation in dunes, but might enrich parts of the coastal forest or salt meadows as well (cf. "Selection of Ecosystem Services and Scenario Development"). Experts also discussed the possibility of beach wrack removal as an easy and cheap way for remediation of the Baltic Sea. Similar to litter, beach wrack was mentioned as a trap, as seeds and seedlings could be entangled and/or transported over long distances (RM9). However, the organic matter could function as an accumulation matrix, it protects seeds from being simply drifted. Dispersal is probably more successful in larger accumulations while protecting seeds from washing away accompanied by an enhanced attraction for animals feeding and further dispersing (e.g., birds).

Similar to litter, perceptions of beach wrack impact on cultural services differed, within the expert group, mostly due to subjective opinions or perspectives. Experts estimated beach wrack concordant as disturbing and a nuisance to beach tourism (C1). This perception likely depends on the location, characteristics, and infrastructure of the respective beaches. Beach wrack could be a disservice to human recreation due to its strong smell during decomposition. Some people are also scared of algae aggregated in the water or at the beach, as they assume it causes allergies, is unhealthy, or the touch creates a bad feeling. Contrarily, experts mentioned that beach wrack accumulations support a higher animal density and thus a better possibility to observe nature and wildlife (C2). Since only scarce ecological studies about its spatial and seasonal composition and respective amounts of beach wrack along the Baltic Sea exist, experts considered beach wrack as an interesting topic for further research and also for education (C3). Only a few experts assessed an impact on landscape esthetics (C6), but as beach wrack is mostly removed from touristic beaches, it was assumed that the "common" beach tourists notice high amounts of beach wrack negatively. Beach wrack accumulations were estimated to increase the intrinsic existence value of beach ecosystems, thus the value of nature (C7).

Scenario 3—combined beach wrack and litter accumulation

Further economical processing of beach wrack is hampered when mixed with litter (especially plastics) (Fig. 8), as experts expected collection and separation need more effort and hence is not cost-efficient (P1-2) (cf. "Ecosystem Service Assessments"). Consequently, contamination of beach wrack with litter decreases biomass quality and usability. Similarly, both sand extraction and further use as fertilizer or soil conditioner are hindered by litter (P3).

Some experts considered litter only as a minor impact on biodiversity and habitat conditions when mixed with beach wrack (RM3). Furthermore, they stated that invertebrates, insects, and birds still inhabit polluted beach wrack even though life within the habitats is affected by pollutants and danger of injury. For pest and disease control (RM4) the negative impacts of litter on survival were balanced by the positive impact of beach wrack as an additional food source and habitat. As also mentioned for P1-3, the amount of litter reduced the potential use of beach wrack and hence the impact on nutrient regulation (RM8) as well as for dispersal of seeds (RM9).

Similarly, impacts on recreation and tourism (C1) were expected even stronger when beach wrack and litter is mixed (−3). For recreation and health (C2) experts argued that positive and negative impacts were off-setting, as beach wrack increased wildlife biodiversity and litter disrupted the "natural appearance". However, the negative litter influence appeared much stronger. As the only exemption among cultural services, namely knowledge systems (C3), impact factors changed only slightly. For culture and heritage (C4) and regional identity (C5), impact factors of beach wrack mixed with litter were almost identical to those of litter only (scenario 1). Impact values of −3 for landscape esthetics (C6) indicated that litter with or without beach wrack represented always a strong negative impression. In relation to the respective single components, for natural heritage (C7) the negative impact of litter prevailed within the mixed composition.

Combined Data-Based Assessment and Weighted Impact Score (IS)

The combined data-based assessment differentiated further between the potential and flow of beach ecosystem services (Table 2). This differentiation is necessary due to hidden data when only assessing the general provision, e.g., by off-setting effects due to different interpretations of terminology or services (i.e., contradicting values). Especially when using the results as an indicator for decision-making, further differentiation is necessary complemented by the weighted impact score for direct comparisons. Furthermore, hereby we aimed to reduce subjectivity and bias of expert results, to fill knowledge gaps and clarify misunderstandings among experts, to confirm and compare experts´ and literature data (if existent). Additionally, based on discussion results and off-setting effects for extraction of minerals (P3) we divided this service further into sand and nutrient extraction.

Comparing RI values, there were only minor differences between expert and data-based results. Anyway, the importance of 3 out of 7 cultural services shifted slightly, while 4 out of 9 regulating and maintenance services gained 20% in importance with the combined approach. The main difference can be seen for nutrient regulation (RM8) which shifted from low (1) to high (4) importance in the combined assessment.

The litter had only little impact on the service potential (no change for 59% of services), but impacted highly the flow (sum moduli: 21), mostly negative (sum: −11) and mainly on the cultural services category. Consequently, experts who assessed the impact of litter (with and without beach wrack) on the general service provision (sum: −12) were mainly referring to the flow. Beach wrack instead exhibited a strong positive impact for both potential and flow (sum: 31 and 28). Compared to the service provision, experts were referring mostly to the potential of beach wrack. All cultural services were affected on the flow level, while only 24% of the values on their potential were impacted by beach wrack and/or litter.

We now calculated the weighted impact score (IS) by multiplying the relative importance (RI) in % with the impact factors for each service and scenario. Thereby, impacts are only considered according to their relevance. Consequently, impacts on services with high importance are considered stronger. With the impact score, we created an indicator for decision-making within coastal management which can be used to compare service categories, individual services, and scenarios. Furthermore, trade-offs and synergies among services can be identified by their negative and/or positive IS. Scenarios 2 and 3 (beach wrack with and without litter) showed main trade-offs between two regulating and maintenance services (RM2-3) and two cultural services (C1, C6) at flow and provision level (positive and negative IS > 30). There are only small trade-offs on potential level (±10.5), here mainly for two regulating and maintenance services (RM3, RM8) impacted by litter (scenario 1).

Several studies state the high potential (+3) (Table 2) of further economical beach wrack processing (P1), e.g., as insulation material for construction, filling material for pillows, and use for dune restoration (Sterr et al. 2019; Chubarenko et al. 2021; Misson 2020). However, due to still an unprofitable processing and additional litter pollution, the flow was assessed only low (+1) to moderate (+2). Studies show a moderate potential (+2) for energy conversion of beach wrack, e.g., as a substrate for biogas plants (Barbot et al. 2015) or biochar production (Misson 2020), while the flow increased only a little (+1) due to its low competitiveness, for example, with energy crops. Current studies emphasize the innovative potential (+2) of removed beach wrack for further use, thus extraction of nutrients (P3a). For example, they propose further use as nutrient-rich fertilizer processed in reed bed systems (Kupczyk et al. 2019) or as high-quality organic fertilizer (Emadodin et al. 2020). Seasonal variability of beach wrack biomass in composition and amounts, and increased costs for further use as fertilizer due to additional effort of litter separation were indicated by a low increase in service flow (+1). In Germany and Lithuania, sand extraction for several construction measures (P3b) is done commonly by seafloor dredging and terrestrial sand mining, but no sand extraction is performed at the coast or beach (Staudt et al. 2019; Pupienis et al. 2014). Litter nor beach wrack impact the service potential (0), but if the sand is contaminated, it needs to be cleaned before further use or processing (flow: −1). As recent literature neglects a correlation of beach wrack (incl. driftwood) and litter at Portuguese sandy beaches (Guerrero-Meseguer et al. 2020), the potential of driftwood (P4) was assessed as not impacted (0). Nevertheless, the flow decreased slightly (−1), as biomass collection and separation need more effort. The service for so-called natural ornaments (P5) included litter items as well, for example, commonly collected sea glass and other items used for art or awareness-raising projects, resulting in a positive impact on service potential (+1) and flow (+0.5). However, higher biomass landings of beach wrack also indicate a higher content of natural ornaments (potential: +3) for the interested target group (Esiukova 2017), while also being a possible nuisance due to smell or entanglement (flow: +2).

Landing of sand and beach wrack in areas with lower currents enables the spreading of larger beach areas like a "storage" (RM1), enriching fore-dunes via eolian transportation and providing additional material dissipating wave energy (potential and flow: +1) (Everard et al. 2010). Concerning coastal protection (RM2), Nordstrom et al. (2011) presented in their study the importance of beach wrack for eolian sand transport, as it is acting like a sand trap, thus influencing the sediment budget and formation of the fore-dune and its crest (potential and flow: +3). Indicated by the negative impact on service flow (−1), litter can be ingested by marine organisms and birds, used as nesting material, and cause entanglement of wildlife (Kühn et al. 2015) (RM3). A low increase in potential (+1) revealed its function as an additional hard structure for new habitats of marine organisms (Kiessling et al. 2015). Other studies indicate that beach wrack (potential and flow: +3) support a rich supralittoral fauna (Defeo et al. 2009) and emphasize their high importance as habitat and food source for dominant species at sandy beaches, e.g., sandhoppers (Ruiz-Delgado et al. 2016; Pelletier et al. 2011). Pest and disease control (RM4) was moderately impacted by beach wrack on their service potential and flow (both +2). However, beach wrack might include harmful substances, but it is a matter of concentration. One important ecological function of organic matter is to maintain the balance and capacity to control pests and diseases due to several decay processes. Plastics were identified as possible carriers of pathogens, harmful microalgae, and invasive species (Audrézet et al. 2020; Kiessling et al. 2015). Keswani et al. (2016) mentioned litter as a possible biotope for spreading further fecal indicators (FIOs) and harmful algal bloom species (HABs). Therefore, even though the potential (−1) slightly decreased, due to a higher demand for this service the flow (+1) increased slightly. With respect to a study of Everard et al. (2010), where sand dunes were mentioned as actively managed parts of the water purification (RM5) infrastructure in Amsterdam for supplying drinking water, we assumed that this service ("Selection of Ecosystem Services and Scenario Development" and "Ecosystem Service Assessments") is only relevant when considering sand dune systems. However, studies on groundwater regulation (RM6) at sandy beaches and within dunes are lacking. Defeo et al. (2009) stated that water storage in dune aquifers and groundwater discharge through beaches is one relevant ecosystem service at sandy shores. With the low importance (1) of this service due to research gaps, the potential could be underestimated. The process of carbon sequestration (RM7) at sandy beaches compared to other ecosystem services and habitats like forests or wetscapes are only of low importance (1) for ecosystem service interpretation. If sand dunes are included in the analysis, the potential would increase, as the plants of vegetated dunes and adjacent coastal forests are able to sequester carbon at a rapid rate (Beaumont et al. 2014). However, several studies reported that beach wrack might be a significant source of greenhouse gas emissions (GHG) like carbon dioxide and methane (Misson 2020; Rodil et al. 2019; Goméz et al. 2018). In conclusion, beaches as land-sea interface possibly play a more important role in carbon cycling than expected. Dugan et al. (2011) showed in their study that sandy beaches play an important role (RI:4) for nutrient regulation (RM8). As primary producers like micro- and macroalgae or seagrass grow in nearshore waters and use nutrients, their service potential is correlated with processing and remineralization of organic material and accumulation of dissolved nutrients. Other studies also emphasize the importance of sandy beaches for nutrient cycling across habitats (Barreiro et al. 2013; Rodil et al. 2019; Gómez et al. 2018). Litter was assessed to increase the service potential slightly (+1) of dispersal of seeds (RM9), while the flow was decreasing due to possible entanglement (−1) (Kiessling et al. 2015).

Litter and beach wrack presence and amounts are a common reason for the visitors' choice of their beaches (Zielinski et al. 2019; Kataržytė et al. 2020). Consequently, for recreation and tourism (C1) moderate (−2) to high (−3) impacts were stated, while the service potential is not impacted (0). With increasing infrastructure and consequently paid spa taxes, acceptance of both beach wrack and litter decreased at German Baltic beaches (Borcherding 2020). They also found a positive correlation between the awareness of the ecological relevance of beach wrack and its public acceptance, which justified the high potential (+3) but only moderate flow (+2) of the service recreation and health (C2). Humans perceive beaches and coasts as very valuable for knowledge systems (C3) that consist of educational and awareness-raising activities (RI:2). The service potential and flow increased (+1) due to activities like beach clean-ups or nature observation hikes, but also scientific studies on beach ecology and the impact of litter (Hartley et al. 2018). Coasts are also highly important (RI = 4) in terms of being part of culture and heritage (C4) as well as (regional) identity (C5). Due to subjective perceptions, they are only impacted on the flow level (litter: −2 and beach wrack: +2/+1). Litter appeared to moderately (−2) disturb the service flow of landscape esthetics (C6), which is of very high importance (RI:8) for coastal regions (Corraini et al. 2018; Hartley et al. 2018). Studies also indicate that coasts are important as a legacy to preserve for future generations (RI:4), thus protecting natural heritage (C7) (Hartley et al. 2018).

Methodological Comparison—Spreadsheet vs. Online Survey

For a methodological test and comparison of the spreadsheet-based method and the online survey, we aimed to assess both methods by pre-defined criteria in order to give recommendations when and why to use which methodological implementation (Table 3).

The assessment design of the spreadsheet and online survey was not identical due to the technical setup and differences in the software used (Table 3). The main differences in the online survey were step-by-step guidance through the

Table 3 Methodological comparison of expert-based ecosystem service assessments via spreadsheet and online survey

	Spreadsheet	Online survey
Technical set up (*Interviewer*)	Less time effort required At least basic software skills (e.g., Excel) required	Basic programming skills recommended (html, php)
Data analysis (*Interviewer*)	Easy data compilation for groups up to 50 experts (otherwise macros possible requiring programming skills) Easy and fast visualization of results for expert discussion	More complex data compilation (extraction from webpage and translation necessary)
Comprehensibility (*Interviewee*)	Additional guideline necessary (pdf)	Step-by-step guidance through webpage
Practicability (*Interviewee*)	More analytical details and information available (formulas, direct calculations of weighting factors, accumulated impact score) Easy and fast comparison of scores between scenarios (horizontal comparison)	Separate and direct assessment of scenarios (no misunderstandings or wrong comparisons) Common type of questionnaire (already used to) More difficult to compare and change score between scenarios No direct visualization of results or own interpretation possible
Technical usability (*Interviewee*)	Internet-only for down-/upload needed IT device needed (only computer) Spreadsheet software needed (excel recommended, but also usable with open source) Basic spreadsheet skills needed	Internet access needed IT device needed (computer, tablet or smartphone) No additional software or skills needed
Time requirements (*Interviewee*)	30–60 min (highly depends on commenting behavior)	15–45 min (highly depends on commenting behavior)

whole assessment (page-by-page). Scenarios were compared individually and directly with the baseline scenario one after another. The main strength of the spreadsheet-based assessment is its fast and easy technical setup, while the online survey requires more time for implementation. On the other hand, while the assessment via the online survey can be done easier and faster, the spreadsheet-based assessment requires some more time from the experts.

Discussion

Ecosystem Service Assessment Approach—Methodology and Application

Within the expert-based assessment, specific ecosystem service terminology such as potential, flow, and demand (Burkhard et al. 2014; Müller et al. 2020) (cf. "Introduction") was intentionally avoided by leaving the respective interpretation to the experts. Thereby, we gathered different arguments, understandings, and perceptions. Afterward, with the combined data-based assessment for a more ecological perspective, we further differentiated into service potential and flow. This approach allows for direct comparison of certain management scenarios, e.g., cleaning methods.

Comparing results of individual experts, values differed strongly, partly along with the whole range of values (from −3 to +3) (Fig. 8). Consequently, individual results were not representative or reliable especially with regard to beach wrack scenarios. In contrast, litter as a man-made problem was assessed very homogenously. However, results compared among expert groups, based on institutional nationality, educational background, and level, revealed low variability (low standard deviation/SD). Thus, our results indicated that a small number of experts within one group ($n = 13$) already showed representative results for the overall assessment ($n = 39$) (Fig. 8). Similarly, Campagne et al. (2017) calculated a minimal number of 30 experts needed for panel discussions in their ecosystem services study. This was also confirmed by our Monte Carlo simulations run beforehand that demanded at least 30 experts for our assessment design (cf. "Method"). However, expert groups should represent diverse institutions, levels, and fields of expertise equally, preferably a minimum of 10 experts per group.

Despite the differences between individual experts, our experience was that neither the institutional nationality nor the educational background and level within our expert groups significantly influenced the results. Although the assessment was specifically tailored to the Baltic Sea, it is, therefore, possible to transfer it to other beach ecosystems and local case studies, i.e., in the Mediterranean, provided that the scenarios used are realistic for these regions.

Furthermore, results showed possible bias due to different interpretations and misunderstandings, i.e., of definitions (e.g., beach wrack) and the descriptions of services (Table 1). Some experts, for example, also included driftwood in the beach wrack biomass or considered amber a mineral and not a natural ornament. Others interpreted pest and disease control with regard to human health and not as defined only for the ecosystem functioning itself leading to stronger perceived impacts. Some services indicated a need for further differentiation of their specific uses, as impacts were off-setting or contradicting. For example, while litter can decrease the potential of polluted beach wrack when used as a soil improver or fertilizer, for insulating materials there is no change. Besides, experts took different reference frames into consideration causing inconsistent data. For example, variability in results based on assessing the impact on services within and across habitats (only beach or including dunes and hinterland, sea and/ or land), on long or on short-term perspective, and on different size classes of litter (macro, micro, nano-level). Off-setting effects and biases within the assessment design may be caused by the selection and wording of services, their descriptions as well as the definition of the study area.

Jacobs et al. (2015) address trade-offs and synergies between ecosystem services using a matrix approach. The main synergy was found between biodiversity and recreation, while the main trade-off was identified between biodiversity and water use for navigation. Another study also assessed the relevance of single ecosystem services for different management scenarios (Schernewski et al. 2017). However, in our study we went one step further, assessing the relative importance of each service for the overall provision at beaches and using this for calculating a weighted impact score (IS). This allows us to compare the change among and between scenarios, as well as to show trade-offs and synergies among them. It can be easily adapted to local beach management by defining their local relative importance. Thus, the impact score (IS) is a suitable indicator for decision-making within practical beach management implementation by directly comparing different measures and identifying trade-offs and synergies in the Baltic and similar beach ecosystems.

Technically, the spreadsheet tool is most suitable for expert-based assessments, while the online survey is more suitable when addressing different stakeholders and larger groups of participants, e.g., "the general public". Additionally, the combined assessment is needed for further, detailed ecological analysis and as a possible indicator for decision-makers. For participatory stakeholder engagement and consensus building, we recommend the general notion of "provision", which necessitates a group discussion. In contrast, working with experts, we suggest using the terms "potential" and "flow" or "provision" when further differentiating in a combined data-based assessment.

Beach Ecosystem Services—Relevance and Impacts

Results of this study showed that cultural services are the most important ones for the overall provision of ecosystem services at sandy Baltic beaches (52.2%) (Fig. 7). This can be partly explained by the assessment design, which is an entirely anthropocentric conceptual framework and thus targeting specifically human benefits derived from the ecosystem functioning. Furthermore, the photo-based visualizations helped to reduce bias by ensuring similar interpretations by the experts. This was important because amounts of beach wrack and its composition can vary strongly among seasons, years, and countries depending on currents, wind, and vegetation. Also, the location of beach wrack at the beach itself can highly influence the results, e.g., smelly and decomposing material near the coastline versus already dried out and partially buried in the sand in front of the dunes. Therefore, a joint understanding based on manipulated photos was crucial. However, the visualizations could also lead to an intrinsic bias towards cultural and provisioning services as they mostly represent visible elements of the ecosystem. Consequently, the expert-based assessments were likely too narrow and too biased for decision-making as a stand-alone, which emphasizes the relevance of further integration of biophysical parameters. However, it can serve as a basis for further in-depth analysis on the most relevant and/or impacted services. Especially for beach management purposes and for tackling man-made problems, our approach is a suitable attempt to weight and present the visible as well as the invisible values of sandy beaches and their ecosystem services.

Despite the low to moderate importance (37.4%) (Fig. 7) of regulating and maintenance services, the cultural services highly depend on and interact with them as underlying or supporting services (Kandziora et al. 2013). For example, bathing tourism requires functioning services like Baltic Sea remediation and water purification (i.e., bathing water quality). Nature observation walks also demand an intact ecosystem with wildlife and biodiversity. Thus, although only a few regulating and maintenance services were rated as highly important (RI:4 to 8) (Table 2), they play an essential role in securing ecosystem functions and thus for overall service provision.

There was a consistent agreement among experts on the high importance (RI:4 to 8) of cultural services. Instead, the impact factors varied much more, indicating disagreement about the extent and impact of litter and beach wrack on such. Especially when assessing cultural services (specifically C2 recreation and health, and C6 landscape esthetics), the experts' subjective perspective affected the results. Impact factors differed considerably (covering 86% of the total range) when comparing respective opinions, for example, of a nature-lover, bird photographer, or hiker to a common beachgoer interested only in recreation and bathing. Some tourists prefer bare sandy and clean beaches, while others appreciate natural beaches with beach wrack. If not sought in a stakeholder workshop, this type of subjectivity could probably be reduced through an indicator-based assessment using socio-economic and biophysical data (Inácio et al. 2018; von Thenen et al. 2020). Another reason for high-value distribution is the low consent within the group, which can also show possible knowledge gaps or lack of understanding. Subjectivity among cultural services and general value distribution of RI and IF results indicated a need for and can be used as a spectrum for awareness-raising activities, adjusted provision of information, and moderation among different stakeholders' perspectives.

Common beach management activities at Baltic sandy beaches reviewed in Borcherding (2020), Zielinksi et al. (2019), and Mossbauer et al. (2012) include different cleaning procedures. They differ with regard to the spatial area (flood accumulation zone, patches) and beach size, amounts, and composition of beach wrack and littering. Other important parameters are weather conditions (dry or wet sand), financial budget, and technical equipment and staff (heavy machinery, manually by hand, semi-manually). Based on these, the municipality thus determines the temporal frequency of the cleaning (daily, weekly or less, seasonal). Major criticism by nature conservationists (besides the removal of beach wrack and litter) is the use of heavy machinery that has an impact on the sediment characteristics and vegetation. This lead to compaction of the sediments/soils and the destruction of the fragile seedlings by the sheer weight of the machinery exerting enormous pressure on upper beach layers (Gheskiere et al. 2005). While there are no studies that focus specifically on the mechanical impact of beach cleaning vehicles, evidence for the disturbance of beach ecosystems through recreational driving with off-road vehicles on beaches is well established (Houser et al. 2013). Sand-dwelling microorganisms and invertebrates were hampered e.g., in the construction of new living tubes, and/or existing ones were destroyed. They are therefore no longer able to live in the swash area as a habitat or, if possible, have to retreat to not disturbed sections of the beach. This in turn affects the abundance and biodiversity of the species that feed on the inhabitants of the beach wrack infauna by depriving them of their food source (Defeo et al. 2009). However, intensive human use of beaches usually has already a strong impact on beach ecosystems, e.g., disturbances due to high trampling intensity by beachgoers (Seer et al. 2015). Hence, in high season it seems not to make a difference in the cleaning technique if cleaned manually or mechanically, while the distance to the next parking, and thus good accessibility, has an even higher impact (Borcherding 2020). Thus, our results can be interpreted as the impact of litter and/or beach wrack removal from the beach regardless of the cleaning technique and their impact and only considering a hypothetical removal. Consequently, our results are representative and can be used for applied beach management in the study area.

However, we also determined trade-offs between the removal of beach wrack and litter and the provision of ecosystem services (Table 2). For example, cleaning procedures usually also remove sand that can be hardly separated on-site when mixed with wet beach wrack. Consequently, the services sand storage (RM1) and coastal protection (RM2) are reduced due to the loss of sand. Another main trade-off refers to biodiversity and habitat, as by removing beach wrack also valuable habitats as well as the function of seed dispersal (RM9) are lost. Central trade-offs of beach cleanings (removal of wrack and/or litter) were identified for regulating and maintenance services, mainly coastal protection and biodiversity, and cultural services, mainly tourism and recreation, at flow and provision level. This indicated that beach management, or beach cleaning, mainly impacts the flow level, but not the potential.

Furthermore, we assume some synergies of tourism-driven beach cleanings, thus the removal of beach wrack and litter, that mainly intends to increase the cultural services (mainly C1, C6) (Table 2). Our data show possible synergies with provisioning services, as the collected material might be used further (P1, P2, P3). Nevertheless, when combined, the technological and economic feasibility of such seems to be very limited and of low potential. Furthermore, we estimate another synergy of beach wrack and litter removal for carbon sequestration (RM7) that might be increased or decreased by management techniques, e.g., storing beach wrack in dune systems or further use and processing, thus avoiding decomposition on-site causing greenhouse gas emissions. Furthermore, by removing beach wrack and litter, nutrients and/or heavy metals/pollutants that would harm the environment can be removed easily (RM5, RM8). In conclusion, beach cleaning can achieve several synergies through the removal of beach wrack and litter for further processing or for the purpose of providing services (e.g., soil fertilization, energy production).

Transmission to and Recommendations for a Sustainable Beach Management

Remove litter, leave wrack

Based on our results and shown trade-offs, the removal of beach wrack is not favorable with regard to the overall service potential and flow, while the removal of litter can lead to an increase in the overall flow (Table 2). For beach management, it is therefore generally recommended to leave beach wrack on sandy beaches where it has landed naturally (if not posing an environmental or health risk), while it is strongly recommended to remove litter with as little shear pressure as possible, e.g., by manual collection.

Minimize the impact of cleaning

Despite our findings in favor of not removing beach wrack, site-specifics of beaches remain a major issue. For example, societal competitive pressures prevail on high tourism beaches. This leads to the conclusion for beach managers to carry out beach cleanings specifically on highly preferred and already degraded beaches due to strong human pressures (e.g., trampling intensity, pollution). To lower the impact of beach cleanings, new innovative techniques are needed. So far, light machinery or manual cleaning in reduced spatio-temporal patterns (e.g., only on-demand, in patches) are recommended.

Use as a valuable resource

The removed organic material is a valuable natural resource. Thus, we recommend using the synergies shown in this study and to support a value-adding process and use of the material. Depending on the composition, quantity, and quality of beach wrack, there are different forms of applications ranging from formerly known and reinvented to new and innovative ways of utilizing. These include beach wrack as filling material for pillows, as a soil improver and fertilizer, but also among others the use of biomass for energy conversion, for coastal protection and dune restoration, or as an insulating material for buildings.

Internalize (indirect) costs of cleaning

However, we also considered the high direct costs for beach cleanings (e.g., staff, machinery, maintenance) as well as the indirect "costs" by decreasing overall ecosystem service provision. Despite a possible loss of income from tourism caused by "polluted" beaches, the removal of beach wrack mainly affects the coastal protection function, the uptake and regrowth of dunes, and beach stabilization. In the long run, beach wrack removal is therefore not favorable in economic terms, as costs for future generations to protect and conserve their coasts and beach ecosystems are increasing. Thus, we recommend internalizing these indirect costs of beach cleanings, for example via taxes and fees following the 'polluters pay principle'.

Increase awareness and environmental education

According to our results, the potential of cultural services at sandy beaches is less impacted by beach wrack and litter than the flow or provision (Table 2). This discrepancy between the combined data-based (potential) and expert-based results (provision) indicated a lack of awareness of the ecological value of beach wrack among our experts. Thus, we recommend implementing management strategies that are targeting awareness-raising and environmental education of beach wrack and its ecology, especially with regard to its function within sand dune formation and coastal protection. Thereby, the acceptance and understanding of beach management measures (less or no cleaning) can be increased through higher acceptance of beach wrack.

Conclusion

This paper has argued that the removal of beach wrack at Baltic sandy beaches is not favorable with regard to the overall ecosystem service provision, as it has a strong positive impact on both service potential and flow. Contrarily, the removal of litter can increase the service flow significantly. In any case, synergies can be found in the cleaning of beaches heavily used for tourism by removing beach wrack for further processing or use (e.g., soil fertilization, energy production). Nevertheless, there are trade-offs between recreation and tourism, i.e., tourism-related removal of beach wrack, and the overall provision of ecosystem services at the beach, mainly coastal protection and biodiversity. The study contributes to our understanding of the interaction of management and policy measures with beach ecosystems and their services. Target audiences can vary from the general public to stakeholders and experts, depending on the purpose, which ranges from participatory stakeholder engagement to consensus building and decision making. This study is the first holistic assessment of ecosystem services provided by sandy beaches in combination with beach wrack and marine litter.

The findings and methodological approach will be of main interest to beach managers and policymakers in the Baltic Sea, but may also be applied and transferred to other beaches in the world showing similar characteristics, e.g., the Mediterranean Sea or the Black Sea. However, the visualizations used make the findings less generalizable, but the study can be repeated easily using photos and experts from new target regions. A limitation of this study is the geographical scope, as it did not cover services provided by dunes nor the near-shore water area explicitly, which could be usefully explored in future research. A further study could assess the impacts of concrete management measures and techniques applied by local municipalities, e.g., different machineries, by hand, or in patches. A challenge now is to develop new and innovative beach cleaning techniques and procedures, as well as economically feasible processing and application of beach wrack, which accumulates at beaches in different amounts, compositions, and high seasonality. Greater efforts of local authorities are needed to develop clear policy and legislation for sustainable beach and beach wrack management. Moreover, more guidance and consultation from research should be integrated into the decision-making of beach managers and policymakers. The approach used may also be applied to management issues in the context of coastal engineering and protection measures (e.g., hard and soft measures, building with nature), biodiversity and habitat management (e.g., recovery of seagrass meadows) or to support specific policy implementations (e.g., acceptance or monitoring of measures, define reference conditions or target values).

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Ethics Approval The study presented in the manuscript did not involve human or animal subjects.

Consent to Participate Informed consent was obtained from all individual participants included in the study.

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PAPER III

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Article

Building with Nature—Ecosystem Service Assessment of Coastal-Protection Scenarios

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Abstract: The aim of this study is to assess existing conventional and hypothetical nature-based coastal-protection schemes using a comparative ecosystem service assessment, based on quantitative data and literature as well as on stakeholder views. We assessed three conventional groin systems and three building-with-nature scenarios including an expanded beach area, a mussel farm and seagrass beds. Stakeholders perceived the nature-based scenarios as positive and assumed an overall increase in the ecosystem service provision. The quantitative data-based approach showed similar results. Building-with-nature approaches were considered to provide economical and/or environmental benefits to human beings, beyond coastal protection and safety. Especially for the combination of coastal-protection measures with submerged vegetation in shallow waters, a strong increase in ecosystem service potential is assumed, e.g., on nature restoration as well as on touristic and landscape attractiveness. Our approach turned out to be suitable for assessing different coastal-protection scenarios with reasonable effort. Our methodology can help to catch the views of people, raise awareness on the multiple consequences of these measures and enable an improved and structured participatory dialogue with locals and stakeholders. Our approach may support coastal-protection planning and help to reduce local resistance against measures and their implementation.

Keywords: Baltic Sea; mussel farm; *Teredo navalis*; groin; stakeholder; tourism; beach nourishment; sea-level rise; erosion; seagrass

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1. Introduction

The southern and south-eastern Baltic Sea coasts consist of glacial sediments and are subject to intensive erosion, sediment re-allocation and accretion. In the southern Baltic Sea region, the absolute rate of sea-level rise recently reached about 2 mm/year. As a consequence, erosion dominates and increased to an average coastal retreat rate above 1 m/year [1]. The German Baltic Sea coastline has a total length of 776 km [2,3]. Already today, up to 10% of the German Baltic coastline can be perceived as not sufficiently protected and an adequate protection would require investment costs between 1.7 and 4.8 billion Euros [4]. Additionally, the design water levels of flood protection were recently increased by 1 m until the year 2100 (LAWA 2020). In consequence, there is further need for high additional future investments in the redesign and extension of coastal protection.

The Baltic Sea is a micro tidal system and already water levels above 1 m are considered as storm surge. Serious damages by storm surges are relatively rare. Therefore, only about 60% of the 377 km coastline in the German federal state of Mecklenburg-Vorpommern are presently protected [5]. Most important protection elements are coastal dunes, 81 km of wooden groin systems, 43 km of sea dikes and a few beach-parallel breakwaters [6].

Dunes and beaches are replenished regularly to maintain their protection function and attractiveness for tourism. Tourism is the dominating economic factor especially at the seaside. In 2016, Mecklenburg-Vorpommern recorded over 30 million overnight stays, resulting in 19 overnight stays per inhabitant [7]. The need to strengthen and expand coastal-protection requires new concepts that preserve the environment and simultaneously take into account the needs of tourism.

Building-with-nature or nature-based coastal-protection concepts became popular during the last decade. The aim is to provide a cost-effective, sustainable and ecologically sound alternative to conventional "gray" or "hard" coastal engineering [8–10]. The concept especially utilizes the protective function of vegetation and became popular first in the USA and the Netherlands [11]. It includes, for example, the protection and re-establishment of intertidal muds, saltmarshes, mangrove communities, seagrass beds, vegetated dunes, intertidal habitats, coastal forests and biogenic reefs [12,13]. It also covers abiotic approaches, such as the usage of dredged material and beach nourishment [14]. Further, artificial fish, shellfish and algal reefs and farms or anchored, large woody debris [15] are considered as nature-based solutions. The concept even includes a "greener design" of hard protection structures [16] and a complementation of artificial measures [10,17]. Assessing the effectiveness of nature-based coastal protection solutions, e.g., for wave attenuation or sediment stabilization, is largely a technical challenge [18], requires field experiments, practical implementations [19] and has to take future developments into account, such as climate change [20]. A full cost-benefit analysis requires a comprehensive approach that also takes into account societal aspects [21].

Building-with-nature options have to fulfill several major requirements: to ensure the needed coastal-protection level, to be realistic, to be adapted to the local situation and to be acceptable for the local population. We considered three hypothetical options (scenarios) that meet these criteria: (a) a combination of coastal protection with improved tourism infrastructure (expanded beach area), (b) with a blue mussel farm and (c) with seagrass habitats. Against the background of sea-level rise and increasing coastal erosion, the maintenance and provision of sandy beaches is of high importance for summer tourism and local economy. Recent studies show that blue mussel farming is a feasible option for the future in the western Baltic Sea [22–24], as mussels filter algae and increase water transparency, meet the increasing demand for high-quality proteins and provide sustainably produced feed for increasing organic fish aquaculture. However, presently it hardly exists at all because of a lack of tradition and poor economic perspectives. Seagrass meadows are common in the western Baltic Sea, but human uses, diseases and eutrophication (reduced water transparency) decreased their spatial coverage [25]. Several projects and measures in the Baltic Sea try to re-establish seagrass meadows, using artificial growing mats. Seagrass forms important ecological habitats, serves as a stepping-stone for spreading species and is an important storage for carbon. [26]. Seagrass and mussel farming are meant to complement, not to replace, the traditional coastal-protection schemes.

The planning of environmental and coastal-protection measures is largely based on science and facts. However, many examples underline the importance of perceptions, especially when it comes to measure implementation [27–29]. Their public acceptance depends on the individual perceptions, e.g., of the local situation, the measure itself or assumed effects. This is especially true for new nature-based coastal-protection measures, which largely lack long-term experience and scientific certainty about their efficiency and effects [30]. Hence, public acceptance could benefit from a comprehensive assessment of the consequences of a measure. This is the focus of our research.

For assessing the benefits, ecosystem services approaches are suitable and have already been applied in coastal-protection planning [31–33]. Ecosystem services are defined as the benefits human beings obtain from ecosystems [34]. The absolute quantification of many ecosystem services is difficult, hardly reliable nor comparable and time-consuming. Thus, an alternative are approaches that compare different measures, locations or time slices with respect to relative changes in ecosystem service provision. Several examples show that it is possible to capture a larger number of ecosystem services in an efficient way by involving stakeholders and experts [35–38].

Our objectives are (a) to assess common conventional coastal-protection measures as well as potential, future-oriented, nature-based coastal-protection options using a comparative ecosystem service-assessment approach based on stakeholder opinions and on quantitative data, and (b) to evaluate the benefits of ecosystem services and of our approach in the planning and local implementation of coastal-protection measures.

2. Materials and Methods

2.1. Study Sites

The case-study sites are located at the southern Baltic Sea coast in the German federal state of Mecklenburg-Vorpommern in the surrounding of the city of Rostock (Figure 1). We carried out two ecosystem service assessments. The first one assessed the public and expert perceptions on the most common protection schemes, namely groin systems to reduce beach erosion supported by a protective vegetated sand dune. Hereafter, this is called coastal-protection assessment and scenarios. The pictures visualizing the scenarios were taken near the seaside resort Markgrafenheide and the Hütelmoor (Figure 2).

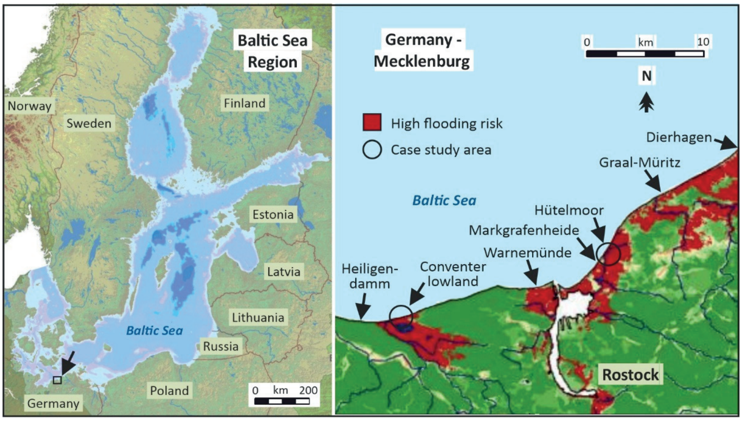

Figure 1. The Baltic Sea Region and the case-study locations at the southern Baltic Sea coast, in the German federal state of Mecklenburg-Vorpommern. The case studies are located in front of the Conventer lowland as well as the Hütelmoor. Areas with high risk of flooding are indicated, modified after LUNG [39].

Markgrafenheide has a total population of only about 550, but has more than 100,000 tourist overnight stays annually, especially during the summer months. The area is also a popular destination during summer for day tourists from the Rostock region who come for bathing, cycling or hiking.

The second ecosystem service assessment focused on an existing coastal-protection scheme in front of the Conventer lowland, near the seaside resort of Heiligendamm. Heiligendamm is the oldest German seaside resort, founded in 1793. It was a summer meeting place for the nobility and, after German re-unification, restored as a high-class tourist resort. The historic buildings are protected from the sea by a rubble embankment in combination with a seawall and a movable protection wall. A five-kilometer coastal strip east of Heiligendamm, including the Concenter lowland, is protected by wooden groins, a dike and a stone wall. In 2006, the last beach nourishment was carried out using 150,000 m^3 sand, deposited over a stretch of 2000 m. For the assessment, this existing scheme was complemented by three building-with-nature scenarios (Figure 3).

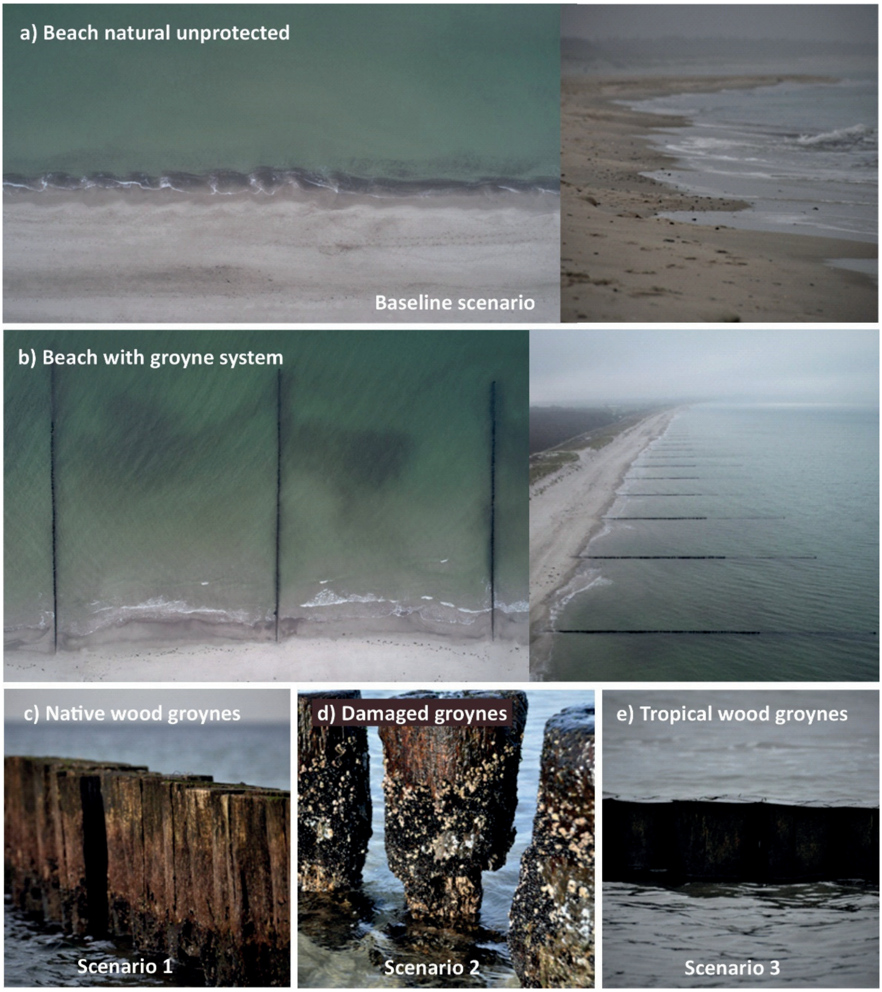

Figure 2. Simplified visualization of the coastal-protection (groins) scenarios: (**a**) the baseline scenario, a beach without coastal protection in Dierhagen; (**b**) a beach in front of the Hütelmoor (Figure 1), near Markgrafenheide, protected by the common single-pile-row groin system. The bottom-line pictures show the three scenarios: (**c**) a groin made from native wood, (**d**) a native wood groin damaged by the shipworm (*Teredo navalis*) and (**e**) a groin using certified resistant tropical wood.

Especially the areas around the Conventer lowland and the Hütelmoor face strong coastal erosion and a very high flood risk. As a consequence, these areas require improved coastal protection in the near future and were chosen as case-study sites (Figure 1) [39].

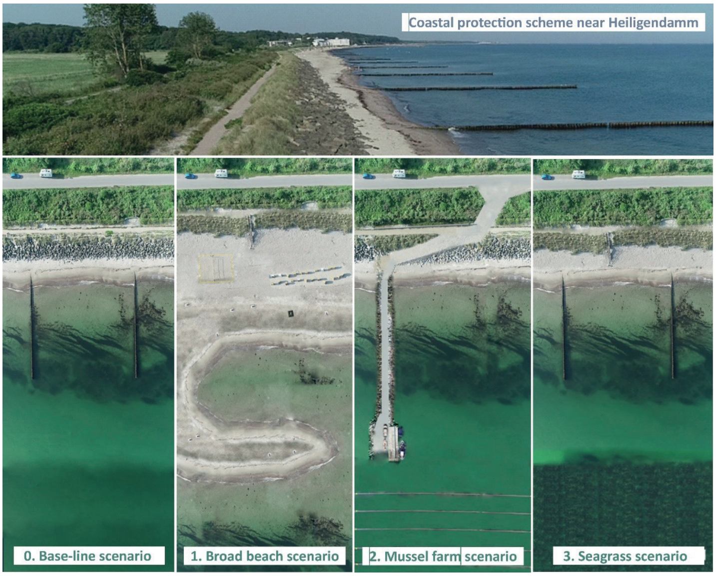

Figure 3. Simplified visualization of the building-with-nature scenarios in front of the Conventer lowland near Heiligendamm used in the ecosystem service assessment: the present situation as (0) baseline scenario, (1) scenario with an extended nourished beach, (2) scenario with pier and mussel farm and (3) scenario with seagrass (*Zostera spp.*) and submerged macrophytes in front of the beach.

2.2. Selection of Ecosystem Services

The selected ecosystem services are based on the CICES 5.1 classification [40], as it is officially used by the European Commission, is hierarchically structured and follows the United Nations Statistical Division guidance. The CICES 5.1 classification is subdivided into the three sections of "provisioning", "regulation and maintenance", and "cultural" ecosystem services. The selection of ecosystem services was carried out by the authors with additional consultation of other scientists. The criteria were their relevance for the issue and fairly equal representation of the three sections. Pre-tests resulted in an upper maximum number between 25 and 30 ecosystem services. This number allows for an assessment by external stakeholders and experts in an acceptable time frame of about 45 min and subsequent discussions. The chosen ecosystem services slightly differ between both assessments, resulting from the different focus and lessons learned during the first approach. The ecosystem services were compiled into tables that enable assessments by externals remotely (Appendix A).

2.3. The Scenarios

In parallel, the scenarios, showing potential protection options, were developed for the two ecosystem service assessments. The coastal-protection assessment (groins) consists of a baseline scenario without coastal protection. This scenario is compared to three scenarios with wooden groin systems, one with native wooden piles, one with largely degraded native wooden piles and the third one with piles made from ecologically certified tropical wood. The background for the second scenario is the situation in front of the Hütelmoor. Here, groin systems are not replaced, as a nature restoration and coastal realignment measure. As a consequence, the wooden piles show infestations with and damages caused by the shipworm (*Teredo navalis*) (Figure 2).

The building-with-nature assessment consists of a baseline scenario showing the existing coastal-protection approach without official public access to the narrow beach (Figure 3, base line-scenario). This is compared to three hypothetical scenarios. Scenario 1 consists of a large-scale sand nourishment resulting in an artificial peninsula and a protective sand dune (covering the stone wall). The area is accessible for visitors over a wooden staircase. Scenario 2 assumes a longline mussel farm with a size of 2 ha parallel to the beach. An access road leads to a stone pier with a ramp for launching boats and a dock for small boats. The stone pier obstructs the longshore currents, while the mussel farm attenuate waves. Scenario 3 consists of seagrass meadows and submerged macrophytes in front of the beach. The plants settle on natural but introduced textile material and stabilize sediments. Next to the seagrass area, the existing groins remain but the revetments of the baseline scenario are replaced by a sand dune that offers beach access over a wooden staircase. All scenarios improve the coastal-protection level compared to the present state.

The scenario visualizations (Figures 2 and 3) are simplified. For the group assessments, all scenarios were explained in detail with additional pictures, complementing information and background data compiled into Powerpoint slide presentations.

2.4. The Assessment Approach

We used two approaches of ecosystem service assessments: a quantitative data and literature-based, subsequently called data-based, approach, and a qualitative group-based approach. The data-based assessment was carried out in both case studies. Students with a suitable scientific background compiled data, literature, regional policy and planning documents as well as monitoring data and carried out the assessment based on this knowledge. This took one to two months. The group-based assessment was carried out by a group of people with different backgrounds and expertise. The single group assessments were always kept separately and later combined into a common assessment.

The group-based coastal-protection assessment involved 17 participants, 6 males and 11 females between the ages 23 to 59, with a variety of knowledge backgrounds, from coastal experts to laypersons. This group was regarded as one joint stakeholder group. Since the assessment was meant as a screening to get a first impression of perceptions and to test the approach, the selection of participants was largely random and did not follow a scientific system.

The group-based assessments on building with nature altogether involved 27 participants. Based on their knowledge of ecosystem services, coastal protection and marine ecology, they were divided into four subgroups. The level of expertise was judged based on a participants' self-assessment prior to the ecosystem service-assessment process. Criteria for the self-assessment were knowledge in ecosystem services, in marine ecology and in coastal protection.

Group A (Coastal-management scientists) consisted of 11 scientists and students working in the field of coastal and marine management in Warnemünde, located close to the study sites. This group had the best knowledge in ecosystem services and marine ecology and some knowledge in coastal protection.

Group B (Student group) consisted of five master students from the "Resource Analysis and Management" course at Göttingen University, 300 km off the Baltic Sea, without local knowledge. The students indicated low knowledge with respect to all three criteria.

Group C (Coastal-protection scientists) included six scientists with varying local knowledge and expertise. Most indicated good expertise in coastal protection and some knowledge in ecosystem services and marine ecology.

Group D (Coastal-protection authority) consisted of five experts working at the local state authority responsible for coastal protection in the study site area. They have very good knowledge in their field, but only basic knowledge in ecosystem services and marine ecology.

To enable a sufficiently large number of participants, both group-based assessments used two survey sub-methods: face-to-face workshops and individual remote assessments. During the face-to-face workshops, the aims were explained, local and scientific background information was provided and the scenarios were presented. Participants then carried out the ecosystem service assessments individually on paper, followed by a discussion.

For the remote surveys, participants were contacted and received all necessary information and the assessment sheet via email. After submitting the individual assessments, participants were contacted online to clarify open questions and gather additional views.

The individual assessment sheets listed all ecosystem services (with explanations) in rows and all scenarios in separate columns. In a first step, participants were asked to assess the relative importance (RI) of every ecosystem service, using the classes 0 (not relevant), 1, 2, 4 and 8 (very high relevance). In a second step, every scenario was compared to the baseline scenario, representing the present situation. This was performed for every ecosystem service. On a relative scale ranging from −4 (very high decrease in a service) to +4 (very high increase), the participants were asked to provide their view on the ecosystem service changes in the scenarios, always compared to the baseline scenario. The coastal-protection assessment used a slightly coarser scale between −3 and +3. The multiplication of the relative importance with the ecosystem service score for the change allowed the calculation of the weighted results.

At the end, participants were asked to rate the complexity, comprehensibility and visualization of the entire approach (1 = low/bad, 2 = moderate/ok, 3 = high/good) and to estimate the time required to complete the assessment. The same assessment sheet (Appendix A) was used for all surveys. The different survey methods resulted from restrictions during the COVID pandemic.

3. Results

3.1. Coastal-Protection (Groins) Assessment

The relative importance of provisioning services for assessing coastal-protection schemes is perceived as low (Figure 4). This is true for the data-based assessment conducted by one student and the stakeholder group. With respect to regulating and maintenance ecosystem services, a few services are considered as very highly relevant (RI = 8), such as coastal protection as well as biodiversity and habitats. While the data-based assessment assumes a minor relevance for all other regulating services, the group assigns a high relevance (RI = 4). The discussions after the assessment revealed that group members consider groins to be a habitat hosting multiple organisms that have a significant effect for instance on nutrients or carbon storage. The different perceptions indicate limited knowledge and experience with respect to wooden groin systems. Unanimously, cultural services are regarded as of highest importance. Altogether, the assessment of the relative importance of ecosystem services seems less reliable when it relies on unexperienced stakeholders. The data-based approach provides better justified scores.

With respect to provisioning services, the differences between a situation without groin systems and the three groin scenarios are relatively low. The average changes for all provisioning services remain below 1 (low increase). Further, the data show a good agreement between stakeholder group and data-based assessment. For regulating and cultural services, the data-based and group assessment are also well in agreement. Scenarios 1 and 3, assuming native and tropical wooden groins, show a similar assessment: an increased sediment storage and improved coastal protection, but reduced services for recreation, natural heritage and aesthetics. Groins in decay (scenario 2) are perceived slightly different. However, significant negative effects of groins in decay on scores for recreation or aesthetics are not evident. Altogether, the data and group-based scenario assessments show largely similar results.

Ecosystem services (ES)			Relative importance			1: Native wood groynes			2: Damaged groynes			3: Tropical wood groynes		
			Expert /data	Stake-holders Mean	Stake-holders Median	Expert /data	Stake-holders Mean	Stake-holders Median	Expert /data	Stake-holders Mean	Stake-holders Median	Expert /data	Stake-holders Mean	Stake-holders Median
Provisioning	1	Wild animals for nutrition	2	2.7	2	1	0.8	1	1	0.5	1	1	0.6	1
	2	Wild plants for nutrition	1	2.0	1	1	0.8	1	1	0.5	0	1	0.6	0
	3	Wild plants for materials (further proc.)	1	1.5	1	1	0.4	0	1	0.2	0	1	0.4	0
	4	Timber / driftwood	1	1.2	1	2	0.4	0	1	0.4	0	2	0.5	0
	5	Natural ornaments	1	1.9	2	1	0.6	1	1	0.5	0	1	0.6	0
	6	Biomass as energy source	1	1.6	1	0	0.2	0	0	0.2	0	0	0.2	0
	7	Extraction of minerals (sand, nutrients)	2	1.9	2	0	0.5	0	0	0.4	0	0	0.6	0
	8	Freshwater for drinking purposes	0	1.7	0	1	0.1	0	0	-0.1	0	1	0.1	0
Regulating	1	Sediment storage and transport	4	4.9	4	3	1.3	2	1	0.4	1	3	1.1	2
	2	Coastal protection / flood control	8	6.2	8	3	2.2	2	1	0.6	1	3	2.2	3
	3	Biodiversity and habitats	8	5.6	4	2	1.5	2	2	0.9	1	2	1.8	2
	4	Pest and disease control	2	4.1	4	-1	-0.1	0	-2	-0.8	-1	0	0.3	0
	5	Water purification	1	4.7	4	0	0.0	0	0	-0.1	0	0	-0.1	0
	6	Groundwater regulation	1	3.7	4	1	0.3	0	0	-0.3	0	1	0.3	0
	7	Carbon sequestration	2	4.3	4	1	0.5	0	2	0.2	0	1	0.4	0
	8	Nutrient regulation	2	3.8	4	1	0.5	0	2	0.2	0	1	0.6	0
	9	Dispersal of seeds	1	2.8	2	-2	0.1	0	-1	0.2	0	-2	-0.1	0
Cultural	1	Recreation and tourism (active)	8	6.8	8	-1	-0.2	0	-2	-0.8	-1	-1	-0.3	0
	2	Recreation and health (observational)	8	5.9	4	0	0.1	0	2	-0.1	0	0	0.1	0
	3	Knowledge systems	8	4.7	4	3	1.3	1	3	1.1	1	3	1.3	1
	4	Culture and heritage	4	4.1	4	0	0.4	0	0	-0.2	0	0	0.3	0
	5	Regional identity	4	3.5	4	0	0.3	0	0	-0.1	0	0	0.2	0
	6	Landscape aesthetics	4	5.4	4	-2	-0.9	-1	-1	-1.5	-1	-2	-1.4	-1
	7	Natural heritage	4	6.5	8	-2	-0.6	0	-1	-0.9	-1	-2	-0.8	0

Figure 4. Comparative ecosystem service assessment of three coastal-protection scenarios (Figure 2) representing the present coastal-protection situation with different groin systems at the southern Germany Baltic Sea coast. Score 3 indicates a high increase and −3 a high decrease in ecosystem service provision compared to a coastline without groin systems for coastal protection. The scores for the relative importance of the ecosystem services used for this assessment range from 0 (irrelevant) to 8 (very important). The shown scores are based on data as well as mean and median values of the stakeholders' group (17 persons).

The differences in scores for ecosystem services between the different scenarios are limited, affect only some services and the direction of changes seem reasonable. It seems that this methodology is not well suited for scenarios with limited differences that are not immediately visible and where thematic and local knowledge is required. The benefit of an ecosystem service assessment of these scenarios is limited and does not provide unexpected insights. One original objective of the assessment was to assess the consequences of ship worm destructions beyond the effects on coastal protection. This objective was not met.

3.2. Building with Nature: Group Assessments and Variability

Looking at the assessment results of individual persons, it is noticeable that the scores for several ecosystem services cover the whole range between −3 and 3. In general, the variability in scores is very high. The use of median instead of using average scores does not solve this problem, since both do not differ much (Figure 4). Very likely, this variability results from the heterogeneity of the group, especially from the different knowledge and regional experience of the persons involved. Therefore, the involvement of better defined, homogeneous groups is recommendable.

The scores for the relative importance of ecosystem services were meant for weighting the ecosystem service scores. In principle, this seems useful, but in this case the services with the highest changes were usually those with the highest relative importance. Therefore, the assessment results were dominated by a few ecosystem services and an additional higher weighting of these services would not provide better insights.

As a consequence of the previous results, the building-with-nature assessments separate different groups and involve experts: group A (coastal-management scientists), group B (student group), group C (coastal-protection scientists) and group D (coastal-protection authority). The scores for the relative importance of the individual ecosystem services for the assessment of the building-with-nature scenarios differ very much between the groups. The median for all provisioning services is 1, ranging from 1 to 2 between the groups. With respect to all regulating (resp. cultural) services, the median is 4 (4) ranging from 1 to 4 (0 to 4) between the groups. Especially group C shows much lower relative importance scores for regulating and cultural services compared to the other groups.

In general, provisioning services are perceived as of minor importance, most cultural services are regarded as relevant and several regulating services are considered as highly relevant (Figure 5). This pattern is similar to the previous coastal-protection assessment (Figure 4) and seems typical for these coastal-protection assessments.

Ecosystem services (ES)			Relative importance Group / Median				1: Broad beach Group / Median				2: Mussel farm Group / median				3: Seagrass Group / Median			
			A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Provisioning	1	Reared aquatic animals for nutrition	4	2	1	1	0	0	-1	0	4	3	3	2	0	0	0	0
	2	Reared aquatic animals for energy	1	1	1	0	0	0	-1	0	2	1	0	0	0	0	0	0
	3	Reared aquatic animals for materials	1	1	1	0	0	0	-1	0	4	2	2	1	0	0	0	0
	4	Wild plants used for nutrition	2	2	1.5	1	0	0	0	0	0	1	0	0	3	4	1	0
	5	Wild plants used for material	2	2	1.5	1	0	0	1	0	0	1	0	0	2	4	2	2
	6	Wild animals for human nutrition	4	4	0	4	0	0	0	0	1	1	1	1	2	2	2	0
	7	Genetic material of plants	1	1	1.5	0	0	0	0	0	0	0	0	0	2	2	1	0
	8	Genetic material of animals	1	1	1.5	0	0	0	0	0	1	1	0.5	1	2	0	0.5	0
	9	Mineral substances for material	4	2	1.5	4	2	2	1	0	0	1	0	0	0	1	0	0
Regulating	1	Mediation of wastes and pollutants	4	4	1	2	0	1	0	0	2	2	0.5	2	3	3	2	1
	2	Mass stabilization and control of erosion rate	8	4	6	4	2	2	3	2	1	3	2.5	0	4	3	3	1
	3	Hydrological cycle and water flow regulation	8	4	8	4	2	2	2	2	2	2	2	-1	2	2	2	1
	4	Seed and/ or gamete dispersal	4	4	2	1	0	0	0.5	0	3	0	2	1	3	2	2	1
	5	Biodiversity and habitat	8	8	1	4	0	0	1	0	2	2	0	-1	4	3	2.5	3
	6	Pest and disease control	4	4	0	2	0	0	0	0	0.5	0	0	-1	1	1	0	0
	7	Decomp. & fixing proc. & effect on sediments	2	4	1.5	2	0	1	1.5	0	0	0	0	0	2	2	2	0
	8	Regulation of chemical water condition	4	8	1	4	0	0	0	0	3	2	1	1	3	2	1.5	1
	9	Carbon sequestration	4	8	1	4	0	0	0	0	1	1	0	2	3	3	2.5	3
Cultural	1	Recreation and tourism on/in water (active)	4	1	0	4	0	1	2.5	3	1	-4	0	-2	2	-1	0.5	0
	2	Recreation and tourism on land (active)	4	1	0	4	3	1	2.5	4	0	-2	0	-1	1	0	0	0
	3	Recreation and tourism (observational)	4	1	0	4	1	1	2.5	3	2	-1	1	0	2	0	0.5	1
	4	Reserach & education	4	4	1	4	1	0	2	2	2	1	1.5	2	3	2	2	2
	5	Aesthetics	4	2	0	4	1	1	1.5	2	-2	-1	-0.5	-2	1	-1	0	1
	6	Enterainment	2	1	0	1	1	0	1.5	2	1	-2	1	0	1	0	0.5	0
	7	Regional identity	2	2	0.5	4	0	0	0	0	-1	0	0.5	0	0	0	0	0
	8	Conservation value	4	8	1.5	4	0	0	0	0	0	0	1	0	2	0	1.5	1

Figure 5. Comparative ecosystem service assessment of three building-with-nature scenarios (Figure 3) at the southern German Baltic Sea coast. Score 4 indicates a high increase and -4 a high decrease in ecosystem service provision compared to the present coastline. The scores for the relative importance of the ecosystem services used for this assessment range from 0 (irrelevant) to 8 (very important). Shown are median scores for four different assessment groups: (**A**) coastal-management scientists, (**B**) student group, (**C**) coastal-protection scientists and (**D**) coastal-protection authority.

The coastal-protection scientists (group C) regard only services that reflect core aspects of coastal protection as of high relevance, namely mass stabilization and erosion control as well as water-flow regulation. All other ecosystem services are perceived as of low relevance. Despite comparable knowledge backgrounds, the coastal-protection authority group (D) assesses the relevance of ecosystem services very differently and considers cultural services altogether as of the highest relevance, similar to the coastal-management scientists (group A). Altogether, the perception of the ecosystem service relevance seems strongly influenced by individual, personal views rather than by the educational and professional background.

In contrast to that, the assessed changes in ecosystem service provision show comparatively similar patterns between the scenarios (Figure 5). For single scenarios and ecosystem services, strong differences in scores between individuals occur, for example the consequence of the mussel farming scenario on active recreation and tourism (C1). However, this can be explained by different potential reactional activities. The type of activity the experts have in mind when assessing the changes (e.g., angling, diving or kite-surfing) can cause strong differences in the scores (Appendix A). This indicates that the scores very much depend on the perceptions and associations people have with each scenario. It underlines the great importance as well as the critical and potentially influential role of scenario visualization and presentation.

The variability of the individual scores for the relative importance of ecosystem services is very high (Figure 6). The variability of the individual ecosystem service change scores is still significant, but much lower.

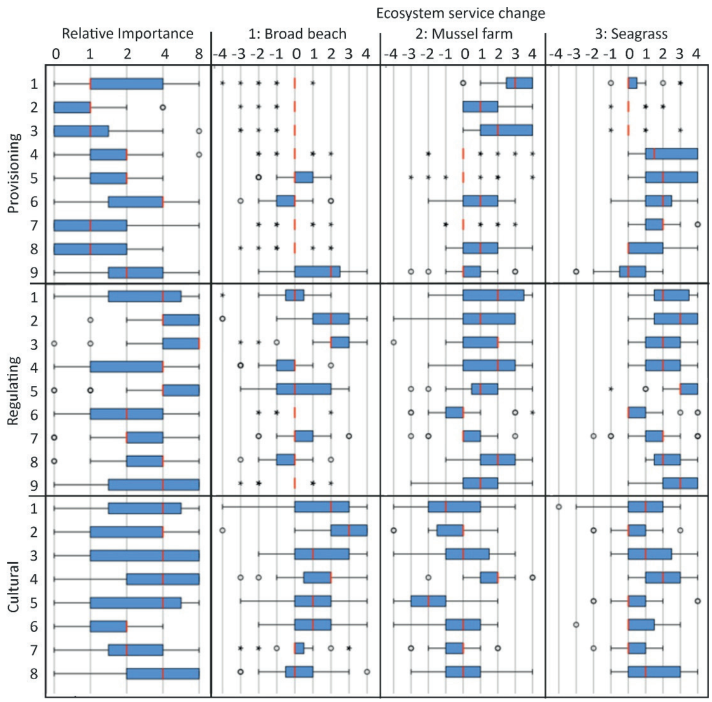

Figure 6. Whisker Box-Plot of the comparative ecosystem service assessment scores for the three building-with-nature scenarios (Figure 3). Score 4 indicates a high increase and −4 a high decrease in ecosystem service provision compared to the present coastline. The scores for the relative importance of the ecosystem services used for this assessment range from 0 (irrelevant) to 8 (very important). Red line = median, blue box = upper/lower quartile, horizontal line = upper/lower Whisker; ° = Outliers; * = Extreme outliers.

Altogether, we can conclude that a separation between the different expert groups does not provide more detailed insights, neither with respect to the relative importance assessment nor with respect to the scores on ecosystem service changes. Therefore, hereafter, the group results are combined to get the joint view of the 27 persons involved.

3.3. Building with Nature: Complete Scenario Assessments

Figure 7 shows the aggregated group results and the data-based assessment by an expert student. Again, the relative importance scores differ between the two, but not as much as in the single group comparisons (Figure 5).

		Ecosystem services (ES)	Relative importance			1: Broad beach			2: Mussel farm			3: Seagrass		
			Expert /data	Expert groups Mean	Expert groups Median	Expert /data	Expert groups Mean	Expert groups Median	Expert /data	Expert groups Mean	Expert groups Median	Expert /data	Expert groups Mean	Expert groups Median
Provisioning	1	Reared aquatic animals for nutrition	4	2.5	1	0	-0.4	0	4	3.0	3	0	0.5	0
	2	Reared aquatic animals for energy	1	1.1	1	0	-0.3	0	2	1.2	1	0	0.2	0
	3	Reared aquatic animals for materials (further proc.)	2	1.4	1	0	-0.4	0	3	2.2	2	0	0.1	0
	4	Wild plants used for nutrition	2	1.8	2	0	-0.1	0	0	0.3	0	3	1.9	1.5
	5	Wild plants used for material	2	1.7	2	0	0.1	0	1	0.2	0	3	2.2	2
	6	Wild animals for human nutrition	4	3.5	4	0	-0.3	0	2	0.7	1	3	1.7	2
	7	Genetic material of plants	2	1.4	1	1	-0.1	0	0	0.2	0	2	1.6	2
	8	Genetic material of animals	2	1.3	1	0	-0.1	0	2	1.2	1	2	1.0	0
	9	Mineral substances for material (futher processing)	4	3.0	2	2	1.4	2	0	0.3	0	0	-0.1	0
Regulating	1	Mediation of wastes and pollutants	4	3.7	4	-1	0.0	0	1	1.7	2	3	2.4	2
	2	Mass stabilization and control of erosion rate	8	5.4	4	2	1.7	2	2	1.0	1	4	2.9	3
	3	Hydrological cycle and water flow regulation	8	5.9	8	2	2.0	2	2	1.2	2	2	2.0	2
	4	Seed and/ or gamete dispersal	4	3.1	4	1	-0.4	0	1	1.8	2	2	2.1	2
	5	Biodiversity and habitat	8	5.2	4	2	0.3	0	1	1.2	1	4	2.9	3
	6	Pest and disease control	4	3.0	2	-1	-0.2	0	-2	-0.1	0	2	0.9	0
	7	Decomposition & fixing proc. & effect on sediments	2	2.6	2	0	0.5	0	-2	0.2	0	2	1.5	2
	8	Regulation of chemical water condition	4	3.9	4	-1	-0.4	0	3	2.0	2	3	2.2	2
	9	Carbon sequestration	8	4.3	4	1	-0.3	0	2	1.1	1	4	2.9	3
Cultural	1	Recreation and tourism on/in water (active)	4	3.9	4	3	1.4	2	-2	-1.0	-1	2	0.6	1
	2	Recreation and tourism on land (active)	4	3.6	4	4	2.6	3	-2	-0.6	0	2	0.4	0
	3	Recreation and tourism (observational)	4	4.0	4	2	1.3	1	-1	0.1	0	2	1.4	1
	4	Reserach & education	2	4.2	4	2	1.3	2	1	1.6	2	2	2.1	2
	5	Aesthetics	4	3.6	4	3	0.9	1	-3	-1.6	-2	1	0.6	0
	6	Enterainment	2	1.5	2	1	1.0	1	1	-0.1	0	1	0.7	0
	7	Regional identity	2	2.5	2	2	0.1	0	-1	-0.3	0	1	0.4	0
	8	Conservation value	8	4.8	4	1	0.1	0	1	0.1	0	3	1.5	1

Figure 7. Comparative ecosystem service assessment of three scenarios (Figure 3) representing building-with-nature examples. Comparison of the quantitative data-based and the accumulated group scores. Score 4 indicates a high increase and −4 a high decrease in ecosystem service provision compared to the present coastline. The scores for the relative importance of the ecosystem services used for this assessment range from 0 (irrelevant) to 8 (very important). Shown are median scores for four different assessment groups.

The lesson learned is that the relative importance of services should be better discussed and agreed upon before the ecosystem service assessment takes place. This should preferably be a joint approach between the group members and the single expert who knows the data. Because of a limited benefit, weighted scores (multiplication of the relative importance with the ecosystem change score) are not shown.

The ecosystem service change assessments between the data-based and group assessments are fairly consistent and in agreement (Figure 7). It seems that a data-based assessment and the one by a group of mainly scientists provide stable and reliable results. Each scenario shows a distinct score pattern between provisioning, regulating and cultural services.

The extended beach scenario (1) shows low changes in provisioning and strong positive changes in cultural services. The regulating services are increased for mass stabilization and erosion, as well as flow regulation. The improved coastal-protection situation of this scenario is well reflected. Important is the increase in cultural service provision. This clearly indicates that improved coastal protection on one side and improved touristic usability and attractiveness on the other are not contradictory. All building-with-nature approaches increase the ecosystem services, thus the benefits to people.

The mussel farming scenario (2) shows the expected increase in provisioning services because mussels can be used for food, feed and processing. Beyond that, mussel cultivation is assumed to provide additional, increased ecosystem services for wild plants and animals. In general, the assessment suggests that mussel farms, on average, increase most regulating services. Some contradictions exist with respect to pest and disease control as well as decomposition and effects on sediments. While the group does not indicate any changes, the data-based assessment suggests a decline of these services. Negative effects of mussel farms on sediments and organic accumulations under the farm are a known potential problem. The consequences for pest and disease control can be positive or negative depending on the perspective. Seed mussels can introduce diseases, but while filtering the water, mussels have the potential to reduce risks from vibrio bacteria or algal blooms, for example. The effects of mussel farms on cultural services (tourism, recreation, aesthetics) are mainly perceived negatively. However, the sum of all ecosystem service changes is positive, meaning that coastal protection and commercial activities can be combined and provide a win-win solution.

The seagrass scenario (3) shows strong positive changes for provisioning, regulating and cultural services, with the strongest impact on regulating services. The experts agree that the combination of coastal-protection measures with submerged vegetation has a strong effect beyond improved protection. The perceived benefits are the restoration of nature and the increase in tourist and scenic attractiveness.

3.4. Building with Nature: Appraoch Assessment

All participants in the ecosystem service assessment on building with nature were asked to finally assess the complexity of the approach, the comprehensibility and the quality of the scenario visualization using scores between 0 and 3. Agreement between the four groups was very high. The complexity of the approach was rated as high (average of 2.3). The comprehensibility was regarded as high (average of 2.1), and the visualization was rated 2.7 in average. Altogether, the involved peoples got the impression that the approach has a high complexity and is comprehensive, but well understandable and feasible. However, it requires a very good and comprehensive visualization of the scenarios. The time people needed to complete the ecosystem service-assessment sheet and the additional questions ranged from 20 to 60 min, with an average of 37 min. The student and the coastal-protection authority groups on average needed above 40 min. The time requirements were perceived as acceptable. If carried out during workshops, the total time required including presentation and discussion is about 90 min.

4. Discussion

Ecosystem service-assessment approaches: Traditionally, assessments aim to provide a defined (monetary) value for each service. The weaknesses of this approach are known, such as the lack of data, the lack of comparability of services because of different valuation methods and the high time-effort. Further, the underlying indicators describing individual ecosystem services usually possess several well-known weaknesses [41]. As a consequence, ecosystem service assessments were used, were measured, or systems were assessed in comparison [35–38]. This approach can provide results based on group knowledge, requires less data, is relatively fast and conceptually easy to understand. A division between actual use (flow) and potential of ecosystem services is not that important. Assessed are only intensity and direction of ecosystem service changes. The disadvantage is that the results are case-specific and only reflect opinions and perceptions of those involved. However, for assessing alternative coastal-protection scenarios, this approach turned out to be useful. It was possible to involve a large group of experts and stakeholders and required only a limited time commitment of about 90 min when carried out via an online or face-to-face group meeting. Therefore, it can be regarded as applicable in coastal management and protection practice. However, it has been shown that the approach is not well suited for scenarios that have limited differences, not immediately visible, and where thematic and local knowledge is required. The data-based approach is a suitable complement to the group results. However, because of the poor data availability, it can also hardly be regarded as reliable. Further, the indicators commonly used for describing ecosystem services are usually not well suitable.

Assessment methods: We applied different assessment methods (individual on paper, face-to-face, online, phone-call, group discussion and workshop). This resulted from the special situation during the COVID pandemic. Our data does not allow us to critically evaluate the effectiveness of each method. One lesson learned is that after the assessment, discussion is important to clarify possible misunderstandings and to gain deeper insight into the reasons behind individual scores. Altogether, the scores for the different building-with-nature assessments were fairly consistent and in agreement, regardless of whether the assessment was conducted by one person based on data or by a larger group. In general, we can conclude that the better the local and thematic knowledge of the persons involved, the smaller the group can be. However, the variability between the individual scores is significant. Our subdivided small groups with only 5–6 comparable experts were not beneficial. Our results indicate that about 10 persons per group would provide sufficiently stable results.

Quality of the results: Our coastal-protection assessment considering different groin systems did not provide unexpected insights. A wider assessment of the consequences of ship worm destructions beyond the effects on coastal protection was not successful. This was different for the building-with-nature scenarios. Here, the group and the data-based results indicate a distinct score pattern between provisioning, regulating and cultural services for each scenario. The lesson learned is that scenarios have to show alternatives that are large enough, distinct enough and comprehensible. However, even the building-with-nature assessment results are opinions and can hardly be regarded as crisp, reliable data on which planning and decision-making can build upon. A critical point that has not been taken into account in our study is the extent to which the assessment results depend on the presentation, scenario visualization and the background information provided.

The spatial assessment area of a measure has to be clearly communicated. Scores for ecosystem service changes depend strongly on whether a few square meters or kilometers are considered. Further, it must be communicated that the changes in ecosystem service potentials are in focus not the personal view on possible changes in ecosystem service flows. The assessment of the latter depends highly on personal preferences, judgment and experiences.

Selection, number and relevance of ecosystem services: Guiding principles for the selection and number of the ecosystem services were relevance, an acceptable assessment time, broad thematic coverage, and balance between provisioning, regulating and cultural services. The selection and the number of 24 and 27 ecosystem services, respectively, proved to be a suitable compromise for our assessments. The services and the suitability of the scoring ranges were confirmed in the feedback discussions with the participants. The scoring pattern between the assessments is comparable. This indicates that our ecosystem service set can serve as a general set for comparable coastal applications.

An important aspect is the assessment of the relative importance of every ecosystem service. The participants get the possibility to express how they perceive the ecosystem and what is important to them. This enables a more differentiated assessment. The relative importance scores give the moderator an impression about the participants and their understanding of the ecosystem. The scores support the discussion, provide better insight into the background of the ecosystem service scores, and allow a weighting of the ecosystem services. The weighting did not provide an added value in this study.

Scoring the relative importance of ecosystem services turned out to be highly variable among the participants. It seems to be influenced strongly by individual personal views rather than by the educational and professional background. The lesson learned is that the relative importance of services should be better discussed and agreed on before the ecosystem service assessment takes place. This should preferably be conducted in a joint approach between the group members and the single expert who knows the data.

Practical role of ecosystem service assessments: Participants from authorities were positive about the practical usability of the approach in their professional work. The discussions and several examples show that the implementation of measures is often hampered by local resistance. It is only years after the implementation of a measure that locals become aware of the benefits, leading to a change in attitude toward a measure [42,43].

During the assessment process and follow-up discussions, participants learn from each other and develop a mutual understanding and better insight into trade-offs between ecosystem service changes [44]. It can reduce imbalances and misunderstandings in planning and lead to an improved outcome. However, due to limited reliability, representativeness and transferability to other cases, the applications are hardly suitable for the formal coastal-protection planning and implementation process. Ecosystem service assessments should preferably be used as a complementary approach. The benefits are in raising participants' awareness of how a measure affects the usability of a system and in providing a more comprehensive understanding of interactions and consequences. An ecosystem service assessment can structure and support a dialogue between a planner and the public and possibly increase the acceptance of measures. Further, it can initiate interdisciplinary discussions between scientists and transdisciplinary exchange with authorities. This is well in agreement with experience by other authors [45–47].

The stakeholders considered all three building-with-nature scenarios as realistic potential options. This kind of scenario analysis can stimulate a general discussion about the potential of building-with-nature solutions on the southern Baltic Sea coast and provide a first insight into public acceptance and feasibility. An implementation in the next years is not realistic, but the increasing sea-level rise will require a re-assessment of the existing coastal-protection schemes and flood levels. This process may offer possibilities for building-with-nature approaches.

5. Conclusions

Comparative ecosystem service assessments are a suitable method to informally evaluate existing and hypothetical coastal-protection scenarios and can complement formal planning, approval and implementation processes. Both, the stakeholder and data-based approaches suggest that the three building-with-nature scenarios increase ecosystem service potentials. This means they provide additional benefits to human beings beyond coastal protection and safety. This is true for the extended beach/sand nourishment example and even for the mussel farming scenario. Here, too, the sum of all ecosystem service changes is positive, meaning that stakeholders see a possibility to combine coastal protection and commercial activities in a win-win solution. In particular, the combination of coastal-protection measures with submerged vegetation is perceived to have a strong positive effect. For example, the restoration of nature and the increase in tourist and scenic attractiveness are seen as benefits. There is no general answer to which scenario is best suited for implementation. It depends on local framework conditions and priorities, legal restrictions, planning and coastal-protection objectives and, last but not least, the costs. The feasibility and cost-efficiency of the assessed building-with-nature solutions still require a detailed analysis.

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Appendix A

Ecosystem service-assessment sheet that was used in all surveys, including the provided additional descriptions for every ecosystem service. Below are the scoring scales used for rating the potential change in ecosystem service provision as well as for the relative importance of an ecosystem service. The scoring scales were similar in all scenarios [48]. The Powerpoint presentation with background information can be obtained on request.

Name	
Self-assessment (0= no knowledge; 1= low; 2= medium; 3= high)	
Knowledge in Ecosystem Services Knowledge in Marine Ecology Knoweldge in Coastal Protection	
Time spent	

Assessment feedback (1= low; 2= moderate; 3=high)	
Complexity Comprehensibility Visualisation	

		Ecosystem services	Description	Relative Importance	Scenario 1	Scenario 2	Scenario 3
Provisioning	1	Reared aquatic animals for nutrition	Animals cultivated in water that we eat e.g. salmon, mussels				
	2	Reared aquatic animals for energy	Animals cultivated in water that we can use as a source of energy				
	3	Reared aquatic animals for materials (further processing)	Animals cultivated in water for material use e.g. shells used in poultry grit				
	4	Wild plants used for nutrition	Food from wild plants e.g. seagras or reed sprouts				
	5	Wild plants used for material	Material use of marine plants e.g. driftwood used as fertilizer in agriculture or reed for thatched roofs				
	6	Wild animals for human nutrition	Food from wild animals e.g. fish				
	7	Genetic material of plants	Seed collection or breeding new species/ population e.g. breeding of red algae to achieve improved strains, genetically modified seaweed, oyster spat collection				
	8	Genetic material of animals	Animals used for replenishing stocks or breeding e.g. Breeding of new oyster strains, gene modification of marine microorganisms				
	9	Mineral substances for material (futher processing)	Natural inorganic material that we can use e.g. sand and gravel deposits				
Regulation & Maintenance	1	Mediation of wastes and pollutants	Filtration/ bio-remediation/ storage/ accumulation by living organisms e.g. plants				
	2	Mass stabilization and control of erosion rate	Sediment stabilization controlling or preventiong erosion/ mass movements e.g. by seagras meadows				
	3	Hydrological cycle and water flow regulation	Regulating water flows and coastal protection e.g. coastal habitats/ natural levees reducing wave energy and providing flood protection				
	4	Seed and/ or Gamete dispersal	Plants or mussels spreading seed or gamete for population maintenance				
	5	Biodiversity and habitat	Providing habitat (inc. Nursery and breeding ground) for wild plants or animals e.g. seagras beds as nursery habitat for commercial fish stock				
	6	Pest and disease control	Controlling pests and invasive species e.g. control of overabundance of phtoplankton by marine plants				
	7	Decomposition and fixing processes and their effect on sediment quality	Remineralisation processes in marine sediments				
	8	Regulation of chemical water condition	controlling chemical condition of water e.g. water purification by plants or mussels				
	9	Carbon sequestration	Carbon sinks provided by e.g. seagras beds				
Cultural	1	Recreation and tourism (Active)	Using the environment for sport and recreation e.g. swimming, water sports, fishing, diving				
	2	Recreation and tourism (observational)	Using nature to distress e.g. seabirds, plants or marine mammals to observe				
	3	Reserach & Education	Studying nature or using nature for educational purposes e.g. coastal dynamics in university courses or school field trips				
	4	Aesthetics	Beauty of nature e.g. absence of algal mats				
	5	Enterainment	Things in nature used to make films or to write books				
	6	Regional identity	Things in nature that help people identify with history or culture of where they live or come from (inc. Spiritual experience)				
	7	Conservation value	Things in nature that think should be conserved for future generations				

ES provision change

-4	-3	-2	-1	0	1	2	3	4
Very high decrease	High decrease	Medium decrease	Low decrease	No change	Low increase	Medium increase	High increase	Very high increase

Scoring for Relative Importance (RI)

0	1	2	4	8
Not relevant	Low	Moderate	High	Very high

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PAPER IV

Environmental Management
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Assessment of Ecosystem Services Provided by Macrophytes in Southern Baltic and Southern Mediterranean Coastal Lagoons

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Abstract
The ecological importance of macrophytes is well known and reflected in nature protection law, for example, as a key biological quality element. However, the socio-economic role, such as the impact of macrophyte presence on recreational activities, is often overlooked. The purpose of this study was to assess the human benefits (or ecosystem services) provided by macrophytes. We developed a list of 25 macrophyte ecosystem services and 79 assessment indicators based on expert knowledge and literature data. First, hypothetical scenarios of coastal lagoons were developed to assess the impact of different ecological states (i.e., macrophyte coverage) and management measures (i.e., fisheries) on the ecosystem service provision. Scenario assessments were carried out by stakeholder workshops and literature search. Second, the ecosystem service potential of submerged and emergent macrophyte habitats were assessed by macrophyte experts and literature data. Results showed that cultural services are most important in terms of the overall actual provision of ecosystem services (scenario assessment) but also showing highest potential of the hypothetical ecosystem service provision (habitat assessment). Highest overall potential is shown for reeds and tall forb communities (83 out of maximum 125), followed by seagrass beds (71) and seaweed communities (61). Our ecosystem service assessment approaches (i.e., scenario and habitat-based) using socio-cultural data (i.e., stakeholders and experts-based) and biophysical data (i.e., indicators-based) can serve as supportive tools for coastal management and policy implementation visualizing the benefits of macrophytes to humans.

Keywords Szczecin lagoon · Curonian lagoon · Bizerte lagoon · Scenarios · Habitats · Indicators

Introduction

Shallow coastal areas, especially sheltered lagoons, are characterized by their highly valuable macrophyte habitats. Macrophytes are aquatic plants and macroalgae, including emergent (e.g., reed and salt meadow species) and submerged types (e.g., seagrass, charophytes and pondweed) that can be rooted or unrooted, floating or attached. They bear important ecological functions, such as nutrient retention, carbon sequestration, coastal protection or habitats for biodiversity (Duarte et al. 2013; Newton et al. 2014; Buczko et al. 2022). Thereby, they support major socio-economic activities in coastal waters, such as leisure and tourism (i.e., by counteracting eutrophication and improving bathing water quality) as well as fisheries (i.e., by providing nursery habitat) (Newton et al. 2014; Sinkeviciene et al. 2017). In the Baltic Sea, especially reeds were historically harvested and used as building material, while nowadays macrophytes play only a minor economic role as raw material (Köbbing et al. 2013; Karstens et al. 2019). In contrast, in the Mediterranean Sea, macrophytes provide sightseeing opportunities for diving tourism, fisheries and seaweed harvesting that are big economic drivers (El Mahrad et al. 2020). These examples show that macrophytes in general provide a vast range of direct or indirect benefits to humans, also referred to as ecosystem services (Millennium Ecosystem Assessment 2005; TEEB 2010).

The concept of ecosystem services (ES) emerged in the 1960 within the field of ecological economics as a response to the need for nature conservation (Costanza et al. 1998). Since then multiple assessment approaches and classifications developed. The most popular classification system in Europe is the Common International Classification of

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Ecosystem Services (CICES; Haines-Young & Potschin-Young 2018). CICES differentiates between three main categories: provisioning services (e.g., charophytes for fish feeding), regulating and maintenance services (e.g., reed belts as wave attenuators), and cultural services (e.g., seagrass beds for diving). Others classification systems exist, for example, including supporting services (The Millennium Ecosystem Assessment 2005) or habitat services (TEEB 2010). For measuring ES, a huge variety of assessment methods and approaches exist, summarized and classified by Harrison et al. (2018) as socio-cultural (e.g., participatory assessments), monetary (e.g., mitigation costs) and biophysical methods (e.g., modelling).

ES of coastal waters, especially lagoons, are reviewed worldwide (Newton et al. 2018). Inventories of ES exist for specific lagoons in the Mediterranean (Velasco et al. 2018) and the Baltic Sea (Inácio et al. 2018). However, studies on ES provided specifically by macrophytes in coastal waters are scarce. They focus usually on single macrophyte species (e.g., charophytes; Schneider et al. 2015) or single services, such as carbon sequestration from seagrass (Reynolds et al. 2016). Studies also assess the ES of macrophytes under certain management measures, for example, seagrass restoration (Chen et al. 2022), seaweed cultivation (Hasselström et al. 2018) or reed harvesting (Karstens et al. 2019). In the Baltic Sea, only a few studies focus on ES provided by macrophytes (Gopal 2016; Heckwolf et al. 2021). For North African countries, interdisciplinary studies on ES including social, economic and cultural aspects are few and only recently studied: while Santoro (2023) studied the ES of agroforestry systems (i.e., traditional oases) and their main threats, El Mahrad et al. (2020) analyzed the socio-ecological importance of coastal lagoons and their management. There are only few comprehensive studies assessing ES provided by macrophytes and their habitats, especially under different management scenarios and/or environmental changes and anthropogenic pressures impacting macrophyte habitats (Lindegarth et al. 2014, Janssen et al. 2021).

Central management concerns in coastal lagoons worldwide, dominated by macrophytes, comprise of combating eutrophication (Erostate et al. 2022), regulating fisheries management (Scapin et al. 2021) and coping with coastal erosion and sea level rise (Inácio et al. 2023). Due to their proximity to the coast, macrophyte habitats are highly disturbed by natural and human-induced pressures, such as eutrophication, pollution, climate change and loss of biodiversity (Kennish and Paerl 2010). Thus, they occur in very dynamic and changing environment with varying hydrodynamics, water transparency, salinity, temperature and nutrient concentrations. This causes a change in the coverage, size and species composition of macrophyte communities (Bučas et al. 2019) as well as in their provision of ES. To address these pressures, macrophytes are well reflected within European Union (EU) water and nature policies, such as in the EU Water Framework Directive (WFD) and the Habitats Directive (HD).

The WFD (Directive 2000/60/EC) is a comprehensive water protection policy of pioneering character (Carvalho et al. 2019). Its overall aim is to achieve a "good ecological status" (GES) of all EU surface waters including "transitional and coastal waters". The ecological status is assessed based on biological quality elements (i.e., phytoplankton, macrophytes, phytobenthos, benthic invertebrate fauna and fish), supporting physicochemical (e.g., nutrient content, water transparency) and hydromorphological elements (e.g., structure of the coastal zone) (BMUV/UBA 2022). Thus, the ecological importance of macrophytes as one key biological quality element is well reflected in the WFD, also shown by their integration in the complex assessment schemes, tools (e.g., PHYBIBCO) and parameters (i.e., ecological significance, species composition and abundance, biomass, depth limits) developed under the WFD over decades. Country-specific "Programs of Measures" to improve water quality status include, for example, agricultural practices (e.g., reducing nutrient loads from fertilization), habitat restoration (e.g., shoreline planting), and sewage treatment (e.g., reducing pollutant loads) (LUNG 2021).

Despite major efforts and numerous measures, almost 50% of all transitional and coastal waters in the EU are still not in a good or high ecological state regarding the status of macrophytes (EEA 2018). In addition to complex administrative procedures, further limitations of successfully implementing measures are the lack of financial resources, trained staff (i.e., in public administration) and required experts (BMUB/UBA 2022). While assessment methodologies require time and expertise (MariLim 2019a; 2019b), their results indicate that implemented measures have only little effect (e.g., because of the slow response time of aquatic systems) or are not always sufficiently reflected by assessment results (BMUB/UBA 2016). The multiple pressures addressed by the WFD (i.e., pollutant loads, lack of habitats) require complex combinations of measures, which are often not measurable quantitatively due to long response times of ecosystems (e.g., 10–20 years in coastal waters) (BMUB/UBA 2022).

Macrophyte habitats also play an important role in the EU Biodiversity Strategy 2030, and thereby also in the associated HD (Directive 92/43/EEC), Birds Directive (Directive 79/409/EEC) and the Natura 2000 ecological network of protected areas. One of the main objectives of the strategy is to maintain and restore ecosystems, thus the provision of ES (pillar 2 from 4; EC 2021). Actions required under the strategy include the mapping and assessment of ES and their integration, e.g., into decision making. Coastal habitats, including macrophytes, were reported to have the lowest share of "good conservation status" assessments and are in need of improvement (EC 2020b).

The concept of ES became subject of political interest recognizing its potential to support implementation processes, being partially integrated into recent EU policies (Bouwma et al. 2018). Despite numerous applications of ES assessments within EU policies (e.g., within national reports), a comprehensive integration of ES approaches is lacking, which is an ongoing challenge in the development of current EU policy and environmental legislation due to high complexity and time-consuming approaches (Schleyer et al. 2015; Bouwma et al. 2018). The benefits of ES assessments in coastal and marine management and policy implementation include, for example, to serve as a decision support tool (Rees et al. 2022) or to support participatory community engagement (Burdon et al. 2022). A simplified but holistic assessment approach for coastal areas, especially the land-sea interface covered by macrophytes, is needed that allows for an easy and fast comparison of different systems and concrete management measures (e.g., improved water quality by achieving GES), also showing their benefits and tradeoffs for human society, and thereby support implementations of EU policies.

The main purpose of this study is to develop and apply a holistic socio-economic and ecological ES assessment for macrophyte habitats in shallow coastal areas. Our aims are 1) to develop a list of ES provided by macrophytes including respective assessment indicators, 2) to assess macrophyte scenarios developed to represent different ecological states according to the WFD and management measures (i.e., coastal protection) by evaluating the relative importance of macrophyte ES and their impact of scenarios perceived by different stakeholder groups, 3) to visualize the socio-economic benefits of macrophytes by assessing the ES potential of submerged and emergent habitats (based on Natura 2000), and 4) to show the general applicability of assessment approaches within coastal management (e.g., to identify tradeoffs between tourism and conservation) and policy implementation (e.g., to show benefits of habitat recovery to achieve GES) in contrasting systems (i.e., from the Baltic Sea to the Mediterranean Sea).

Methodology

Study Sites

Our main study area are shallow coastal areas in the Baltic Sea (Szczecin and Curonian lagoon) and the Mediterranean Sea (Bizerte lagoon) with focus on coastal lagoons that are often characterized by macrophyte habitats (Fig. 1). The primary management issue of coastal lagoons worldwide is eutrophication (Erostate et al. 2022), accompanied by fisheries management (Scapin et al. 2022) and coastal erosion (Inácio et al. 2023). In order to test the general applicability of our approaches internationally, we chose and tested three lagoons (all subject to mentioned management issues) from diverse and contrasting systems (see Table 1) in terms of climate zones (i.e., warm summer climate in the Baltic, and Mediterranean climate), different physico-chemical conditions (low to high salinity; low to high turbidity; good to poor ecological states), socio-economic parameters (uses, pressures, pollution), and data availability (poor, good).

Curonian Lagoon

The main economic driver of the biggest Baltic lagoon is the historically developed artisanal and small-scale fisheries. Anthropogenic pressures include the increased nutrient discharge from the catchment, overfishing and recreational activities along the shoreline. Despite significant efforts in preventing eutrophication, the lagoon is regarded as being in a poor ecological status (Vaičiūtė et al. 2021). Bottom sediments consist mostly of fine sand, while coarse silt and fine silty mud are common at the depth over 3 m (Stragauskaite et al. 2021). In the estuarine part of the Curonian lagoon, typical brackish water species (*Chara baltica* and *Tolypella nidifica*) are restricted to the areas affected by brackish water up to a salinity of 0.4 psu (Bučas et al. 2019). Freshwater species (*Nitellopsis obtusa*) are mainly found from the Nemunas Delta to Dreverna. *Chara contraria* and *Chara aspera* are dominant species and wide spread in the eastern littoral of the lagoon down to 2.5 m depth. Apart from abundant *Phragmites australi*s belts, the most dominant angiosperms are *Potamogeton perfoliatus, Potamogeton rutilus*, and *Stuckenia pectinat* (Stragauskaite et al. 2021). Despite a decline of submerged macrophytes due to eutrophication in 1960–1980, recent data of Sinkevičienė et al. (2017) state a current increase of charophytes. The Lithuanian part of the lagoon is designated as Natura 2000 site, under both Habitats and Birds Directives and is adjacent to the Curonian spit, which is a UNESCO world heritage site.

Szczecin Lagoon

For centuries, the main economic sector of the lagoon has been fisheries and, more recently, also tourism. Thus, many settlements nearby directly or indirectly rely on the goods supplied by the lagoon. Nutrient enrichment of the lagoon causes an unsatisfactory ecological state, classified as 'poor' according to the WFD (Friedland et al. 2019). Riverine nutrient loads from agriculture and urban areas keep the lagoon in a polytrophic to hypertrophic state. Most

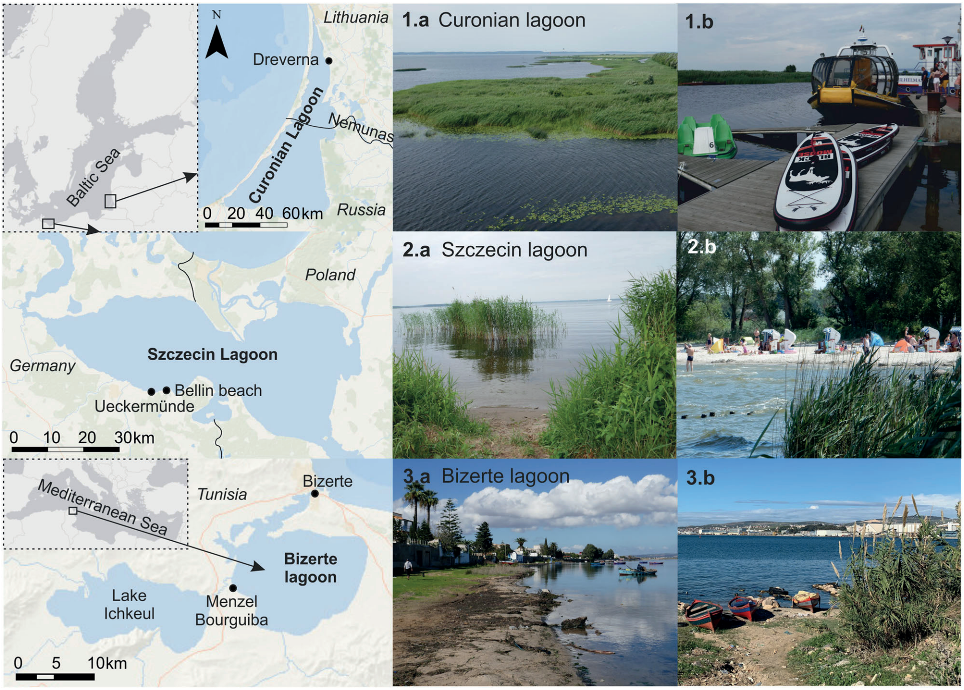

Fig. 1 Location of the three study sites Curonian lagoon (Baltic Sea), Szczecin lagoon (Baltic Sea) and Bizerte lagoon (Mediterranean Sea). Pictures show dominating macrophyte habitats (**a**) and human uses (**b**): protected reed belts (1.a) and water sport center (1.b) in Dreverna (Lithuania), reed belts (2a) and beach tourism (2.b) in Ueckermünde (Germany), and a city beach (3.a) in Menzel Bourguiba and fishing boats (3.b) in Bizerte (Tunisia)

Table 1 Physico-chemical parameters of the three study sites: Szczecin lagoon, Curonian lagoon and Bizerte lagoon

Parameter	Szczecin lagoon	Curonian lagoon	Bizerte lagoon
Sea	SW Baltic	SE Baltic	SW Mediterranean
Country	Germany/ Poland	Lithuania/ Russia	Tunisia
Climate zone (acc. to Koeppen)	Humid continental climate (Dfb)	Humid continental climate (Dfb)	Hot-summer Mediterranean climate (Csa)
Ice coverage (days a^{-1})	59	110 (min: 12; max: 169)	0
Area (km^2)	669 (GER: 277)	1.584 (LT: 413)	150
Largest inflowing rivers	Oder	Nemunas	Ichkeul Lake
Catchment area (km^2)	118,000	98,200	ca. 2500
Mean depth (m)	3.8	3.8	7
Maximum depth (m)	12	14.5	12
Secchi depth (m)	< 1	< 1	< 2.5
Salinity (max/min in psu)	1–3	0.1–7	20–40
Water temperature (°C)	10 [0–20]	10 [0–21]	17 [10–29]
Trophic state	eutrophic	eutrophic	eutrophic

Data from: Schiewer (2008), Alves Martins et al. (2015), Friedland et al. (2019), Mensi et al. (2020), Stragauskaite et al. (2021)

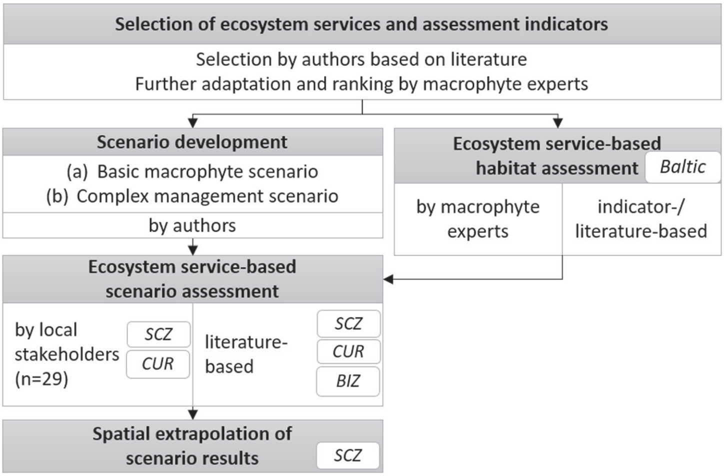

Fig. 2 Work flow diagram of applied assessment methods and data sources (i.e., experts, stakeholders, literature) indicating applied study sites in the small boxes (SCZ Szczecin lagoon, CUR Curonian lagoon, BIZ Bizerte lagoon, Baltic - Shallow coastal areas of the Baltic Sea)

dominant habitats include common reed (*Phragmites australis*), usually occurring in bands or patches, and charophytes (*Chara spp.).* Despite the recent increase in macrophytes, historical records for the Szczecin lagoon show a strong decline in macrophyte habitats, mainly due to eutrophication, from an estimated 36% coverage 130 years ago to a current state of 12% coverage (Schernewski et al. 2023). The lagoon is a designated Natura 2000 site with additional huge parts under landscape protection, two adjacent national parks in the coastal area and several nature reserves.

Bizerte Lagoon

Since the 1950s, the lagoon has been being highly modified and intensively used by humans, mainly for fishing activities, and mussel and oyster farming (Khammassi et al. 2019). The lagoon is a highly industrialized area with around 130 industrial factories located nearby (El Mahrad et al. 2020). Thus, the main pressures include discharges from urban and industrial pollution sources (i.e., textile dyeing industry and metallurgic factory, domestic sewage) (Zaabar et al. 2017). Only 15 years ago, the ecological state was considered to be in an overall satisfactory condition (Afli et al. 2008). However, due to the high nutrient inputs a current change towards eutrophication is observed (Zaabar et al. 2017). Dominant sediments are muddy sands covered by main macrophyte compositions of seaweeds (*Ulva lactuca*, *Cladophora sp*., *Gracilariopsis longissima* and *Gracilaria bursa-pastoris*) and seagrass (*Cymodocea nodosa*) (Zaabar et al. 2017). Compared to other Mediterranean waters, Bizerte lagoon has a low species richness and abundance due to its extremely fluctuating environmental conditions. Consequently, a major ecological constraint is the high seasonal variability in temperature, salinity, and nutrient concentration (Zaabar et al. 2017). The lagoon is connected to the Ichkeul lake which is a National Park and UNESCO world heritage site.

Ecosystem Service Assessment

Our ecosystem service assessment consists of five components (Fig. 2). Based on the selection of ecosystem services and assessment indicators, we followed two main assessment approaches. First, after scenario development, we conducted ecosystem service-based scenario assessments (i.e., stakeholder and literature-based) to evaluate the perceived impacts of different ecological states of lagoons on service provision by macrophytes (including spatial extrapolation). Second, we applied an ecosystem service-based habitat assessment (i.e., expert and literature-based) to compare the service potential of different macrophyte habitats typical for coastal waters of the Baltic Sea, visualizing their socio-economic benefits. These results were also combined with scenario assessment results.

Selection of Ecosystem Services and Assessment Indicators

With the aim to develop a list of macrophyte ecosystem services and respective assessment indicators, we provide the basis for the overall objective of developing a generally valid ES assessment scheme for macrophyte habitats in shallow coastal areas. Following selection criteria were

Table 2 List of stakeholder workshops in which the ecosystem service-based scenario assessment approach was applied

	Date	Location	Study site	Scenarios	# Participants	Stakeholder groups
1	03.09.20	Rostock, Germany	Szczecin lagoon	Complex management scenarios (0.b, 1.b)	12 (German)	Academia & science: local experts (100%)
2	07.08.22/ 18.08.22	Rostock, Germany	Szczecin lagoon	Basic macrophyte scenarios (0.a, 1.a)	12 (German: 25%, Dutch: 75%)	Academia & science: local experts (42%), public authorities (50%), public audience (8%)
3	03.10.22	Klaipeda, Lithuania	Curonian lagoon	Basic macrophyte scenarios (0.a, 1.a)	5 (Lithuanian)	Academia & science: local graduate students (100%)

applied: socio-economic and ecological relevance, frequency, tolerable assessment time for stakeholders/ experts, and balance between ES categories. The set of ecosystem services were derived from the ecological functions and processes related to macrophytes (Hossain et al. 2017), then defined and classified according to CICES V.5.1 based on Haines-Young and Potschin-Young (2018) and Burkhard et al. (2014), adapted according to Gopal (2016) and von Thenen et al. (2020). We then compiled a set of assessment indicators for each service. The indicators are based on literature (von Thenen et al. 2020), but also complemented and adapted with the help of local macrophyte experts in separate, individual and remote assessments. They were asked to rank the three most suitable and important indicators per service by a ranking score of 1 to 3 (most suitable). The selection list of indicators comprises the three highest-ranked indicators (according to the sum of all expert scores). Afterwards, we pre-tested the importance and comprehensibility of the services (including descriptions) in an expert workshop (Workshop 1 in Table 2), and further adapted and tested them again with experts from local study areas.

Scenario Development

In the scenario building, we developed scenarios that aim to assess the impact of a prospective good ecological state (GES) of coastal lagoons (basic macrophyte vs. turbid water scenarios) and of certain management measures (coastal protection and fishery) on ecosystem service provision as perceived by stakeholders. For this, we developed five hypothetical scenarios showing a coastal transect typical for the Szczecin and/or Curonian lagoon based on the current state of Bellin beach (Szczecin lagoon, Fig. 1) which was taken as references state (1.a) (Fig. 3). In the Curonian lagoon, similar conditions can be found, for example, in Dreverna (Fig. 1) assuming the transect to be representative for both lagoons (also confirmed by local experts). We differentiate between basic macrophyte scenarios (0.a., 1.a. and 2) representing different ecological states according to the WFD (poor, moderate, good) and complex management scenarios (0.b. and 1.b.) depicting concrete management measures, i.e., regulating fisheries and coastal protection structures. Hereby, we aim to identify possible tradeoffs or synergies between achieving a GES (acc. to the WFD), coastal protection measures and different fishing intensities with regard to the recovery of macrophytes. These scenarios are used for stakeholder-based workshops and the application of ecosystem service-based scenario assessments.

- *Baseline scenario 0* (poor ecological state) represents a heavily eutrophic water body with almost entire macrophyte disappearance; in addition, the complex management scenario (0.b.) includes concrete management demands as coastal protection measures (wooden groins) and a high fishing intensity (three fish traps).
- *Scenario 1* (moderate ecological state) shows a narrow reed belt along the shore, representing the most common current state of the study sites; in a complex management scenario (1.b.) macrophyte belt performs coastal protection function, therefore artificial protection infrastructure is no more needed, whereas a low fishing intensity (one fish trap) was added – corresponding to achieved sustainable fishery landings.
- *Scenario 2* (good ecological state) represents a state after possible conservation or nature protection measures are implemented without any commercial fisheries, and no need for artificial coastal protection; the system shifts from domination of phytoplankton production to domination of macrophyte production and increase in habitat coverage (no need for complex management scenario).

Ecosystem Service-based Scenario Assessment

The scenario assessment was further performed based on ecosystem service assessment approach carried out by three participatory workshops with different stakeholder groups (see Table 2). In Workshop 1 (Szczecin lagoon) targeting the local scientific community, 12 local environmental researchers (or coastal management experts) from five different research institutes and from relevant disciplines

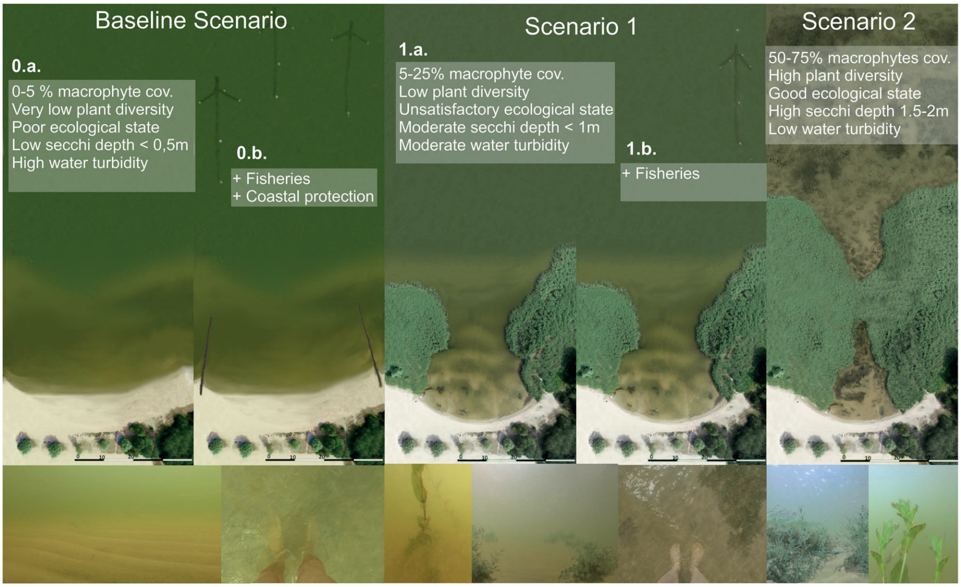

Fig. 3 Visualization of basic macrophyte scenarios used for stakeholder and literature-based assessments by orthophoto view of coastal area transect (above) and its underwater view (below): The Baseline Scenario (0.a.) represents a poor ecological state, Scenario 1.a. a moderate ecological state and Scenario 2 a good ecological state (GES). Additional scenarios presented for assessment include complex management context (fisheries: high intensity (0.b.) and sustainable yields (1.b); and coastal protection: installed groins (0.b.), protection function by macrophyte stand (1.b.)

(ecology, biology, geography) participated and assessed the complex management scenarios (0.b, 1.b). In Workshop 2 and 3 the basic macrophyte scenarios (0.a, 1.a) were assessed. For assessing the Szczecin lagoon, Workshop 2 aiming at practitioners and coastal managers comprised of 12 stakeholders from different sectors (science, government and NGOs), who worked in coastal waters and macrophyte management (legislation, conservation, monitoring). Workshop 3 performed in Lithuania targets local graduate students in the related fields (marine biology, ecology, coastal engineering) to assess scenarios in the Curonian lagoon ecosystem.

Workshops were conducted in groups, face-to-face or in person, online or combined. The duration of the workshops was between 90 and 120 min, including introduction (~30 min), assessment (~30 min) and discussion (30–60 min). In the introduction, the scenarios, their visualizations and the assessment method were presented. First, we asked them to indicate the "Relative Importance (RI)", which indicates how important each ES is perceived relatively to the overall ES provision of the given transect. By doing this, we evaluated the suitability of selected ES. The scoring scheme ranges from "not important" [0], "low" [1], "moderate" [2], "high" [4] to "very high importance" [8] based on Robbe et al. (2021). Second, experts assessed the relative "Change" of Scenarios 1 and 2 compared to the Baseline scenario. These values based on stakeholders´ perceptions and knowledge indicate how the ES are changed or impacted by different states of the given transect. The scoring scheme ranges from high [+/−3], moderate [+/−2], low [+/−1] negative or positive change or no change [0]. In Workshop 1, the additional score of [+/−4] was tested. Stakeholders indicated their level of expertise (1 = low, 2 = moderate, 3 = high) for ES, macrophyte ecology, and management and policy. As a basis for discussion, participants were asked to explain their extreme low or extreme high values in order to identify under-/overestimations, misunderstandings and/or misconceptions. In particular, services with high standard deviations (SD > 1.5) of the relative importance values and the impact scores indicate a need for further discussion and clarification. To calculate the SD of the logarithmic scale of RI (0, 1, 2, 4, 8), we converted RI values into an arithmetic scale, assuming a normal distribution. In Workshop 1, experts were allowed to change values after discussion (in case of misunderstandings). For a quick data validation analysis of Workshop 1 (experts), 50% of the experts (three with each high and low expertise) were asked to repeat the assessment after one week.

Complementary to the stakeholder-based assessments, separate literature-based assessments compiled area-specific and local literature data for each ecosystem service using scientific databases (i.e., Web of Science, Google Scholar). When not available from the study sites, data from similar areas in the Baltic or Mediterranean Sea were used. Following a semi-structured narrative approach, most recent to 30-year-old literature was scanned for keywords of each ecosystem service, their descriptors, indicators and respective lagoon. Exemplary search strings were as following: ("Szczecin lagoon") AND ("reed") AND ("coastal protection" OR "erosion rate" OR "height of vegetation"). Based on this compiled knowledge, we followed the same approach as the stakeholders described above, allocating the RI and impact scores according to literature found. With this method we can compare the perception of stakeholders with the scientific view reflected in scientific literature. Using literature survey approach, we analyzed the basic macrophyte scenarios (0.a., 1.a. and Scenario 2) in the Mediterranean Sea and in the Bizerte lagoon. However, due to the still ongoing and projected eutrophication processes, the Baseline scenario for the Bizerte lagoon represents the predicted eutrophic state in the future (poor ecological state), which is compared to the current good ecological state (Scenario 2) and to a moderate ecological state (Scenario 1).

Spatial Extrapolation of Scenario Assessment

In the next step, we carried out a spatial extrapolation exemplarily for the scenario assessment results of the Kleines Haff of the Szczecin lagoon (German part) to test the applicability of our results on water body level. For transferring our small-scale results to large-scale system level, we used the most robust data of the three lagoons (Szczecin, Curonian and Bizerte lagoon) being provided for the real scenario transect of Bellin beach (Szczecin lagoon). Thereby, we aim to identify areas for which our scenario results are relevant and applicable, and to identify areas most suitable for management and policy measures to mitigate tradeoffs between human use and nature protection. We combined spatially explicit data on human uses (i.e., urban settlements, protected areas, recreational use) and habitat distribution (i.e., submerged and emergent habitats based on depths) with our scenario assessment results (i.e., RI and impact values).

For this, we first mapped the current submerged vegetation (i.e., angiosperms and charophytes) adopted from Paysen (2016) and Porsche et al. (2008) (Fig. 3). Based on the assumptions that submerged vegetation expands up to a depth limit of 3 m according to Porsche et al. (2008), we mapped the potential submerged distribution of macrophytes. We defined a coastal zone of 1000 m along the shoreline. We then chose areas for extrapolation that show similar conditions as given in the transect of Scenario 1 (current state of Bellin beach) in terms of vegetation, beach access and proximity to urban settlements, and thus recreational use (i.e., beach tourism). By linking spatial data and the RI values of scenario assessment, we mapped the current spatial use for the extrapolated areas, including macrophyte habitats, recreational use (services C1 and C2) and fisheries (service P2), representing Scenario 1. For Scenario 2, we mapped the potential spatial use under the assumption of achieving the GES (i.e., increased water transparency and habitat expansion), establishing nature-protected areas and subsequently banning fisheries. We evaluated the increase or decrease in spatial uses (i.e., habitats, recreational use, fisheries, nature protection) of Scenario 2 (potential) compared to Scenario 1 (current) and linked these to our scenario assessment results (i.e., impact values).

Ecosystem Service Provision Potential by Macrophyte Habitats

We aim to assess and compare the ES potential of submerged and emergent macrophyte habitats using expert knowledge and indicators. Our assessment units constitute for ideal and hypothetical scenarios based on EUNIS and HD classifications (detailed descriptions in Online Resource 1) and show seven different macrophyte habitats and species along the land-sea gradient (see Fig. 4): 1) seagrass beds, 2) seaweed communities, 3) charophytes, 4) pondweed, 5) reeds and tall forb communities, 6) salt meadows dominated by *Salicornia*, and 7) salt meadows dominated by *Aster tripolium*. We selected the macrophyte habitats according to following criteria: a. most dominant species and habitats of the study areas (i.e., lagoons and shallow coastal areas), and b. most important species and habitats from a management perspective (i.e., local iconic species, cultural and economic value). We assume a total area of 100 m^2 for all habitats, which is the minimum area to be considered as such by the HD. They are based on and adapted from the definitions of the HD and the categories from the European Nature Information System (EUNIS 2022). Detailed descriptions of the habitats can be found in Online Resource 1. We consider all shallow coastal areas of the Baltic Sea between 1.5 and 12 psu.

Due to the high complexity and in-depth knowledge required, the habitat assessment approach involved only macrophyte experts. In total, eleven experts from two countries (Germany: 82%, Lithuania: 18%) carried out the assessment individually and remotely between June and September 2022. Experts were provided with an assessment guideline including detailed habitat descriptions (Online Resource 1) and distribution maps based on observational data from HELCOM (2023) and GBIF (2023) (Fig. 4). Main criteria for expert selection was their field of expertise

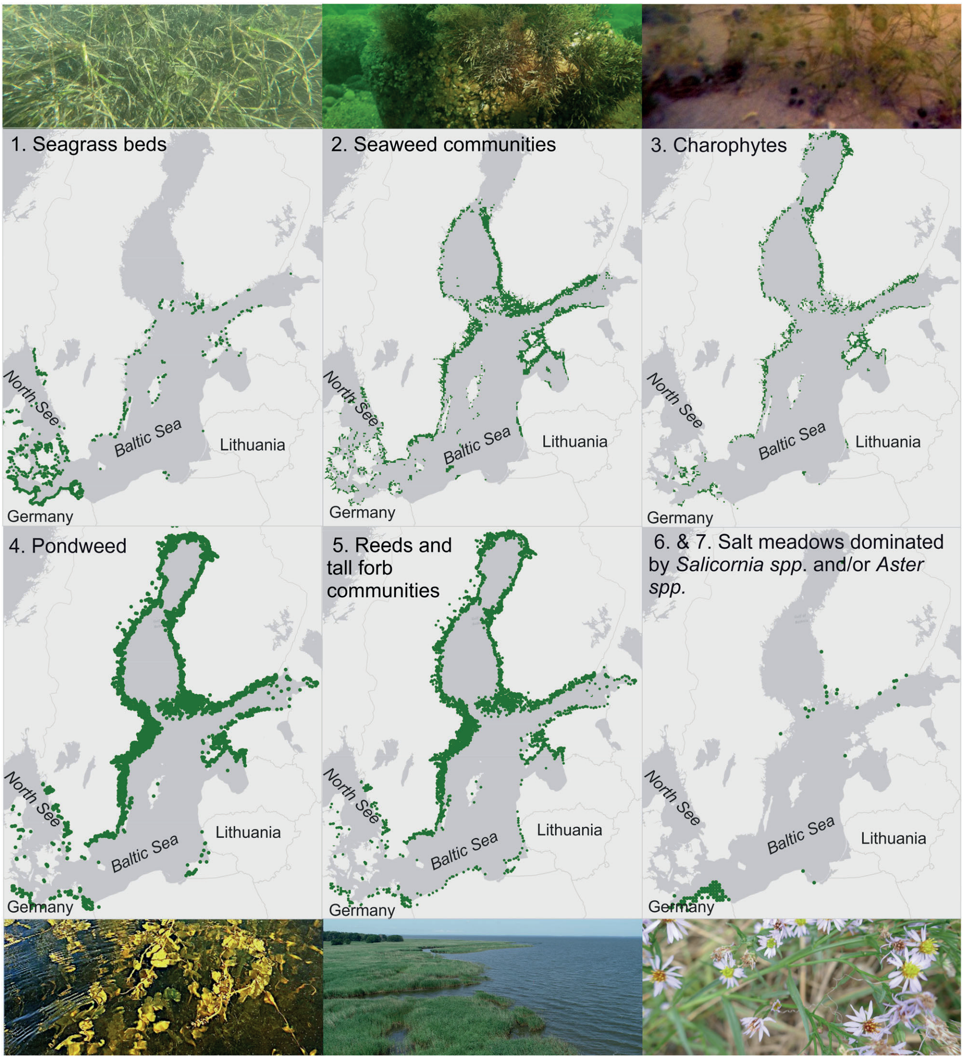

Fig. 4 Macrophyte habitats (according to EUNIS and HD classifications) and their current distribution in the Baltic Sea that were used by macrophyte experts for the habitat assessment. Observational data for distribution maps were received from HELCOM (2023) and GBIF (2023)

and work duration in this field (minimum of 5 years) and in the region (Baltic Sea), i.e., for each macrophyte habitat at least one expert specifically working on one single habitat was selected. Ten experts hold doctoral degrees related to macrophyte ecology (i.e., aquatic, benthic, landscape, coastal ecology, marine biology) including two professorships coming from five different research institutions, while one expert came from a state authority being responsible for coastal and marine water quality control. For analysis and interpretation of results, experts indicated their level of expertise for ES, management and policy, and each macrophyte habitat (detailed list in Online Resource 4). First, experts assessed the "Ecologically Sustainable ES Potential" for each habitat and service. In Balzan et al. (2018), ES potential is referred to as the capacity of an ecosystem to provide an ES. Burkhard et al. (2012) define ES potential as 'the hypothetical yield of selected ecosystem services'. Here, we further define the ES potential as the "hypothetical yield" provided by the ecosystem without disturbing the natural ecosystem state nor causing a regime shift. The scoring ranges from "very low" [1], "low" [2], "moderate" [3], "high" [4] to "very high" [5] potential or "none" [0]. They had the opportunity to comment on their values, ask questions and/or express uncertainties in an extra column. Experts spent on average 60 to 90 min for the whole assessment, including the ES assessment and indicators selection. We carried out a correlation analysis for the level of expertise and the services using the R package 'CORRPLOT' (Wei and Simko 2021).

In a second step, we carried out a literature-based assessment applying the developed indicator list (see Table 3) and using the same habitats and scoring scheme as the experts. For the literature-based assessment, we used automated literature search scanning the database Web of Science (WoS). Literature was searched for quantitative data on the selected indicators. We aimed to find comparable data at least for one indicator from the developed list per ecosystem service and complemented this by an additional indicator "Number of WoS articles" indicating the scientific relevance of given keywords, which we assume represents the ES potential. The general search string includes the regional focus, the macrophyte habitats and the ecosystem service descriptors as following: ("Baltic") AND ("seagrass" OR "zostera") AND ("bioethanol" OR "bioenergy" OR "ethanol production") (see Online Resource 5 for full list of search strings). The highest value found in literature was designated a score of 5, while the others were automatically classified according to the following scheme, as also used in the Marine Ecosystem Services Assessment Tool by Inácio et al. (2018): 5 (1 to 1/1.3), 4 (1/1.3 to 1.7), 3 (1/1.7 to 1/2.5), 2 (1/2.5 to 1/4.1) and 1 (1/4.1 and less).

Results

Compilation of Ecosystem Services and Assessment Indicators

In order to provide a generally valid ES assessment scheme for macrophyte habitats, we developed a list of services and indicators. As a result of our literature review and expert consultations, we found 25 services relevant for assessing macrophyte habitats (Table 3). For each service, we listed 3 to 14 relevant indicators suggested by the literature review. Experts were asked to select the three most suitable indicators and score their suitability by giving a rank from 3 (most suitable) to 1. The full list shows the individual rankings and values of each participating expert (see Online Resource 2). Based on the opinion of 11 macrophyte experts, we chose 79 indicators out of a total of 174 indicators pre-selected from literature by their total sum of expert rankings (including four indicators of equal sum). Ten additional indicators were mentioned and ranked by experts. This comprehensive list of services and indicators served as the basis for our further literature surveys and assessments.

Evaluation of the Relative Importance (RI) of Ecosystem Services

With the aim to evaluate the suitability of selected services, we assessed the RI of each service as it is perceived by stakeholders and as reflected in the literature. According to the literature sources, the most important services provided by macrophytes in the Baltic lagoons are among the cultural services, as recreational activities (C1, C2), landscape aesthetics (C6) and nature conservation (C8), accompanied by the service of coastal protection (RM3) (Fig. 5). Experts (Workshop 1) show a rather high agreement with the literature data, which indicates the common pool of knowledge.

For the Szczecin lagoon, the most important services (> 6) according to both stakeholders (Workshop 2) and experts (Workshop 1) are biodiversity and habitat (RM7) and recreation and tourism both active (C1) and observational (C2). However, local stakeholders could provide contrasting information on the RI of some ES. In contrast to expert opinion and literature survey, stakeholder groups downgraded the RI value of coastal protection (RM3), regulation of water quality (RM10), and landscape aesthetics (C6) provided by macrophytes. For the Curonian lagoon (Workshop 3), the most important services (=8) according to the student group are research and traditional knowledge (C3) and education and training (C4). For both lagoons, the most important among the three ES categories are the cultural services with more than 40% (Curonian lagoon) and 60% (Szczecin lagoon) of all services assessed as highly or very highly important (> 4). Regulating and maintenance services are of high importance in the Szczecin lagoon (~4) and only of moderate importance in the Curonian lagoon (~2). Provisioning services show moderate importance in the Szczecin lagoon (~2) and low importance in the Curonian lagoon (~1).

Differences in expert/ stakeholder valuations are reflected within individual scores and comments during discussions (see Online Resource 3). To test data quality and reliability, we use discussion content and standard deviations (SD) as indicators. SD values indicate high agreement

Table 3 List of selected ecosystem services (P – provisioning, RM – regulating and maintenance, C – cultural) provided by macrophytes and assessment indicators ranked by experts (see Online Resource 3 for full list including units and sources)

Ecosystem services	Description	Indicators
P1: Marine plants used for human nutrition	Use of wild and cultivated plants as human food source or supplements, e.g. seaweeds or reed sprouts for consumption	1) Amount of harvested biomass, 2) Total sales or market value of harvested biomass, 2) Abundance/ biomass of (potential) stock/habitat, 3) Generated income or employment (farmers, processors and/or vendors), and other: nutritional value of target species (e.g. vitamins or antioxidative capacity)
P2: Marine plants used as material (direct use, processing)	Use of wild and cultivated plants incl. fibers as material, e.g. as fertilizer in agriculture or reed for thatched roofs	1) Amount of harvested biomass, 2) Abundance/ biomass of (potential) stock/habitat/raw material, 3) Abundance/ number of species with potential/ actual use for processing
P3: Marine plants used for energy	Use of wild and cultivated plants as biomass for energy conversion	1) Amount of energy produced by harvested biomass, 2) Amount of harvested biomass, 3) Abundance/ number of species with potential/actual energetic value, 3) Area or coverage of potential stock/habitat, and other: Biochemical methane potential (BMP)
P4: Marine animals used for nutrition, material or energy	Wild and reared animals, e.g. fish and mussels used as source for human nutrition, direct use, processing or for energy conversion	1) Amount of harvested biomass/catch/landing, 2) Abundance/ biomass of (potential) stock/habitat, 3) Total sales or market value of products
P5: Genetic material of marine plants	Seeds and spores and other plant materials that can be used to maintain or establish a new population (seed collection) or develop new varieties	1) Number of species/genes utilized, 2) Abundance/ number of species with potential/actual useful genetic material, 3) Quality of species with potential/ actual useful genetic material
P6: Genetic material of marine animals	Marine animals (e.g. fish or mussels) used for replenishing stocks or breeding of new species, e.g. breeding of new oysters' strains	1) Abundance/ number of species with potential/actual useful genetic material, 2) Number of species/genes utilized, 3) Number of patents and published articles, 3) Quality of species with potential/actual useful genetic material
RM1: Mediation of wastes and pollutants	1) Bio-remediation; 2) Filtration/ sequestration/ storage/ accumulation by micro-organisms, algae, plants, and animals	1) Nitrogen removal/ storage, 2) Phosphorus removal/ storage, 3) Coastal recreation associated with reduced nutrient concentration
RM2: Mediation of nuisances of anthropogenic origin	1) Smell reduction, e.g. shelter belts that filter particulates that carry odors; 2) Visual Screening: Shelter belts to screen unsightly things e.g. reed belts	1) Elevation/ height of vegetation, 2) Length of coastal vegetation, 3) Abundance/ biomass of coastal vegetation (density)
RM3: Mass stabilization and control of erosion rate	Sediment stabilization controlling or preventing erosion/ mass movements e.g. by seagrass meadows	1) Area or coverage by emerged, submerged or intertidal vegetation, 2) Shoreline erosion and/or accumulation rate, and other: Stem density and seasonality of plants (e.g. perennial, annual, litter production,…)
RM4: Hydrological cycle and water flow regulation	Regulating water flows and coastal protection, e.g., coastal habitats/ natural levees reducing wave energy and providing flood protection	1) Wave attenuation potential, 2) Shoreline erosion rate, 2) Replacement cost for coastal protection
RM5: Wind protection	Shielding people from wind e.g., reed belts alleviate onshore wind	1) Elevation/ height of vegetation, 2) Abundance/ biomass of coastal vegetation (density), 3) Length of coastal vegetation, and other: configuration of coastal vegetation including length and width, stem density
RM6: Lifecycle maintenance and pollination	Seed and/ or gamete dispersal for population maintenance, e.g., providing a habitat for native pollinators	1) Extent of nursery and feeding areas, 2) Species abundance, richness and distribution, 3) Juvenile fish density
RM7: Biodiversity and habitat	Maintaining nursery populations and habitats (incl. breeding grounds) for wild plants or animals, e.g., seagrass beds as nursery habitat for commercial fish stock	1) Species abundance, richness and distribution, 2) Extent of nursery and feeding areas, 3) Total number or coverage of protected areas, 3) Habitat health status (Habitat fragmentation index)

Table 3 (continued)

Ecosystem services	Description	Indicators
RM8: Pest and disease control	Providing a habitat for native pest (incl. invasive species) and disease control agents, e.g., microbial antagonists for the control of postharvest diseases	1) Presence and distribution of pests/ diseases, 2) Presence and distribution of pathogens, 3) Presence and distribution of alien species, and other: algae blooms, water exchange time
RM9: Nutrient regulation (soil quality)	Decomposition and fixing processes and their effect on sediment quality, e.g. sequester and store nutrients in sediment enhancing remineralization processes	1) Nitrogen removal/ storage, 2) Phosphorus removal/ storage, 3) Carbon stock
RM10: Regulation of water conditions	Controlling chemical condition of salt water by living processes, e.g., water purification by marine plants or animals	1) Oxygen concentration, 2) Primary production, 3) Nitrogen removal/ storage
RM11: Atmospheric composition and conditions	Regulation of air, temperature and humidity, including ventilation and transpiration, e.g., carbon sequestration	1) Primary production, 2) Carbon sequestration, 3) Carbon stock
C1: Recreation and tourism (active)	Using the environment for sports and recreation, and to help stay fit, e.g., swimming, water sports, fishing	1) Total number of tourists, 2) Available beach or recreational area, 3) Number of suppliers of recreational activities (boating, surfing, diving..)
C2: Recreation and tourism (observational)	Using nature to distress, e.g., watching seabirds, plants or marine mammals	1) Number of viewpoints/ birdwatching points, 2) Species abundance, richness and distribution, 3) Total income or market value of ecotourism, 3) Presence of endangered, protected, iconic and/or rare species or habitats
C3: Research and traditional knowledge	Studying nature for scientific purpose or the creation of traditional ecological knowledge	1) Presence of endangered, protected, iconic and/or rare species or habitats, 2) Number of patents and published articles, 3) Total income or value of research funds, and other: Number of local research institutes
C4: Education and training	Using nature for educational purposes, e.g., university courses, in-situ teaching or field trips	1) Number of educational activities (in-situ teaching or field trips), 2) Presence of endangered, protected, iconic and/or rare species or habitats, 3) Revenues or number of documentaries, books and other educational publications, and other: Educational capacity (beds in youth hostels, camp sites, educational stands…)
C5: Culture and heritage	Things in nature that help people identify with history or culture of where they live or come from; that contribute to cultural heritage.	1) Social perception of identity/heritage, 1) Presence of endangered, protected, iconic and/or rare species or habitats, 2) Number of cultural events related to the area
C6: Landscape aesthetics	The inherent beauty of nature	1) Number of pictures published on social media, 2) Hedonic pricing: cost of property next to aesthetic sites, Resident population/ Net migration, and other: Landscape richness
C7: Symbolic or religious meaning	Things in nature that have symbolic or spiritual meaning, or sacred and religious meaning.	1) Number of symbolic or religious sites (church, monuments..), 2) Number of religious events (ceremonies, wedding, funerals..), 3) Presence of endangered, protected, iconic and/or rare species or habitats
C8: Natural heritage and conservation	Things in nature that should be conserved and preserved for future generations, and have a non-use value (also existence, option or bequest value)	1) Total number or coverage of protected areas, 2) Willingness-to-pay to maintain/preserve/conserve, 3) Presence of endangered, protected, iconic and/or rare species or habitats

Relative Importance (RI)

Ecosystem Services	SZC LIT	SZC 1 Experts MD	SZC 1 Experts SD	SZC 2 Stakehold. MD	SZC 2 Stakehold. SD	CU LIT	CU 3 Students MD	CU 3 Students SD	BI LIT
P1: (Marine) Plants used for human nutrition	1	2	0.8	1	1.1	1	1	0.9	1
P2: (Marine) Plants used for material	4	2	1.0	2	0.9	4	1	0.9	4
P3: (Marine) Plants used for energy	1	2	0.8	1	0.9	2	1	0.7	2
P4: (Marine) Animals used for nutrition, material, energy	4	4	1.0	4	1.1	4	2	**1.4**	8
P5: Genetic material of (marine) plants	1	1	1.2	2	0.8	1	1	**1.4**	4
P6: Genetic material of (marine) animals	1	1	**1.4**	1	0.9	1	1	1.2	2
RM1: Mediation of wastes and pollutants	1	2	0.7	4	1.0	1	4	0.7	4
RM2: Mediation of nuisances (anthropogenic origin)	2	2	0.7	2	1.0	2	4	**1.8**	1
RM3: Mass stabilization and control of erosion rate	8	8	0.6	2	1.1	8	1	**1.6**	4
RM4: Hydrological cycle and water flow regulation	4	4	0.5	3	1.0	4	1	1.2	4
RM5: Wind protection	2	2	0.9	2	0.8	2	0	1.2	1
RM6: Lifecycle maintenance and pollination	4	2	0.6	2	0.9	4	1	1.2	8
RM7: Biodiversity and habitat	8	8	0.3	8	0.9	4	1	1.0	4
RM8: Pest and disease control	4	2	0.9	2	1.0	2	1	0.7	2
RM9: Nutrient regulation (soil quality)	2	2	0.6	4	0.9	2	1	1.5	4
RM10: Regulation of water conditions	8	6	0.5	3	1.2	4	1	1.5	4
RM11: Atmospheric composition and conditions	2	4	0.5	2	**1.4**	1	1	0.5	2
C1: Recreation and tourism (active)	8	8	1.2	4	0.7	8	2	1.5	2
C2: Recreation and tourism (observational)	8	8	0.5	4	0.9	8	1	1.5	2
C3: Research and traditional knowledge	4	4	0.8	2	1.0	4	8	**1.6**	4
C4: Education and training	nv	nv	nv	2	**1.3**	2	8	0.8	1
C5: Culture and heritage	4	2	0.7	3	**1.5**	4	4	1.6	4
C6: Landscape aesthetics	8	4	0.8	4	0.9	8	1	1.4	1
C7: Symbolic or religious meaning	nv	nv	nv	1	1.0	2	1	0.7	1
C8: Natural heritage and conservation	8	6	1.0	6	1.5	8	2	1.4	1

nv = no value (24)

Impact - Scenario 1

Ecosystem Services	SZC LIT*	SZC 1* Experts MD	SZC 1* Experts SD	SZC 2 Stakehold. MD	SZC 2 Stakehold. SD	CU LIT	CU 3 Students MD	CU 3 Students SD	BI LIT
P1: (Marine) Plants used for human nutrition	1	2	1.1	1	0.6	1	2	0.4	1
P2: (Marine) Plants used for material	3	2	0.7	1	0.6	3	2	0.0	2
P3: (Marine) Plants used for energy	1	2	0.9	1	0.9	1	2	0.4	1
P4: (Marine) Animals used for nutrition, material, energy	1	0.5	1.5	1	0.7	1	2	0.6	2
P5: Genetic material of (marine) plants	1	1	0.6	1	0.6	1	1	0.7	1
P6: Genetic material of (marine) animals	1	1	0.7	1	0.5	1	2	0.7	1
RM1: Mediation of wastes and pollutants	1	1	0.5	1	0.5	1	1	1.2	1
RM2: Mediation of nuisances (anthropogenic origin)	2	1.5	0.5	1	0.6	1	1	1.0	1
RM3: Mass stabilization and control of erosion rate	2	2	0.7	1	0.6	1	1	1.0	1
RM4: Hydrological cycle and water flow regulation	2	1.5	0.6	1	0.7	1	2	0.7	1
RM5: Wind protection	2	1	0.6	1	0.5	1	0	1.0	1
RM6: Lifecycle maintenance and pollination	2	1	0.6	1	0.7	2	2	0.4	2
RM7: Biodiversity and habitat	2	2	0.6	1	0.7	2	2	0.4	2
RM8: Pest and disease control	2	0.5	1.1	0	0.7	1	2	0.4	1
RM9: Nutrient regulation (soil quality)	2	1	0.7	1	0.7	1	2	0.4	1
RM10: Regulation of water conditions	2	1.5	0.5	1	0.4	1	1	0.5	2
RM11: Atmospheric composition and conditions	1	2	0.7	1	0.6	1	1	0.4	1
C1: Recreation and tourism (active)	1	0	**1.6**	0	**1.4**	1	1	**1.9**	1
C2: Recreation and tourism (observational)	1	2	0.8	1	0.8	2	2	0.4	1
C3: Research and traditional knowledge	0	1	0.6	1	0.9	1	2	0.5	0
C4: Education and training	nv	nv	nv	1	0.6	1	3	0.5	1
C5: Culture and heritage	2	1	0.8	0	0.6	1	2	0.7	2
C6: Landscape aesthetics	2	2	0.8	1	0.5	2	2	0.7	1
C7: Symbolic or religious meaning	nv	nv	nv	0	0.0	1	1	0.7	1
C8: Natural heritage and conservation	2	1	1.1	1	0.6	1	2	0.6	1

Impact - Scenario 2

Ecosystem Services	SZC LIT*	SZC 1* Experts MD	SZC 1* Experts SD	SZC 2 Stakehold. MD	SZC 2 Stakehold. SD	CU LIT	CU 3 Students MD	CU 3 Students SD	BI LIT
P1: (Marine) Plants used for human nutrition	3	4	**1.8**	1	1.1	2	3	0.4	2
P2: (Marine) Plants used for material	4	4	0.9	2.5	1.0	3	3	0.4	3
P3: (Marine) Plants used for energy	2	4	1.3	1.5	**1.3**	2	3	0.5	2
P4: (Marine) Animals used for nutrition, material, energy	4	-1	**2.9**	2	0.9	3	3	0.5	3
P5: Genetic material of (marine) plants	3	3	1.2	2	0.8	1	3	1.2	2
P6: Genetic material of (marine) animals	3	3	**1.7**	2	0.9	1	3	0.5	2
RM1: Mediation of wastes and pollutants	2	2	0.8	2	0.8	2	2	**1.9**	2
RM2: Mediation of nuisances (anthropogenic origin)	4	4	0.8	2	1.1	2	3	**1.7**	2
RM3: Mass stabilization and control of erosion rate	4	4	0.4	2	0.5	3	2	**1.4**	2
RM4: Hydrological cycle and water flow regulation	3	4	0.8	2	0.7	3	3	0.8	2
RM5: Wind protection	3	2	0.9	2	0.8	2	0	**1.5**	2
RM6: Lifecycle maintenance and pollination	3	2.5	1.1	1	1.2	3	3	0.4	3
RM7: Biodiversity and habitat	4	4	0.6	2	0.6	3	3	0.0	3
RM8: Pest and disease control	4	1.5	**1.9**	1	**1.5**	2	2	0.7	2
RM9: Nutrient regulation (soil quality)	3	3	1.1	2	0.7	3	3	0.5	2
RM10: Regulation of water conditions	4	3.5	0.9	2	0.6	3	3	0.8	3
RM11: Atmospheric composition and conditions	3	4	0.9	2	0.8	2	3	0.4	2
C1: Recreation and tourism (active)	-2	-3	0.8	-0.5	**1.6**	-2	1	**2.5**	1
C2: Recreation and tourism (observational)	3	3	0.8	3	1.2	3	3	0.0	3
C3: Research and traditional knowledge	0	2.5	**1.3**	2	1.2	0	3	0.0	0
C4: Education and training	nv	nv	nv	2	1.0	1	3	0.0	1
C5: Culture and heritage	3	1	**1.4**	0	0.8	2	3	0.4	3
C6: Landscape aesthetics	3	3	1.1	2	1.2	3	3	0.0	1
C7: Symbolic or religious meaning	nv	nv	nv	0	0.4	2	2	**1.4**	1
C8: Natural heritage and conservation	4	3.5	1.2	2	1.0	3	3	0.0	2

*Additional scoring possibility of (+/-) 4 only in workshop 1 and literature-based assessment

Fig. 5 Results of scenario assessments for three lagoons (SZC Szczecin, CU Curonian, BI Bizerte) on their provision of ecosystem services (P Provisioning, RM Regulating and maintenance, C Cultural). The relative importance ranges from 0 (not important) to 8 (very high). The impact score 4 indicates a strong increase in ES provision and −4 a high decrease. Literature results (LIT) are compared to median values (MD) and standard deviations (SD) of three workshops: (1) coastal-management experts, (2) coastal-management stakeholders and (3) student group

among experts (SD = 0.8) and lower agreement among students (SD = 1.2). On the service level, most experts disagreed (SD = 1.3) on the importance of natural heritage and conservation (C8), and culture and heritage (C5), while they mostly agreed (SD = 0.7) on the very high importance of biodiversity and habitat (RM7).

During the discussions, experts argued that, for example, the service biodiversity and habitat (RM7) serves a basis for the whole ecosystem functioning, and is thus pivotal for other services. Some stakeholders assumed that the importance of services changes depending on the actual ecosystem state. One example of this is the service coastal protection (RM3). Its importance increases with higher exposition and hydraulic loads on the coast. Students and some experts stated that cultural services are the easiest to assess, but the most difficult to interpret as they reflect personal preferences and behaviors. Stakeholders considered management implications within their assessment scores. For example, while some only assessed potentially available biomass, others considered if biomass should actually be harvested. Some argued that the potential should not be used to maintain the natural quality, and thus they evaluated too conservative and low. Summarizing, differences in workshop results mainly derive from different interpretations (e.g., needed provision or potential of ecosystem state), subjectivity (especially cultural services) and possible management implications (e.g., impact of harvesting).

Discussions revealed the importance of the participants´ level of expertise with regard to data quality. Stakeholders indicated certain difficulties when carrying out the assessment due to the lack of own expertise, but also due to missing background information. They sometimes felt insecure about their given values. For example, in Workshop 3 students stated their lack of knowledge with regard to current use of marine plants (P2, P3), e.g., local management and further use of reed. Their insecurity is well reflected by their values that differed considerably compared to literature results. Stakeholders (Workshop 2) indicated that they learnt about and became aware of some services, e.g., wind protection of reed belts. Thus, the level of expertise is important in terms of data quality, but stakeholders, usually of lower expertise, experience an increasing understanding of the impact of management measures (here of achieving a GES), leading to an increased acceptance and learning process.

These discussion results are also reflected in Workshop 1, where experts were allowed to change values directly after discussion (in case of misunderstandings), which was done for 3.4% of all values ($n = 23$). Besides, 50% of the experts repeated the assessment after one week. Of all values given, 46% of the high expertise group and 68% of the low expertise group were changed. The results of the high expertise group show a lower standard deviation (SD = 0.89) than the low expertise group (SD = 1.24). Most values of both groups were changed for Scenario 2 (52 and 93%), especially for provisioning (67 and 94%) and cultural services (50 and 100%). The results show that expertise has a positive impact on data quality, but can be improved by increasing the number of participants. Besides, results of the second assessment indicate higher agreement among participants, assuming this being the results of workshop discussions. Due to subjectivity (especially for cultural services), different perspectives and interpretations (e.g., spatial scale), possible tradeoffs and synergies (e.g., motor entanglement), the results show, despite minor differences, that discussions are vital for clarifying misunderstandings and interpreting the scores.

Comparing workshop and literature results of the Szczecin lagoon, we observed main differences for regulating services, where literature results indicate only low importance for mediation of wastes and pollutants (RM1), but very high importance for regulation of water conditions (RM10). In contrast, workshop and literature results of the Curonian lagoon show clear differences, as more than 50% of the services differ more than one scale class. We can state that the student group (Workshop 3) assessed the RI of many services much lower, which can be explained by their lower expertise, misinterpretation and/or misunderstanding. As we find only minor differences between expert and stakeholder results (except from students) compared to literature data, we assume a high compatibility of expert, stakeholder and literature-based assessments in terms of data reliability.

Our literature results for the Bizerte lagoon differ considerably compared to the results of the Baltic lagoons. The main differences are found among cultural services, where the average importance in the Bizerte lagoon is lower (RI ~ 2) than in the Baltic lagoons (RI ~ 6). Provisioning services are more important in the Bizerte lagoon (RI ~ 4) than in the Baltic lagoons (RI ~ 2). Regulating and maintenance services were assessed similarly of moderate importance (RI ~ 3). While for the Baltic lagoons, cultural services are perceived most important according to our results, these are almost negligible for the Bizerte lagoon (Mediterranean Sea), where provisioning services are currently most important.

Reasons for these differing results of the Baltic and Mediterranean lagoons can be multifold, but we assume that our results mainly reflect the different socio-cultural and economic conditions, as well as species representing macrophyte communities. By this, we identified the most important services for each lagoon, which are of highest interest for the regional management and policy makers. From this, we learnt that the developed list of services is suitable and applicable in an international context, as all selected services are assessed at least of low relative importance for all lagoons.

Assessment of Management Scenarios Based on ES Provision

The aim of the scenario assessment is to test the applicability of our approach for management purposes, specifically here to assess the impact of achieving a GES of lagoons, using expert, stakeholder and literature data. Our results indicate the perceived impact of scenarios on ES provision (Fig. 5). For the Szczecin and Curonian lagoon, 24 of 25 services provided by macrophytes show low to moderate positive impacts (increase in ES provision) for Scenario 1 and a moderate to strong positive impact for Scenario 2. In Scenario 1, results indicate the strongest increase (+3) for marine plants used for material (P2). While moderate macrophyte coverage (in Scenario 1) shows a slight positive impact on active recreation and tourism (C1), in Scenario 2 this turned into a clear negative impact by strong macrophyte coverage.

In Scenario 2, results for Szczecin lagoon show one negative outlier for marine animals used for nutrition, material or energy (P4), also showing the highest disagreement among stakeholders in this regard (SD = 2.9), probably reflecting difficulties to forecast fishery landings along with increasing macrophyte coverage. In general, the experts and student group assessed a stronger positive impact of the higher macrophyte coverage on all services (similar to literature data) than the stakeholder group which assessed more conservatively. However, the workshop and literature results of both Baltic lagoons show only minor differences. While our results generally indicate a positive impact on ES provision by improving the lagoon´s ecological state, the strong macrophyte coverage (in Scenario 2) marks a clear tipping point, as experts and stakeholders perceived a strong negative impact on active recreation and tourism (C1).

Despite minor differences of workshop results, during discussions experts showed opposing arguments based on high subjectivity and personal preferences. For example, while one expert finds that reed belts block the view of the water reducing recreational quality (C1), others perceive reed as a habitat and enjoy it for observational purposes (e.g., bird watching). Experts discussed the impact on carbon sequestration (RM11), which highly depends on the perspective (small-scale or large-scale) and interpretation of the impact (e.g., local or global). Stakeholders mentioned tradeoffs and synergies between services. For example, they emphasize on the conflict between regulating and cultural services, i.e., macrophytes providing clear and clean water for bathing versus entanglement of macrophytes in sport boats. Besides, it was pointed out that emerged macrophyte stands are appealing to tourists, as they also use reed stands to hide and search for wind protection, but also often limit the access to the water. Moreover, stakeholders discussed the role of positionality and personal evaluation behavior, thus people´s "habit" to assess more extreme, conservative and moderate or optimistic and pessimistic. Thus, our approach is useful to hear the concerns and questions raised by society and in turn use this information for revising the elements of scenarios e.g., include macrophyte management options such as reed cut.

In the Bizerte lagoon (literature data only) we find only minor differences from the Baltic lagoons derived during workshops and literature-based results. The main difference in Scenario 2 is that for the Bizerte lagoon we also find a slightly positive impact of increasing macrophyte coverage on recreation and tourism (active) (C1). This can be explained by different recreational uses of the Baltic and Mediterranean lagoons, as in the Bizerte lagoon water transparency plays a more important role due to diving activities, whereas increase in macrophyte coverage would imply improvement of diving sites. For landscape aesthetics (C6) we only find a low increase, which is explained by their function as buffer zone and trap of (plastic) pollution, i.e., extended macrophyte stand would also accumulate more litter and therefore reduce the overall aesthetic value provision. In Mediterranean lagoons, fisheries and aquaculture play a significant role, thus the economic value of ecosystem outputs (e.g., fish, shellfish) is very important (El Mahrad et al. 2020). Besides, there is higher potential for economic income sources within blue economy sectors, for example seaweed cultivation and salt production, as biomass is often abundant but not exploited (El Mahrad et al. 2020; Ktari et al. 2022). Seaweed cultivation bears especially in Tunisia and North Africa great potential as a mitigation measure to preserve the intensively used coasts by industrial, urban and touristic activities (Ktari et al. 2022). In general, for the impact scenarios there are only minor differences between lagoons, ES, service categories and standard deviations (i.e., stakeholder agreement). Therefore, we can conclude that our scenario assessments, both workshop and literature-based, are suitable and applicable for comparative studies on lagoons of different ecological states, geographical locations (Baltic vs. Mediterranean Sea) and socio-cultural contexts (e.g., different recreational activities).

Spatial Extrapolation - Implications for Management

In order to transfer our small-scale results of the chosen transect to large-scale system level, we extrapolated scenario results exemplarily to designated areas of the Kleines Haff (German part of the Szczecin lagoon). Our scenario transect (see Fig. 3) has an area of approximately three hectares (ha). Current submerged vegetation of the Kleines Haff covers an area of 5795 ha (Fig. 6a). Potential submerged vegetation (including angiosperms and charophytes) may increase by 78% to an area of 10,334 ha under the premise of achieving a GES and a growth limit of up to 3 m (according to Porsche et al. 2008). For extrapolating scenario results to the whole area of the Kleines Haff, we identified a possible area of 2137 ha or 25% of the coastal zone. Exemplarily, we focused on three extrapolated areas surrounding our scenario transect (Bellin beach). In Scenario 1 under current use or state, emergent vegetation (mainly reed belts) covers only small areas of 20 ha (3% of the total extrapolated area) (Fig. 6b), while under potential use or nature protection in Scenario 2 it increases to 17% (of the total extrapolated area) or 109 ha (Fig. 6c). Due to discussions during scenario assessments, we further subdivided recreational use (or area) for the extrapolation into activities on water and on land (mainly beach area). While water area for recreational use decreased from 397.57 ha (61%) to 131.13 ha (20%), recreational use on land did not change in area. Extrapolation results indicate a strong spatial tradeoff and conflict between recreational use (here mainly on water) and expansion of macrophytes (i.e., submerged and emergent vegetation).

Compared to the impact values of our scenario results (Fig. 5), the main difference is that the decrease in beach activities is not visible in our extrapolation results, as the spatial area for recreational use on land is not subject to changes in macrophyte distribution. However, from our scenario results we learnt that the increase in emergent and submerged vegetation is perceived as a cause for reduced recreational activities also and especially on land. For example, bathing opportunities are limited by reed belts prohibiting water access, or beaches just lose their attractiveness due to the blocked view. Therefore, macrophyte recovery by achieving a GES cannot be a desired state over the whole areas, as it is significantly inhibiting coastal tourism being an important economic driver of the region. In such case some macrophyte removal from the designated areas will be necessary.

By identifying areas for extrapolation, we also identified areas that are of high interest and importance for management and policy measures. Extrapolated areas are highly important for the tourism sector. Thus, extrapolation results can serve as a basis for decision-making when designating, for example, nature protected areas, fishing grounds, water

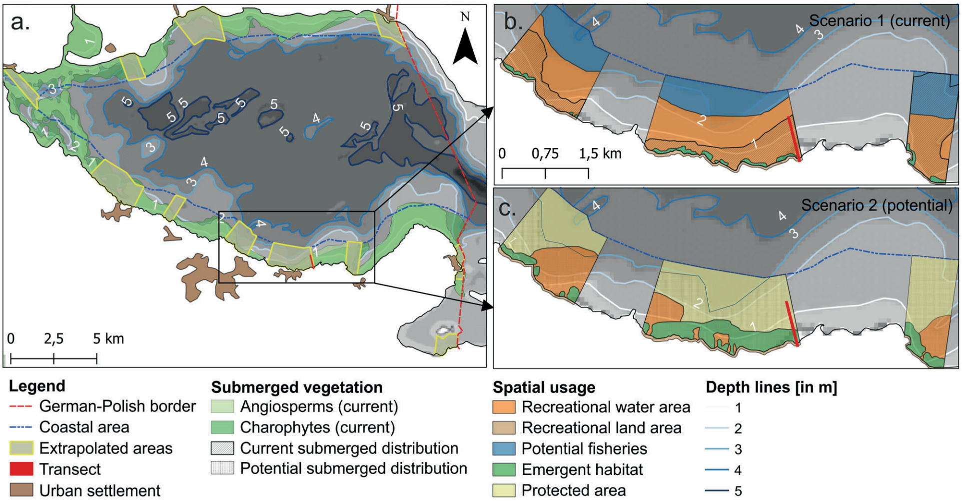

Fig. 6 Spatial extrapolation maps of the Szczecin lagoon showing all extrapolated areas of the German part Kleines Haff (**a**), the current spatial use mainly recreation on water and fisheries (**b** Scenario 1) and the potential spatial use under nature protection and GES (**c** Scenario 2)

sport areas or other use rights. In summary, while some human activities (or spatial usages) show clear tradeoffs in terms of space (e.g., vegetation vs. recreational area on water), other spatial usages even provide synergies (e.g., vegetation and nature protection) or do not compete for space at all (e.g., fisheries and recreational activities on water).

We learnt that scenario results can be extrapolated to entire water body level when areas share similar characteristics as the transect. Extrapolation results even combine the importance of services (or spatial uses) with possible macrophyte expansion. However, the scenario and extrapolation results represent a very broad macrophyte composition and coverage, often considering only monocultures of reed belts. Therefore, our extrapolation results are suitable to discuss possible management outcomes for human activities. However, more scientific research is needed to estimate the total scenario impact on regulating and maintenance services.

Assessment of Different Macrophyte Habitats based on ES Potential

In order to test the applicability of our approach for broader coastal environmental conditions and macrophyte diversity, we assessed the ES potential of macrophyte habitats, differentiating between submerged (i.e., seagrass, seaweed, charophytes, pondweed) and emergent macrophyte habitats (i.e., reeds, salt meadows dominated by *Salicornia spp*. and by *Aster spp*.). Shown in Fig. 7, the experts assessed the highest overall potential (calculated by total sum of all ES scores for each habitat) to be provided by reeds and tall forb communities (sum of scores: 83 out of a maximum of 125), followed by seagrass beds (71) and seaweed communities (62). The lowest overall potential is indicated for pondweeds (51). Our literature-based results show in general a similar trend as the expert, showing main differences for the habitats of charophytes (29.5) and pondweed (28.5) that show the lowest potential. For detailed literature-based results see Online Resource 5.

Based on expert results, the individual services with the highest potential (indicated by the median value of each ES) provided by macrophytes are natural heritage and conservation (median value of C8: 5), education and training (C4: 4), research and traditional knowledge (C3: 4), genetic material of (marine) plants (P5: 4) and biodiversity and habitat (RM7: 4). The results depict a slight land-sea gradient, with decreasing potential from sea (submerged) to land-dominated macrophytes, and from marine to brackish and freshwater habitats. For example, seagrass beds and seaweeds show very high potential for biodiversity and habitat (RM7: 5), while salt meadow species show only moderate to high potential (< 4). Contrarily, emergent habitats show higher potential for “visual” services like landscape aesthetics (C6: > 4), but also for observational recreation (C2: > 3.5). In general, expert results of all habitats show the highest ES potential for cultural services (median: 3), followed by regulating and maintenance

	Expert values (n=11; median values)									Indicator values							
	Submerged hab.				Emergent hab.					Submerged hab.				Emergent hab.			
Ecosystem services	Seagrass	Seaweed	Charophytes	Pondweed	Reeds	Salicornia sp.	Aster sp.	**Median**	**SD** (average)	Seagrass	Seaweed	Charophytes	Pondweed	Reeds	Salicornia sp.	Aster sp.	**Median**
P1: (Marine) Plants used for human nutrition	0	2	0	0	1	2.5	1	*1*	*1.1*	1.5	3.5	0	2	2.5	3	0.5	2
P2: (Marine) Plants used as material	4	2	1	1	5	0.5	0.5	*1*	*1.2*	4	5	1	1	5	2	0	2
P3: (Marine) Plants used for energy	1	1	0	1	3	0.5	0.5	*1*	*0.9*	2.5	5	0.5	0.5	5	0.5	0	0.5
P4: (Mar.) Animals used for nutrition, material, energy	3	3	1.5	2	2	0.5	0.5	*2*	*1.4*	5	2	1	1	1	1	1	1
P5: Genetic material of (marine) plants	4	3	4	3.5	3	4	3.5	*4*	*1.1*	1	1	1	1	5	1	1	1
P6: Genetic material of (marine) animals	3	3	3	2.5	2	1	2	*2*	*1.1*	5	2	1	1	1	1	1	1
RM1: Mediation of wastes and pollutants	3	3	3	3	4	2	2.5	*3*	*1.3*	1	5	1	1	3	2	2	2
RM2: Mediation of nuisances (anthropogenic origin)	2	0	1	0.5	4	1	1.5	*1*	*1.3*	2	1	1	1	3	1	1	1
RM3: Mass stabilization and control of erosion rate	4	2	3	3	5	3	3	*3*	*1.2*	3	1.5	1	0.5	5	2.5	4.5	2.5
RM4: Hydrological cycle and water flow regulation	4	2	1	1.5	4	1.5	1.5	*2*	*1.4*	2	1	0.5	0.5	5	3	3.0	2.0
RM5: Wind protection	0	0	0	0	4	1	1	*0*	*0.6*	0	0	0	0	5	1	1	0
RM6: Lifecycle maintenance and pollination	2	2	2	1	2	2	4	*2*	***1.7***	4	3.5	1	1	1	1	1	1
RM7: Biodiversity and habitat	5	5	4	4	5	3	4	***4***	*1.1*	4	4	1.5	1.5	3	2.5	2.5	2.5
RM8: Pest and disease control	3	3	3	2.5	2.5	2	2	*2.5*	*1.0*	1	1	1	1	5	1	1	1
RM9: Nutrient regulation (soil quality)	3	1	2	2.5	4	2	1.5	*2*	*1.4*	3	2	2	2	3	2	2	2
RM10: Regulation of water conditions	3	3	3	3	3	2	2	*3*	*1.1*	4	3	3	3	4	2	2	3
RM11: Atmospheric composition and conditions	3	2	2.5	2.5	4	1	2	*3*	*1.4*	5	4	1	1	5	1	1	1
C1: Recreation and tourism (active)	1	1	1	1	1	1	1.5	*1*	*1.3*	3.5	3.5	1.5	1	3	2.5	3	3
C2: Recreation and tourism (observational)	3	3	2	2	3.5	4	4	*3*	*1.3*	4	4	1.5	1.5	3	2.5	2.5	2.5
C3: Research and traditional knowledge	5	5	4	4	4	4	4	***4***	*1.1*	3	5	1	1	2	1	1	1
C4: Education and training	3	4	4	3	4	4	4	*4*	*1.2*	3.5	3	1.5	1.5	5	4	4	3.5
C5: Culture and heritage	2	3	1	1.5	3	2	2	*2*	***1.6***	5	3	2	2	5	4	4	4
C6: Landscape aesthetics	4	3	3	2	4	4	5	*4*	*1.2*	1	5	1	1	2	1	1	1
C7: Symbolic or religious meaning	1	1	0.5	0	1	1	1	*1*	*1.2*	3	2	1	1	5	2.5	2.5	2.5
C8: Natural heritage and conservation	5	5	5	4	5	5	5	***5***	*0.6*	5	3.5	1.5	1.5	5	3.5	4.5	3.5
Sum	71.0	62.0	54.5	**51.0**	**83.0**	54.5	59.5			76.0	73.5	**28.5**	29.5	**91.5**	48.5	47.0	

Fig. 7 Results of ES assessment (P Provisioning, RM Regulating and maintenance, C Cultural) in macrophyte habitats of the Baltic Sea. Values indicate no potential (0) to very high potential (5). Median values and standard deviations (SD) from macrophyte experts and literature-based results are shown for each habitat (listed according to the sea-land gradient)

services (median: 2.5), and lowest ES potential for provisioning service (median: 2). Similarly, literature-based results indicate the same trend with highest ES potential for cultural (median: 2.5), then regulating and maintenance (median: 2) and provisioning service (median: 1).

As an indicator for data quality, we focused on standard deviations (i.e., expert agreement). Most disagreement among experts (high SD), in general for all habitat, can be seen for lifecycle maintenance and pollination (RM6: 1.7) and culture and heritage (C5: 1.6) (for result of individual experts, see Online Resource 4). Due to the high expertise among selected experts, the data quality is high, as SDs are on average relatively low (~1.2), with the highest for seaweed communities (~1.3) and the lowest for charophytes (~1.1).

We carried out a correlation analysis to identify the relevance of expertise for the quality of results and to identify possible tradeoffs and synergies between the services. Testing the dependence of ES potential results on the level of expertise, we find moderate correlation (Spearman's rank correlation coefficient's $r = 0.5$ to 0.79) for 12.6% of all services and strong correlation for 3.4% ($r > 0.8$) of all services, especially provided by salt marshes dominated by S*alicornia* (24%), charophyte habitats (20%) and reed and tall forb communities (20%). Regarding the dependence between ES potential results, the data show strong positive correlations between biodiversity (RM7) and research (C3) when provided by seaweed (0.88), seagrass (0.95), and pondweed habitats (0.91). Analysis results show a slight negative correlation trend between provisioning services and regulating as well as cultural services, and partly even among provisioning services themselves. Contrarily, regulating services show a slight positive correlation to cultural services and between regulating services themselves. Summarizing, the low correlation of the level of expertise and of services can be neglected, while the correlations between services and ES categories may indicate possible tradeoffs mainly between provisioning services and others.

By comparing the ES potential of macrophyte habitats to the RI values of the scenario assessments (Fig. 5), we can identify which habitat has highest potential (5) for contributing to the most important services (RI = 8) provided by Baltic lagoons. Thereby we assume that this relates to the actual ES provision. While reed shows the highest overall potential among lagoon macrophyte habitats, it probably contributes mainly to coastal erosion prevention (RM3). Macrophyte habitats that are main providers for biodiversity (RM7) are reeds, seagrass beds and seaweed communities. The most striking service we found is active recreation (C1), as it is of very high importance for Baltic lagoons, but all habitats show only low or very low ES potential (< 1.5). Despite this, results of the scenario assessments even showed a strong negative impact on active recreation (C1) by macrophyte expansion perceived by stakeholders. Contrarily, for observational recreation (C2), results show clearly the highest ES potential (> 3.5) of emergent macrophyte habitats (i.e., reeds, salt meadows dominated by *Salicornia spp*. or *Aster spp*.). Similarly, the emergent habitats, especially salt meadows dominated by *Aster spp*., also contribute mostly to landscape aesthetics (C6). Regarding natural heritage and conservation (C8), all habitats bear high to very high potential.

Discussion

Methodological Assessment

Our comprehensive list of services and assessment indicators is based on a common international classification (i.e., CICES) and literature, our developed management scenarios and macrophyte habitats build upon definitions of the WFD, HD, and EUNIS, both being beneficial for general applicability and transferability of approaches to other Southern Baltic Sea and Southern Mediterranean lagoons. Our approaches offer several opportunities as well as face some methodological limitations that we want to point out and that need to be addressed in future studies.

The suitability of the selected ES list was confirmed by stakeholders, assessing all listed services to be at least of low importance. Our ES list allows for integration of both scenario and habitat approaches, and allows to develop the scenarios with different dominant macrophyte species in the specific local growth conditions. We recommend minor adaptations of ES descriptions and examples to local and case-specific conditions. For example, while roof thatching is a good example for reed harvesting in the Baltic Sea, this does not apply in the Mediterranean Sea.

Due to a high complexity or the lack of harmonized indicator schemes within monitoring and assessment of ES (Czúcz et al. 2018), especially for coastal and marine services (von Thenen et al. 2020), our indicator list can serve as a solid base for assessing ES provided by macrophytes. The number of pre-selected indicators (174) constitutes the limit for such selection process due to experts´ time constraints. For each service three to four indicators were chosen and ranked by experts. In case of low data availability, indicators can serve as additional guidance and description for stakeholders and experts in order to improve data quality (i.e., common understanding). However, we learnt that some of the listed indicators were too general and could not be used to differentiate between single macrophyte habitats, e.g., contribution to coastal tourism (income € per year). Due to a lack of data and when assessing on large-scale habitat level indicators were partly difficult to apply. However, we tried to use at least one indicator from the developed list complemented by "Number of Web of Science (WoS) articles" indicating the relevance of given keywords, which we assume represents the ES potential. Despite this, we assume that indicators work well on specific water body level, e.g., for well-defined and precise study areas, where data availability is higher.

Scenario methodology is widely applied in developing spatial planning with integrated ecosystem services assessment or modelling more in the terrestrial (e.g., Kabaya et al. 2019). than marine areas (e.g., Farella et al. 2020). Scenario assessment appeared to be a successful tool to start discussions among participants supporting decision-making processes, e.g., for marine mussel cultivation (Ritzenhofen et al. 2022). As shown by Schernewski et al. (2019), this approach can be applied to assess the implementation of EU policies, for example, the measure of WFD to achieve a GES. For scenario assessments, only low expertise of participants is needed allowing for broad stakeholder involvement. The approach focuses on perceptions, identifying misunderstanding and finding a common understanding (Robbe et al. 2021), as also stated by stakeholders of this study. Another opportunity for application, as we learnt during the discussion, can be as a learning tool for awareness raising and for teaching graduate students (i.e., lecture, thesis), which is also supported by Rodríguez-Loinaz and Palacios-Agundez (2022) and Barracosa et al. (2019). Although the level of expertise being important in terms of data quality, a low level of stakeholder expertise may lead to an increased understanding of management measures and thereby to an increased acceptance of such. Regarding the transferability of scenario assessments, this approach can be used in general not only for coastal areas that have similar ecosystem characteristics (i.e., Baltic lagoons), but also for contrasting systems (i.e., Mediterranean lagoon).

Spatial extrapolation represents a common method for assessing and mapping ES (Martínez-Harms and Balvanera 2012; Andrew et al. 2015; Le Clec'h et al. 2018). Our spatial extrapolation approach has the limitation that extrapolated areas and scenarios build upon simplified assumptions (e.g., macrophyte expansion up to 3 m depth) and have a strong focus on touristically important areas. We further differentiated between recreational activities on land (e.g., beach area) and on water (e.g., boating), which stakeholders criticized for being merged in scenario assessments. However, the extrapolation results only show changes by different scenarios in water area for recreational activities, but no change in land area. This neglects changes in recreational activities on land, as scenarios will affect land not in area but in activity type (e.g., no sun bathing because of limited water access for swimming). We learnt that scenario results are suitable to be extrapolated to the entire water body level when areas share similar characteristics as the transect. However, for further studies we recommend to include transects of different focus, e.g., touristic use, fisheries, and nature protection. Despite these limitations, the approach can serve as a basis for decision making, for example, when designating nature protected areas, fishing grounds, water sport areas or other use rights. Especially for spatial planning measures, this approach could support local spatial planning processes (compare Schernewski et al. 2023) by identifying areas of highest interest for different spatial uses (tourism vs. nature protection). For this, further development of the approach is needed, for example, by integrating ES assessment results (i.e., importance of services and impacts of spatial planning measures on services) and concrete spatial land and/or water use data.

Our habitat assessment was tested for the Baltic Sea and considered to be suitable for identifying differences between ES of emerged and submerged macrophyte habitats when assessing comparatively but not individually. Similar approaches exist for terrestrial, coastal and marine ecosystem types in Northern Germany (Müller et al. 2020) and ecosystems across the land-sea interface in the Baltic (Schumacher et al. 2021). We learnt that the application on a Baltic Sea wide level works well when using expert knowledge, but only very limited when using indicators. Regarding the literature-based results, there is a strong bias towards representation in literature, as we used the relevance indicator (i.e., number of WoS articles) for 60% of the services, complementary or single. We can state that there is a discrepancy between expert opinion and literature with regard to the service potential in particular of charophytes and pondweed. Results clearly show the need for expert knowledge when assessing macrophyte habitats on a large-scale due to the lack of literature data for selected habitats (i.e., charophytes and pondweed). For future studies we suggest to apply our habitat assessment to specific lagoons, thus using smaller and well defined spatial areas where data availability is higher and indicators are more easily applicable. This approach allows for comparative assessments of individual macrophyte habitats (e.g., seagrass beds), possibly in different seas. We assume a good transferability of our habitat approach to other systems internationally, for example Mediterranean lagoons, by mainly using expert knowledge where data availability is possibly low.

Implications for Management and Policy Implementation

As the status of macrophytes is still not in a good or high ecological state for around 50% of all transitional and coastal waters in the EU (EEA 2018), there is a need for supporting policy implementation to achieve its goals (i.e., achieving GES). This study provided holistic approaches of ES assessments, specifically targeting macrophytes, to support coastal management and policy implementation. Transferring main results of this study to current coastal management and policy implementations, we learnt that our approaches can support the evaluation of different management measures. Main areas of macrophyte management in coastal areas that we identified by the high ES potential and importance of macrophytes are 1) nature protection (incl. climate protection), 2) coastal protection, 3) blue economy, and 4) coastal tourism, which are also reflected in relevant EU policies (WFD, HD, Sustainable Blue Economy).

First, the protection of macrophyte habitats is addressed by several EU policies, mainly the WFD and HD. However, measures of implementation are partly unsuccessful as either assessment results indicate only little effect or are not sufficiently represented in the results (BMUB/UBA 2016). For example, benefits of protecting nature are often economically invisible and regarded as intrinsic (TEEB 2010). With our approaches we can justify the values of macrophyte habitats and thereby the benefits of protecting them. For instance, we can demonstrate the value of the halophyte *Aster tripolium*, a red list species, located in the protected area "Smeltes botaninis draustinis" (Klaipeda, Lithuania) that is in the industrial harbor area of the Curonian lagoon (Olšauskas et al. 2013). Additionally, macrophyte habitats play a role within climate change mitigation measures, for example by reed belts (Buczko et al. 2022) and sea grass beds (Stevenson et al. 2022) as carbon storages. Summarizing, our results can support the implementation of management and policy measures by explaining the benefits to humans, for example, of achieving the GES (e.g., restoration of macrophyte habitats by reducing agricultural nutrient loads) and of enhancing the biodiversity of macrophyte habitats (e.g., to protect rare species and prevent monocultures).

Second, especially reed belts (Coleman et al. 2023) and seagrass beds (Chen et al. 2022) are of great importance for coastal protection by reducing wave energy in the foreshore area. A recent project specifically targets planting and reforestation of seagrass beds in the Baltic Sea (SeaStore). In the Curonian lagoon, reed belts were already used as dune protection in the 1960s when planted in front of Juodkrante in order to decrease coastal erosion (Galiniene et al. 2019). This example reflects well on our ES results showing the tradeoff between coastal protection (i.e., planting reed belts), biodiversity (i.e., loss by monoculture) and tourism (i.e., blocking view or limiting access), but also one synergy by providing material for further use when harvesting reed regularly. In the context of sea-level rise and storm surges, the importance of emergent macrophytes (i.e., reed), in particular, may increase even further due to higher demand of coastal protection.

Third, the EU Sustainable Blue Economy Strategy (EC 2020a) recognizes the economic potential of marine macrophytes and their biomass, also reflected in our ES potential results for provisioning services (e.g., plant biomass as material for further processing). Besides, Lillebø et al. (2017) highlight the potential of marine macrophytes in the blue energy sector by substituting non-renewable energy sources, for example, biogas production or direct combustion (Wichmann 2017). Within the EU Farm-to-Fork strategy, which includes specifically aquaculture guidelines (Council of EU 2020a; 2020b), macrophytes can be farmed and harvested for the purpose of human nutrition (Wells et al. 2017), either by saline agriculture (Nikalje et al. 2018) or by marine aquaculture. The latter, commercial seaweed farming in the Baltic Sea bears not only economic potential, but also reduces nutrient loads to combat eutrophication (Kotta et al. 2022). Besides, the genetic material of macrophytes bears the potential for pharmaceuticals and cosmetics (Puchkova et al. 2022), as well as for further processing and use of the material, e.g., thatching (Karstens et al. 2019). Concluding, the potential of macrophyte habitats to deliver provisioning services for blue economy (e.g., food, feed, fuel) is given, but often limited due to poor or uncertain economic viability, requiring synergies (i.e., seaweed farming for biomass production and for nutrient removal).

Forth, with regard to coastal tourism, macrophyte management is pivotal. For example, at sport boat harbors, macrophytes are either removed or destroyed by frequent boating activities or contrarily cause damage to motors by entanglement in macrophytes (Verhofstad and Bakker 2019). Both results in a need for management measures, i.e., cutting or removing macrophytes, which can also cause high costs for municipalities if not further used economically (Wichmann et al. 2017). As shown in our scenario results of cultural services (high macrophyte coverage), high-growing reed belts can be also seen as nuisances to tourists by blocking the view, or contrarily being pivotal for the aesthetic experience (Karstens et al. 2019). Though results show in general a positive impact of macrophytes and their recovery (e.g., within achieving the GES), the question remains, if the GES in terms of macrophytes is always a desired state? Due to spatial tradeoffs and conflict between recreational use and expansion of macrophytes, management and policy measures need to be clearly adapted to the regional importance of human activities (i.e., demand for ES). Macrophyte expansion within the GES may significantly inhibit coastal tourism, which can be an important economic driver of coastal regions. Our approaches can be used to identify areas of high importance for tourism or, for example, biodiversity hotspots. Therefore, management and policy measures could target specific areas of high or low importance of ES provision (or demand) to avoid tradeoffs and to use synergies.

Conclusion

To the best of our knowledge, this is the first systematic ES assessment of macrophyte habitats comparing their ES provision and potential under different management scenarios (i.e., different ecological states) and in different seas (i.e., Baltic and Mediterranean Sea).

Macrophytes are beneficial to humans. However, management measures have to be in accordance with the spatial use of coastal areas. Our approaches give fast and easy results on the perception of management measures, here macrophyte expansion and improvement of ecological states. This research has shown that macrophytes are generally perceived as beneficial to humans. Nonetheless, macrophytes are also considered to mainly inhibit coastal tourism and recreation, which are the most important services in the Baltic lagoons. This finding strengthens the need to integrate spatial use data and ES assessment results for identifying specific tradeoffs and synergies of management measures. As the understanding of the good ecological status as dominance of macrophyte habitats within the WFD is often too narrow and bound to main benefits, i.e., water transparency, our holistic ES assessment approaches might be beneficial for multi-sectorial management. We applied and integrated different assessment approaches (i.e., scenario and habitat level) as well as different data sources, namely socio-economic data (by stakeholder and experts) and biophysical data (i.e., indicator-based). It is unfortunate that the indicator-based assessments are highly limited due to the lack of data on the selected habitats. Inspite of its limitations, this study presents two ES assessment approaches that are internationally valid and applicable for assessing macrophyte habitats and coastal lagoons. We further recommend to carry out future research applying these approaches to other coastal habitats worldwide, e.g., mangroves, ice-dominated habitats (other climate zones, tropical, ice).

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Author Contributions ER, LR, and GS contributed to the study conception and design. Material preparation, data collection and analysis were performed by ER and LR. The first draft of the manuscript was written by ER and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

Ethical Approval All stakeholders and experts were informed and consented to publishing assessment results, with clear explanations on information use, highlighting voluntary participation and withdrawal rights. Ethical considerations included safeguarding confidentiality and minimizing any potential risks or discomfort to participants.

Consent to Participate Informed consent was obtained from all individual participants included in the study.

Consent for Publication Informed consent was obtained from all individual participants included in the study.

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Doctoral dissertation

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