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Testing the concept of green infrastructure at the Baltic Sea scale to support an ecosystem-based approach to management of marine areas

Anda Ruskule [a,*], Jonne Kotta [b], Champa Rani Saha [c], Philipp Arndt [d], Didzis Ustups [e], Solvita Strāķe [f], Lena Bergström [g]

[a] Baltic Environmental Forum, Latvia
[b] Estonian Marine Institute, University of Tartu, Estonia
[c] Centre for Environmental and Geographic Information Services(CEGIS), Bangladesh
[d] Federal Maritime and Hydrographic Agency (BSH), Germany
[e] Institute of Food Safety, Animal Health and Environment BIOR, Latvia
[f] Latvian Institute of Aquatic Ecology, Latvia
[g] Department of Aquatic Resources, Swedish University of Agricultural Sciences, Sweden

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ABSTRACT

The concept of Green Infrastructure (GI) can facilitate integration of ecological considerations and ecosystem service mapping into spatial planning. GI has been introduced in EU policy as a key tool for implementing the objectives of the EU Biodiversity Strategy 2020 on halting the loss of biodiversity as well as addressing other global environmental problems. Unlike terrestrial ecosystems, mapping of marine GI is still in infancy. Here, application of GI concept in mapping was developed and tested for a large marine region, the Baltic Sea, using existing regional spatial data sets on the distribution of different ecosystem components. Using a qualitative valuation approach, experts assessed 36 marine ecosystem components with respect to their relevance for six ecological value criteria and ten ecosystem services. Then, maps representing the ecological value of Baltic Sea ecosystems and their potential supply of ecosystem services were developed based on a hierarchical aggregation structure, designed to avoid double-counting of features that appeared in many data layers. Finally, results of the ecological value and ecosystem service supply mapping were integrated into the marine GI map. These pioneering results are used to discuss how marine GI mapping can support the ecosystem-based approach in MSP, by improving the knowledge base on the roles and connectedness of ecosystem components. Applied at the transboundary regional scale, as here, the GI concept can support cross-border coherence in spatial planning and provide practical management solutions to improve connectivity and functioning of MPA networks, or develop sustainable planning solutions of marine space.

1. Introduction

The EU Maritime Spatial Planning Directive calls for application of an ecosystem-based approach, which should “contribute to promoting the sustainable development and growth of the maritime and coastal economies and the sustainable use of marine and coastal resources”. It also refers to the Marine Strategy Framework Directive, which requests the implementation of an ecosystem-based approach to “the management of human activities, ensuring that the collective pressure of such activities is kept within levels compatible with the achievement of good environmental status (GES) and that the capacity of marine ecosystems to respond to human-induced changes is not compromised, while enabling the sustainable use of marine goods and services by present and future generations”. In order to implement ecosystem-based management it is very promising to include ecosystem services in decision-making [53].

Ecosystem services are the many and varied benefits to humans provided by the natural environment and from healthy ecosystems [50]. Marine ecosystems are the largest of Earth’s aquatic ecosystems and thereby vital for significant portions of the global human population. Marine and coastal ecosystems provide multiple benefits to people including food and raw materials, genetic and medical resources,

* Correspondence to: Baltic Environmental Forum, Antonijas 3-8, Riga LV-1010, Latvia.
E-mail addresses: anda.ruskule@bef.lv (A. Ruskule), jonne@sea.ee (J. Kotta), champasaha21@gmail.com (C.R. Saha), philipp.arndt@bsh.de (P. Arndt), didzis.ustups@bior.lv (D. Ustups), solvita.strake@lhei.lv (S. Strāķe), lena.bergstrom@slu.se (L. Bergström).

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climate regulation, mediation of waste, coastal protection as well as cultural identity, leisure and recreation [5,48,52,63]. Marine ecosystem service supply is determined by the structure and functions of ecosystems, their state and integrity [15]. Shallow vegetated habitats and reefs are known to be highly important for maintenance of marine biodiversity, providing nursery and spawning habitats as well as nutrient regulation, and other services (e.g. [49]; Kotta et al. [45]; Heckwolf et al. [32]). These properties and functions of the living ecosystem constitute elements of green (or blue) infrastructure, a network providing necessary "ingredients" for solving environmental and climatic challenges by building with nature (e.g. [27]). The idea of ecosystems as a type of infrastructure was proposed already in the 1980 s [68]. The green infrastructure concept acknowledges that healthy ecosystems are not only important to maintain biodiversity but also to provide services to humans, some of which are used directly, while others bring benefits to society only in interaction with human-made infrastructure [61].

The concept of Green Infrastructure (GI) was introduced in EU policy as a key tool for implementing the objectives of the EU Biodiversity Strategy 2020 on halting the loss of biodiversity [22] as well as a means for addressing other global environmental problems such as climate change and land degradation. The EU Strategy on Green Infrastructure defines GI as "strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services" both in terrestrial and marine areas [23]. The strategy encourages the deployment of GI across Europe, as well as calls for GI becoming a standard part of spatial planning and territorial development. The new EU Biodiversity Strategy 2030 is focusing on the need to develop a truly coherent and resilient Trans-European Nature Network, by setting up ecological corridors and maintaining healthy ecosystems, to be supported by investments in green and blue infrastructure and cross-border cooperation among Member States [25].

When integrated in spatial planning solutions, the GI concept can be expected to significantly improve sustainability, as it stimulates a greater engagement of planners in ecological considerations and ecosystem service quantification. Strategic plans can identify priority areas for GI protection or enhancement, resulting in completely different and more environment-friendly spatial networks [64]. Further, implementation of GI initiatives could help expand biodiversity conservation outside of protected areas by improving their connectivity through ecological corridors, preventing genetic isolation, and maintaining ecosystem services [37]. Mapping of green and blue infrastructure can also facilitate achievement of the EU Biodiversity Strategy 2030 target to protect at least 30 % of the land and 30 % of the sea [25] by indicating areas to be protected as ecological corridors or established as other effective area-based conservation measures (OECMs), which are governed or managed in a way that has positive effect of conservation of biodiversity with associated ecosystem functions and services [26].

Following the strategic objectives, several initiatives for GI mapping and strategic planning have been implemented, ranging from local scale [18,43] to national (Mander et al., 2018) and EU level studies [47,64]. The European Commission [21,24] demonstrates the mainstreaming of GI in other EU policies as well as delivers best practices of GI deployment at different scales and planning contexts. However, despite a plenitude of the land-based initiatives, mapping of marine GI can still be considered as a novelty. European Commission [21] concludes that GI "is not sufficiently used in maritime spatial plans, whereas it could contribute to healthy marine ecosystems and deliver substantial benefits in terms of food production, recreation and tourism, climate change mitigation and adaptation, shoreline dynamics control and disaster prevention". A significant knowledge gap in the use of GI in the marine environment was also identified by the Joint Research Centre (JRC) of the European Commission [20].

The poorer development of GI mapping in the marine realm could be attributed to slower progress of marine ecosystem service research, compared to terrestrial environments, and also to scarcity of spatial data and technical difficulties in data acquisition. Key marine knowledge gaps and challenges concern understanding of spatial and temporal dynamics and the interconnectivity of marine ecosystem processes, differences between areas where services are generated and where they are valued, as well as how to consider societal values in publicly owned space [63]. Hence, the links between ecosystem structure, functioning and services need further in-depth research. Due to the connectedness of marine ecosystems over geographical and jurisdictional borders, overcoming key challenges could be facilitated by transnational collaboration at the scale of a marine region.

The Baltic Sea is a region of significant socio-economic importance in the northern hemisphere. It can be considered also as one of the most advanced in Europe with regard to strategies and actions for marine protection and sustainable development [60], including coordinated data collection. This was achieved as a result of many years of cooperation among countries under the umbrella of HELCOM (the Helsinki Commission - an intergovernmental organisation for protection of the marine environment in the Baltic Sea) as well as several other transnational cooperation initiatives, e.g. for enhancing maritime spatial planning in the region [29]. During recent years, several local or national studies have been undertaken in the Baltic Sea region on the mapping and assessment of ecosystem services, including the quantification of linkages between marine ecosystem components, functions and service supply [2], development of approaches to assess marine and coastal cultural services [1,58], as well as application of ecosystem services assessments to support environmental management and maritime spatial planning [16,60,65].

Identification and assessment of ecosystem components (species or habitats) that have particular importance for maintaining ecosystem integrity and ecosystem services supply can contribute to the mapping of green (or blue) infrastructure [47]. Heckwolf et al. [32] systematically reviewed the primary literature on coastal ecosystem services in the Baltic Sea region. The study revealed good quantitative information on the ecological foundation of ecosystem services whereas links between ecosystems and their derived socio-economic benefits were very poorly established. Armoškaitė et al. [2] demonstrated high importance of some keystone species (e.g. mussels, annual and perennial algae) in ecosystem service supply but concludes that such highly valuable habitats occupy a relatively small area.

In order to advance the concept of green (or blue) infrastructure in the marine realm, the current paper proposes a methodology for marine GI mapping at the scale of the Baltic Sea region. The presented concept was tested in the Pan Baltic Scope project [59], which aimed to develop tools and approaches to contribute to coherent maritime spatial plans in the Baltic Sea Region, including implementation of an ecosystem-based approach (EBA). In the current paper, the conceptual framework and the Pan Baltic Scope approach to mapping of marine GI were further explored. The current paper describes the applied concept, as well as discusses challenges, limitations and potentials for its application in management and the protection of marine ecosystems. The study represents a pioneering attempt in marine GI mapping - by applying the concept for the first time at the scale of a marine region. The results contribute to implementation of the EBA by offering a novel way for consolidating complex ecological and ecosystem service information, which may, inter alia, support the identification of ecological 'hot-spot' areas to be considered in the spatial planning process.

2. Methods

2.1. Case study area

The Baltic Sea is one of the largest semi-closed brackish water sea basins in the world covering around 377 000 km^2 with an average depth of only 55 m and a maximum depth of 459 m. It is connected to the North Sea through shallow straits, resulting in very low water exchange with the world ocean.

The Baltic Sea is characterised by strong seasonal variability and decreasing gradients of salinity and temperature from southwest to northeast. It is an almost non-tidal sea that spans from the temperate, highly populated and industrialised south with intensive agriculture, to the boreal and rural north. Moreover, at smaller scales the gradients of wave exposure, nutrient and oxygen availability, and topography define conditions for its biota.

Due to its brackish water conditions, the Baltic Sea environment has low species richness compared to marine areas. The low salinity allows only a few marine species to extend their distribution into the Baltic Sea whereas freshwater species are restricted to even more diluted bays and estuaries [42]. Sometimes marine and freshwater occur within the same habitat. Low species richness and the presence of organisms near their physiological tolerance renders vulnerable the whole ecosystem of the Baltic Sea [9]. Furthermore, the Baltic Sea is geologically young. An ongoing ecological adaptation is seen in many marine species in response to the brackish environment, leading also to the development of locally adapted populations and ultimately to the evolution of new species [51,54]. Despite low species richness, considerable geographical variation in environmental and topographical conditions contributes to a high variability of habitat types. Various pelagic and benthic species, birds, mammals, fishes interact and potentially contribute to a variety of services to society.

The ecosystems of the Baltic Sea are under threat from a broad range of multiple interacting human stressors often resulting in species loss and habitat degradation. Such intensifying and diversifying human pressures jeopardise the sustainability of these ecosystems and services they provide. Marine transportation and fishing are the most widely occurring sea uses in the Baltic Sea region. Importantly, land-based activities in all its drainage areas, inhabited by about 85 million people [35] significantly influence its ecosystems. Such effects are mostly due to agriculture, forestry and urbanisation. Hence, eutrophication and the presence of hazardous substances are identified as the pressures having the most widespread impact on the Baltic Sea ecosystem today. Although several human activities in the Baltic Sea are highly dependent on its ecosystem services [10], the human-derived pressures on the ecosystems have an impact on service supply and consequently on society. GI mapping could contribute to the efficiency of planning and management, contributing to raising concern for the restoration of degraded ecosystems and contributing to planning, management, and sustainable use of marine areas.

2.2. Methodological framework for marine GI mapping

Application of the GI concept in the marine realm was tested at the pan-Baltic scale while using available regional datasets covering a broad range of ecosystem elements. The study encompassed three major steps: i) framing of marine GI concept; ii) development of assessment and mapping approach; and iii) testing of marine GI mapping (Fig. 2). Key stakeholders were engaged throughout the process, including formulation of the concept, discussing the mapping results and opportunities for operationalising the concept with MSP processes.

2.2.1. Framing of marine GI concept

The framing of marine GI concept was based on the definition suggested by the European Commission [23], which states that the GI is formed by the network of natural and semi-natural areas, providing a wide range of ecosystem service. Accordingly, the GI concept integrates the notions of biodiversity conservation, ecological connectivity, and multi-functionality of ecosystems [47].

The pathway from ecological structures to ecosystem services and human well-being was demonstrated by the cascade framework proposed by Haines-Young & Potschin [28,56] and further elaborated by La Notte et al. [46]. The cascade framework demonstrates the role of biophysical structures and biodiversity for ecosystem processes and functions, which underpin ecosystem service supply. Thereby it is well suited as a conceptual basis for the green infrastructure mapping, which should feature natural or semi-natural areas important for ecosystem service supply. Identification of core GI areas can be based on ecological structures of high value for biodiversity as well as for ecosystem service, as demonstrated by several studies within terrestrial areas [4,47,64].

A survey on former efforts in the mapping and assessment of GI and/or ecological value of marine ecosystems in the Baltic Sea Region was carried out by the Pan Baltic Scope project in spring 2018. The survey identified 19 national attempts at mapping ecologically valuable or sensitive areas from Estonia, Latvia, Poland, Germany, Sweden, Finland and Åland, revealing that the most often used criteria for assessing the ecological value were biodiversity, rarity and importance for threatened species/habitats, as well as aggregation (i.e. areas important for particular species groups) [59].

The interpretation of GI as a concept in the marine context was discussed at the first regional workshop in Riga, May 2018. Participants of the workshop suggested and considered the following marine GI forming elements: i) the network of the existing marine protected areas (MPAs); ii) Ecologically or Biologically Significant Marine Areas (EBSAs) defined within the framework of the UN Convention on Biological Diversity (CBD), iii) benthic habitats of high conservation value and/or core habitats for species e.g. (shallow vegetated habitats); iv) areas important for the main species groups (birds, fish, mammals) at different life stages; v) ecosystem components vulnerable to human pressures; vi) areas important for connectivity of the core habitats; as well as vii) areas important for ecosystem integrity, functions and service supply. The option of using the existing MPA network as basis for GI mapping was rejected by the workshop participants as there was no reason to expect that MPA designation was generally linked to an underlying mapping process. The option of using the network of EBSAs as a basis was considered not suitable for GI mapping at the Baltic Sea regional scale since criteria for identification of EBSAs are adapted to the global scale. Therefore, a bottom-up approach to the identification of GI areas was advocated, i.e. by basing the mapping on available spatial data on benthic habitats and main species groups aggregated at the pan Baltic scale. Connectivity analyses were also acknowledged as highly essential in GI mapping, although less constitutive compared to terrestrial environments, due to a generally high mobility of marine species. Due to insufficient data on species migration and/or dispersal as well as lack of established methodologies for connectivity analyses of marine ecosystems, this aspect was considered as not feasible to include in the Pan Baltic Scope study.

Based on the results of the workshop as well as a preceding synthesis of existing efforts to the mapping and assessment of GI and/or ecological value of marine ecosystems, the marine GI was defined as a spatial network of ecologically valuable areas which are significant for the maintenance of marine ecosystems' health and resilience, biodiversity and multiple delivery of ecosystem services essential for human well-being [59] (Fig. 3).

2.2.2. Development of marine GI mapping approach

The approach for marine GI mapping was based on methods previously tested in terrestrial areas. Estreguil et al. [20] highlighted the utility of using complementary approaches for GI mapping: i.e. starting from physical mapping of existing identified ecosystem components (e.g., protected areas, ecological networks and other valuable natural areas) and followed by an ecosystem services-based mapping, targeting connectivity and delivery of multiple ecosystem services. Liquete et al. [47] proposed a comprehensive methodology for the mapping of GI at the European (EU) scale, which integrates mapping and connectivity analysis of essential core habitats with analyses of their natural capacity to deliver ecosystem services. Areas with highest contribution to one or both aspects were identified as forming the GI network. A similar approach was followed in the current study, in which marine areas of the relatively highest ecological value and/or ecosystem service supply potential were classified as core areas for marine green (or blue)

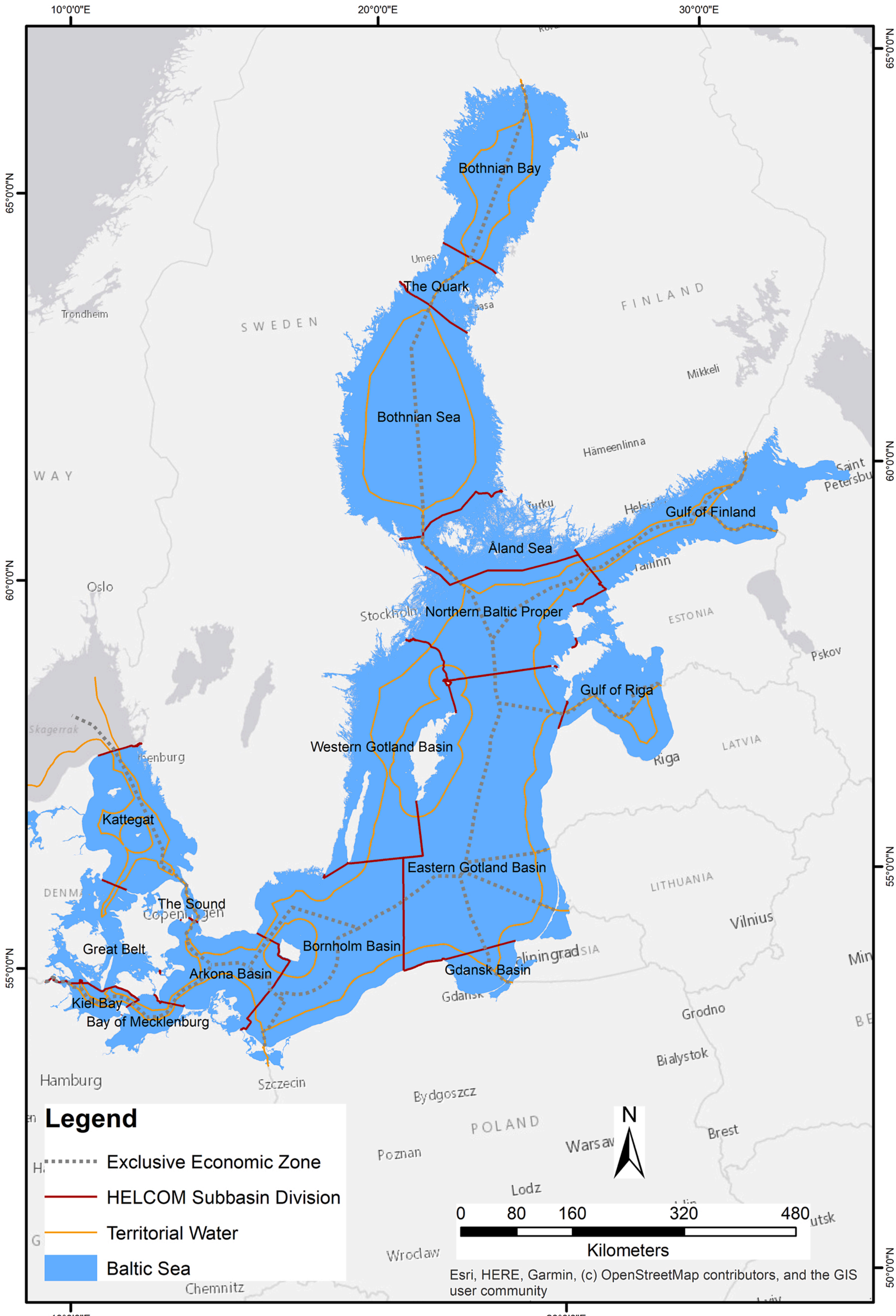

Fig. 1. Location of the case study area showing administrative boundaries and sub-basins.

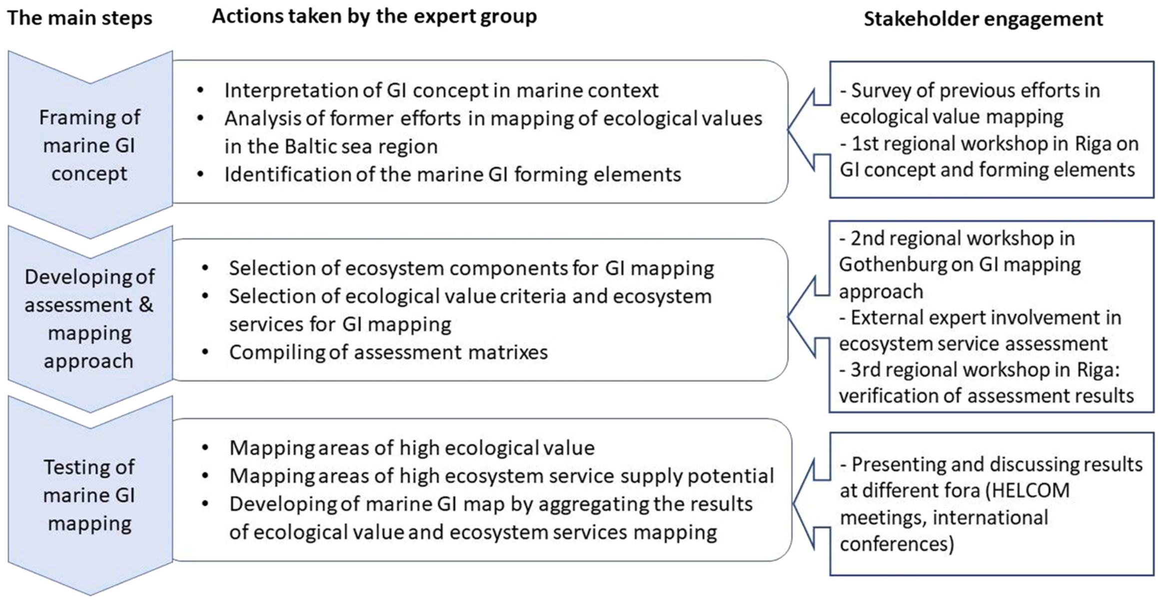

Fig. 2. Workflow of the marine GI concept development and testing in the Baltic Sea region.

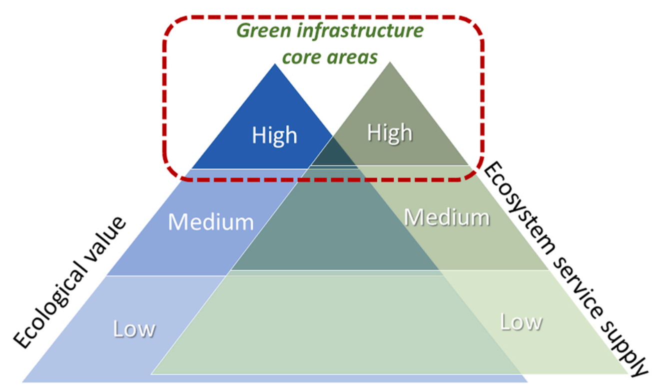

Fig. 3. Conceptual approach to the mapping of marine GI. Core areas for GI are formed by those areas, which represent high ecological and/or ecosystem service value. In the GI mapping, areas of high importance for ecosystem services supply might, but are not expected to, be identical to areas of high ecological value. Both qualities contribute independently to GI.

infrastructure (Fig. 3).

A range of methods can be applied for the biophysical mapping of ecosystem services supply, including direct or indirect measurements as well as modelling. In this paper a spatial proxy method was used [66] in which mapped ecosystem components were linked to different ecosystem services based on their expected potential to deliver such services. Ecosystem service potential was estimated for essential marine ecosystem components using the expert scoring or matrix method [11,12,13,40]. Such an assignment relies on certain assumptions e.g. that the current scientific evidence is sufficient to identify links between ecosystem components and the ecosystem services potential, and that ecosystem service delivery is constant within each ecosystem component. Nevertheless, using expert knowledge in ecosystem services assessment has proven as a suitable method for reducing the complexity of human-environmental systems and thus solving the urgency-uncertainty dilemma [40,52]. The same approach was applied for mapping marine areas of highest ecological value: the relevance of each ecosystem component for selected ecological value criteria was defined based on expert knowledge, provided by marine ecologists, using the matrix method.

2.2.2.1. Selection of ecosystem components for GI mapping. Both the capacity of service supply and the ecological value of marine ecosystem components were assessed at the spatial scale of the Baltic Sea region. The mapping was based on regionally coherent spatial data covering the entire Baltic Sea, as derived from HELCOM [35] and available from the HELCOM Maps and Data services.

36 data layers were initially considered, covering ecosystem components in six broader groups:

- pelagic habitats and species (represented by one data layer - productive surface waters);
- benthic habitats and species (including marine landscapes based on geology; EU protected benthic habitat types; and key benthic species);
- essential fish habitats (spawning, nursery and recruitment areas of commercially important fish species);
- bird habitats (wintering and breeding seabird colonies)
- mammal habitats
- mobile species (including distribution and abundance of few fish and seal species).

Some of the initially considered data layers were however later discarded from further use, due to data quality aspects. The data layer on pelagic habitats was included in the ES assessment (matrix development) but was not applied in the GI mapping as it covers the entire region with equal weight, meaning that adding it to the final GI maps would not reveal any spatial differences. The data sets on mobile species were also discarded due to insufficient data accuracy. Only very coarse maps on the distribution of fish and seal species were available at the scale of the entire Baltic Sea, so that these would not reveal any meaningful spatial differences, and no spatial data set on harbour porpoise was available at the time. In case of essential fish habitats the HELCOM data layers of 2018 were replaced by updated maps developed within the Pan Baltic Scope project, including spawning areas of cod, sprat, herring, European flounder, Baltic flounder, recruitment areas of perch, pikeperch, and nursery areas of flounder [6].

The full list of the ecosystem components used in the marine GI mapping are presented in Table S1 in supplementary material.

2.2.2.2. Selection of ecosystem services. At the second regional workshop (Gothenburg, September 2018), experts selected relevant ecosystem services to include, based on the Common International Classification of Ecosystem Services (CICES) Version 5.1 (published in 2018), and also agreed on a scoring method. Only regulation & maintenance and cultural services (those related to recreation) were identified as relevant, since these link more directly to the concept of GI by reflecting the natural capacity of the ecosystem to deliver services, without considering human demand or depending on human inputs [47]. Provisioning services were not included, e.g. areas providing fish for food. However, data on essential fish habitats, namely maps on spawning and nursery areas of commercially important fish species, were included to highlight the role of biophysical structures in the ecosystem ensuring the fish resource, hence representing a regulating service. Another criterion for selecting relevant ecosystem services was the availability of suitable data sets which they could be linked to, based on data availability in HELCOM Maps and Data services. For two CICES ecosystem service classes, sub-categories were used. To further support the identification of relevant ecosystem services, previously published indicators were considered [30,38] and findings of other ongoing marine ecosystem studies in the Baltic Sea (e.g. the BONUS BASMATI project). These sources were used for guiding the expert assessment, but not for quantifying the service value. The list of selected services and indicators is provided in Table 1.

2.2.2.3. Selection of ecological value criteria. The ecological value of marine areas was assessed in relation to their importance for maintenance of biodiversity. Criteria for assessment of the ecological value were also selected at the second regional workshop (Gothenburg, September 2018). Guided by experience gained from previous studies on mapping ecologically significant areas in the Baltic Sea, the expert group decided to base the assessment on the criteria used for identification of ecologically or biologically significant marine areas (EBSAs) within the framework of the UN Convention on Biological Diversity (CBD) [19]. The selected criteria include the following: biological diversity; rarity; importance for threatened, endangered or declining species and/or habitats; vulnerability, fragility, sensitivity, or slow recovery; special importance for life-history stages of species; and biological productivity.

2.2.2.4. Compiling of assessment matrices. To estimate the potential contribution of each ecosystem component to ecosystem service supply, as well as its ecological value, the expert-based matrix approach [13] was used, drawing on the knowledge of involved expert and the results of previous studies (e.g., [15,57]). Two matrices were developed, one for quantifying links to the ecosystem services potential, and one to ecological value.

The ecosystem services matrix included 36 ecosystem components

Table 1
Ecosystem services selected for mapping of marine green infrastructure.

Division	Group	Class (including the CICES V5.1 code)	Sub-categories of ecosystem services*	Explanation/proposed indicators
Regulation & Maintenance services				
Transformation of biochemical or physical inputs to ecosystems	Mediation of wastes or toxic substances of anthropogenic origin by living processes	2.1.1.2. Filtration/sequestration/ storage/ accumulation by micro-organisms, algae, plants, and animals	Filtration of nutrients	Fixing and storage of an organic or inorganic substance: Total Nitrogen-loss (kt yr^{-1})
			Storage of nutrients	Fixing and storage of an organic or inorganic substance: N-fixation (kg yr^{-1} km^{-2}) Burial of P (kg yr^{-1} km^{-2})
			Storage of hazardous substances	Sequestration of toxicants by living organisms: Body biomass of toxicants
Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	2.2.1.1. Control of erosion rates		Reduction of wave energy by near shore habitats: Change in wave energy by near shore and intertidal habitats (Stone/reefs, macrophytes, islands) (Jm^{-2})
Regulation of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	2.2.2.3. Maintaining nursery populations and habitats (Including gene pool protection)		The presence of ecological conditions/habitats necessary for sustaining populations of species that people use or enjoy: Nursery areas (EFH)
Regulation of physical, chemical, biological conditions	Pest and disease control	2.2.3.1. Pest control (including invasive species)		Abundance of piscivorous
Regulation of physical, chemical, biological conditions	Atmospheric composition and conditions	2.2.6.1. Regulation of chemical composition of atmosphere and oceans	Regulation of atmospheric CO^2 and other greenhouse gases by biological fixation in the process of photosynthesis	Pelagic and benthic fixation of carbon through photosynthesis: Concentration of chlorophyll (mgm^{-2} or mgm-3) primary productivity (mol C m^{-2} d^{-1})
			Regulation of atmospheric CO^2 and other greenhouse gases by sequestration in sediments	Deposition and burial of carbon in seabed sediments through bioturbation: Carbon storage (g C m^{-2} $time^{-1}$) – carbon buried in sediments
Cultural services				
Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	Physical and experiential interactions with natural environment	3.1.1.1. Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions		e.g. swimming, diving, windsurfing, kiteboarding Indicators: In-water activities occurrence (number); recreational trips (number/year)
		3.1.1.2. Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions		e.g. bird/seal watching Indicators: Presence of iconic/ endangered species (number): extent of MPAs

*sub-categories are proposed based on the marine ecosystem service classification applied in the BONUS BASMATI project.

and the ten selected ecosystem services (Table S2 in supplementary material). The potential contribution of each ecosystem component to the supply of each ecosystem service was scored using a binary scale, where 0 represented either no or negligible contribution of the ecosystem component to the ecosystem service, while 1 denoted a situation when the ecosystem component was expected to contribute in an important way to the service. The binary scale was used to accommodate for uncertainty in the assessment regarding the intensity of ES provision by any particular ecosystem component. There are currently almost no functions to reliably quantify relationships between ecosystem structure, functioning and the intensity of services they provide, and such knowledge gap currently represents a major obstacle to model intensities of ES in the marine realm (e.g. Heckwolf et al. [32]).

The scores were obtained through an iterative process. At first, the assessment matrix was sent out by e-mail to experts from Estonia, Latvia, Sweden, Finland, Germany and HELCOM (representing the Pan Baltic Scope project expert group, as well as a few external experts), who filled the matrix individually, or in some cases jointly for experts representing the same country. Then, the replies were compiled together and an online meeting inviting all contributing experts was organised to discuss

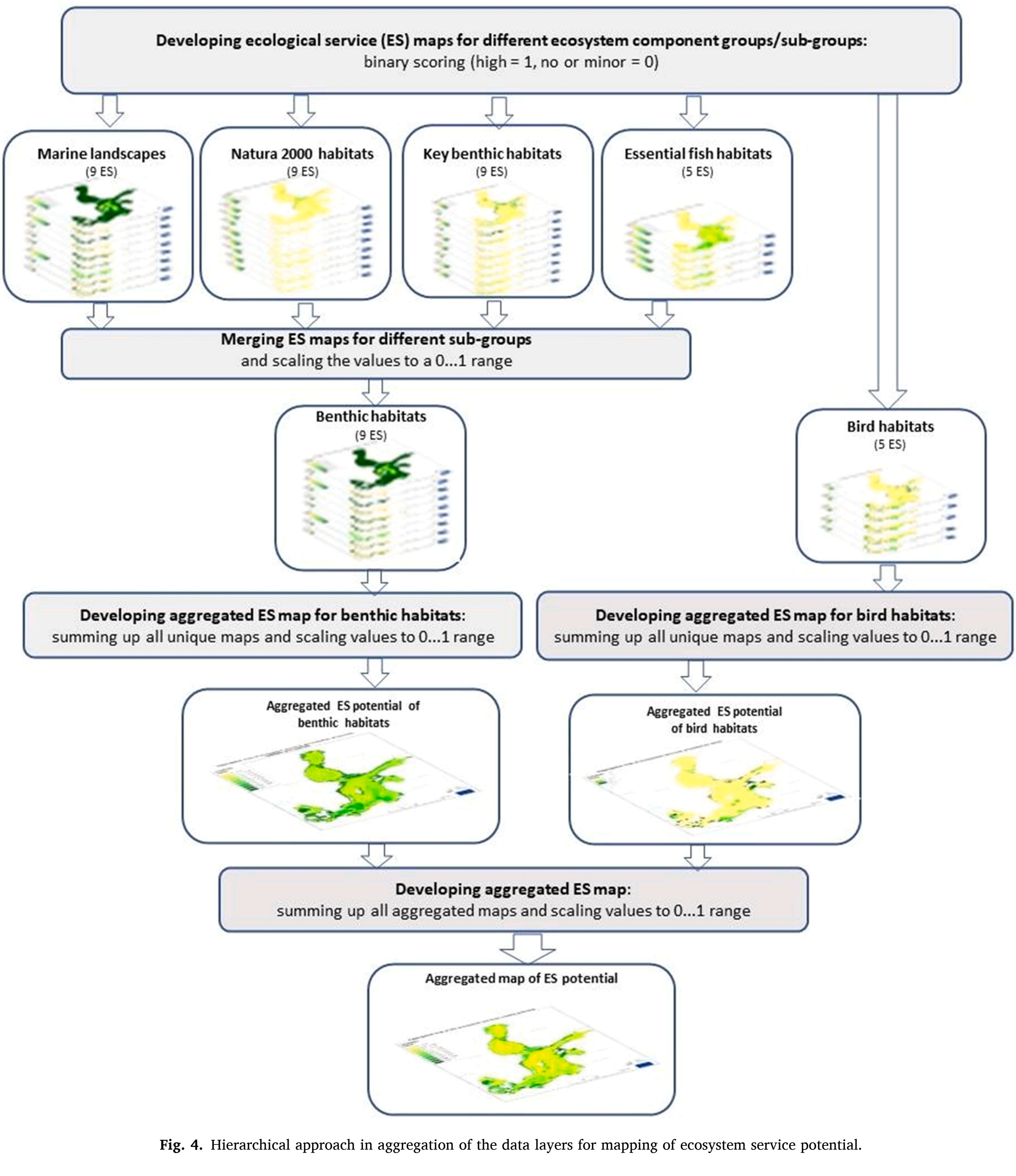

Fig. 4. Hierarchical approach in aggregation of the data layers for mapping of ecosystem service potential.

any inconsistencies or differences in the interpretation of particular services. During the discussion, scores were adjusted until consensus was reached. In general, there was a very high agreement among experts and the discussions centred around a few ecosystem components and services. For example, there were initially differing views on the link between nutrient filtration and different benthic habitats, caused by different interpretations of the extent of service supply. The consensus assessment was validated by consulting any experts who could not take part in the on-line meeting as well as by discussing the results at a following regional workshop also including external experts (Riga, December 2018).

The ecological value matrix also included 36 ecosystem components, and the six selected criteria for ecological values (Table S3 in supplementary material). The assessment was carried out by marine ecologists

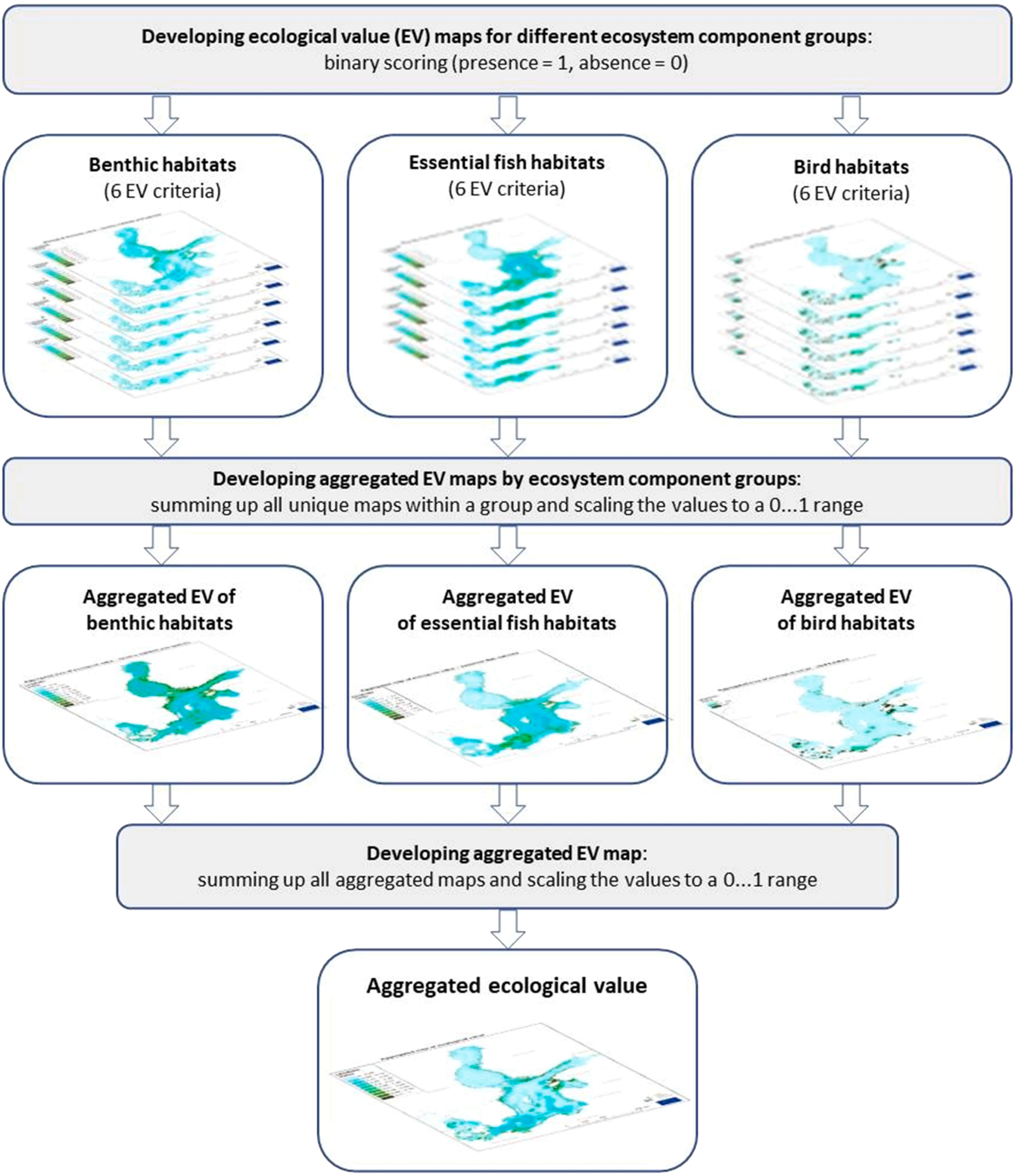

Fig. 5. Hierarchical approach in aggregation of the data layers for mapping of ecological value.

involved in the Pan Baltic Scope project with competencies in the particular field (e.g. benthic habitats, fish, birds and mammals). In case the ecosystem component was identified as relevant for that criterion, the value 1 was assigned, otherwise the value 0 was given, in alignment with the corresponding process for the ecosystem service matrix. The assessment results were discussed during the extended regional workshop in Riga (December 2018).

2.2.3. Testing of the marine GI mapping

The spatial distribution of the ecosystem service potential and ecological value was mapped using the Baltic Cumulative Assessment Tool, which is designed to compute the HELCOM Baltic Sea Impact Index (BSII), and was extended to incorporate the production of GI maps according to the method provided below [7,34].

2.2.3.1. Mapping areas of high ecosystem service potential. A hierarchical data aggregation approach was followed (see Fig. 4) to avoid over-representation of any ecosystem features that appeared in many data layers, hence, to prevent double counting of the same features to the same ecosystem service supply. In the applied data set, this was considered for the benthic habitats layers, where different sub-groups of data represented different aspects of benthic underwater habitats. Including all sub-groups was preferred over selecting only one of them, as the sub-groups were considered complementary to each other in order to achieve a comprehensive and coherent dataset at the Baltic regional scale.

The first step in data aggregation produced separate maps of each ecosystem service based on maps representing broad sub-groups of ecosystem components (i.e. marine landscapes, Natura 2000 habitats, key benthic species, essential fish habitats, and bird habitats). Based on the ecosystem services matrix, initial values in each grid cell of the resulting raster layers represented the sum for all ecosystem components which had been assigned score 1 for the concerned ecosystem service within that sub-group. These values were then scaled to a range 0–1 in the resulting maps. Second, maps of each ecosystem services at the level of two main ecosystem component groups (i.e. benthic habitats and birds) were produced. In effect, this step did not involve any changes to the bird habitats maps, while maps for the sub-groups representing benthic habitats were merged by their maximum values, so that the highest value from any of the subgroup maps was retained in each cell. The values in the resulting maps were again re-scaled to a 0–1 range. At the third step, an aggregated ecosystem services map for each group was produced by summing all ecosystem services maps, and rescaling. The final aggregated ecosystem services map was produced by adding together the aggregated ES maps for benthic habitats and bird habitats.

2.2.3.2. Mapping areas of high ecological value. To generate the maps of ecological value the following steps of the hierarchical data aggregation were applied (Fig. 5). First, separate maps for each ecological value criterion in relation to each of three selected ecosystem component groups (benthic habitats, essential fish habitats and bird habitats) were developed. This was achieved by summing up all ecosystem component layers for each group, selecting for each grid cell those layers which were assigned score 1 in the ecological value matrix for the given criterion. The obtained data layers were scaled to a 0–1 range in order to avoid over-representation of ecosystem groups represented by a higher number of ecosystem data layers. Second, aggregated ecological value maps for each ecosystem component group were produced by summing up the single criterion maps from the preceding step, and again scaling to a 0–1 range. The final aggregated ecological value map was produced by adding together the aggregated ecological value maps for benthic habitats, essential fish habitats and bird habitats.

2.2.3.3. Producing of the aggregated GI map. Finally, the aggregated GI map was produced by merging the aggregated map of the ecosystem service potential and the aggregated map of ecological value (each scaled to a range 0–1), to identify areas with high contribution to either (or both) of these. Obtained results were again normalised to range on a 0–1 scale, for the visualisation. However, to identify core areas for marine GI, a cut-off had to be determined, in order to delineate the areas of relatively highest value. The expert group suggested a threshold that results in 30 % of the Baltic Sea area being classified as marine GI, which corresponds to the conservation target proposed by the European Commission in the Biodiversity Strategy 2030.

3. Results

3.1. Aggregated results of mapping ecosystem service potential

The separate maps of ecosystem services representing different ecosystem component groups are presented in Figure S1 in supplementary material.

The aggregated map of ecosystem service potential provided by benthic habitats (Fig. 6a) shows generally higher values in coastal areas. According to the map, shallow coastal waters have high potential for ecosystem services in south-eastern Sweden, southern Finland including the Archipelago Sea, and the Estonian Archipelago Sea. In addition, the southern Baltic Proper, including the Danish belts and the Kattegat have a very high ecosystem services potential. The areas of high ecosystem service potential related to birds (Fig. 6b) are largely connected to the existing MPAs, with higher values appearing near the West Estonian islands, southern Finland as well as the southern Baltic Proper and the Danish belts. The map, however, reflects a current bias of data on bird habitats at the pan-Baltic scale, which were restricted to information from the standard forms for Natura 2000 sites on the Special Protection Areas (SPAs) with reported breeding and wintering areas for birds [35]. The aggregated map on the ecosystem service potential of all ecosystem component groups (Fig. 7) reflects the properties of the aggregated benthic habitat and bird maps, indicating the highest potential for ecosystem services observed in areas rich in islands, shallow bays and straits.

3.2. Results of mapping ecological value

The maps on aggregated ecological value of benthic habitats, fish habitats and bird habitats are presented in Fig. 8, while maps for each of the six ecological value criteria are presented separately for each of these ecosystem component groups in Figure S2 supplementary material.

The mapping of areas with high ecological values shows that benthic habitats have relatively higher values in more shallow archipelago areas as well as in open sea shallows of the Baltic Proper and the Bothnian Sea, and prominently so along the south-eastern coast of Sweden (Baltic Proper), south-western and south-eastern coast of Finland (Bothnian Sea, Archipelago Sea, Gulf of Finland), and the entire coast of Estonia (Fig. 8a). These coastal areas are also characterised by protected habitats of EU importance (reefs (1170), sandbanks (1110), Boreal Baltic islets and small islands (1620) and large shallow inlets and bays (1160). Similarly, the southern Baltic, near coasts of Germany, Poland and Latvia have relatively high values represented by reefs (1170), sandbanks (1110) habitats and estuaries (1130). Although these areas have relatively low areal extent, they are likely to have utmost importance for the functioning of local ecosystems.

As for ecosystem service potential mapping, areas identified as being of high ecological value of birds strongly overlap with the delineations of existing MPFish habitats of high ecological value partly overlap with high-value areas for benthic habitats (Fig. 8b). Coastal areas are essential for the reproduction of both marine fish species such as herring and Baltic flounder, as well as for freshwater species such as perch and pikeperch. Potential herring recruitment areas extend practically all over the Baltic Sea, while the recruitment of Baltic flounder is excluded from the Bothnian Sea and the Bothnian Bay due to low salinity. Perch

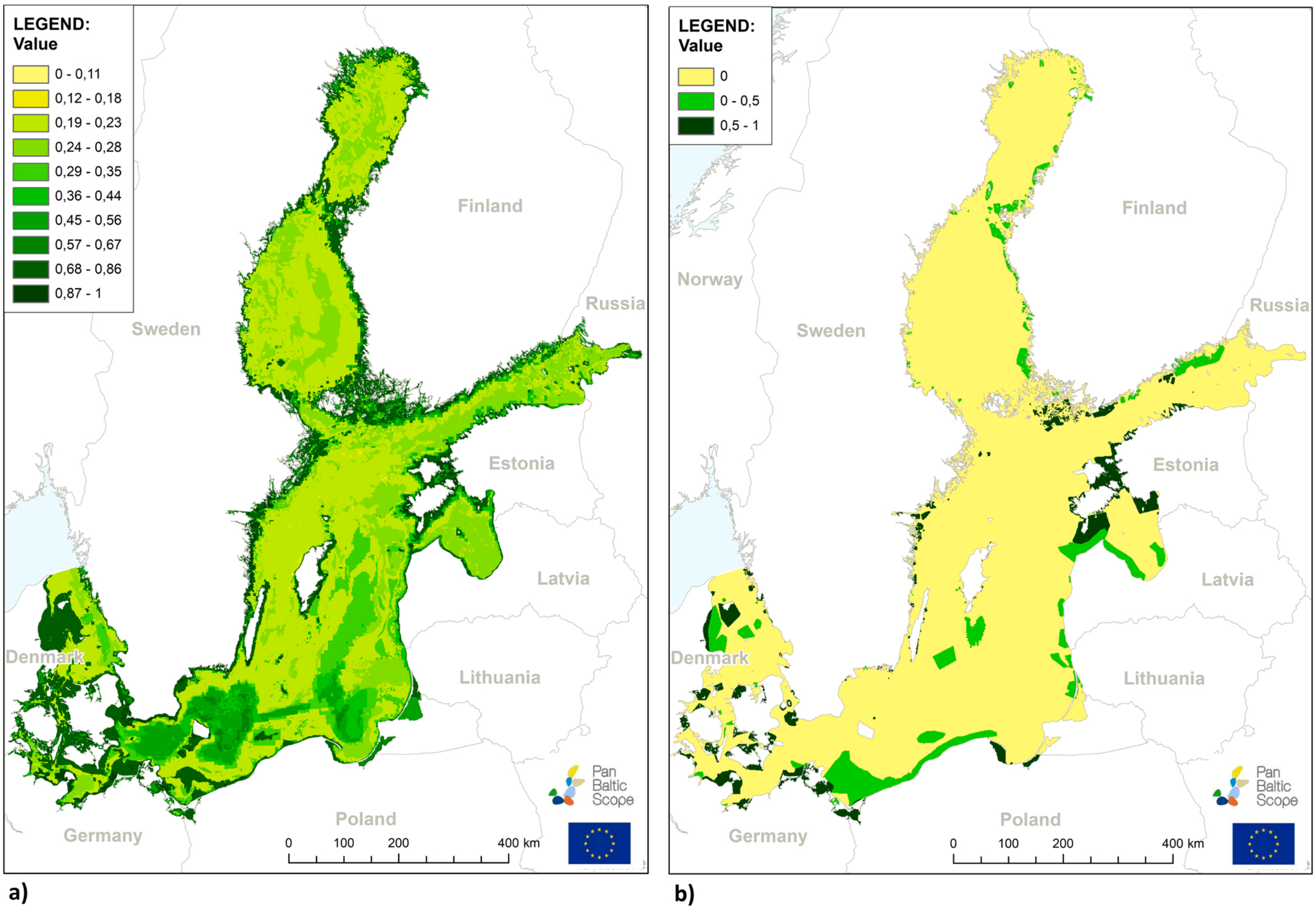

Fig. 6. Aggregate maps of ecosystem service potential provided by the broad groups of ecosystem components: a) benthic habitats (including essential fish habitats); b) bird habitats.

and pikeperch spawn in freshwater tributaries throughout the region and with recruitment areas extending to the coastal zone in most of the region, provided salinity is not too high (both species) and climate conditions allow (pikeperch). In addition, deeper parts of the Southern Baltic Proper (in particular the Bornholm Basin) are essential for spawning of cod, European flounder and sprat. The extent of potential spawning habitats in the open sea is currently clearly restricted by poor oxygen conditions as a result of eutrophication, which prevented the identification of areas of high ecological value in the Gotland basin. As (Fig. 8c). This was caused by limited availability of bird occurrence data at the time when the applied data layers were developed.

The aggregated map of the ecological value including the three broad ecosystem groups (benthic, fish and birds habitats) indicates that the main areas of highest value are concentrated around the West Estonian islands as well as in the coastal waters of the Southern part of Finland and south-eastern part of Sweden (Fig. 9). These areas cover a wide range of environmental gradients (e.g. salinity, temperature, nutrient availability, exposure, bottom characteristics) and thereby host a diverse range of benthic habitats and support a high number of fish and local bird species. Moreover, the archipelago is also well known as an important bird migration and wintering area (e.g. [44]).

3.3. Aggregated map of marine GI

The final map of marine GI (Fig. 10), formed by merging the aggregated ecosystem services and ecological value maps (Figs. 7, 9), highlights the most valuable areas from either of these aspects, or both. Following Liquete et al. [47], the area containing the 30 % highest values (marked in dark green colour) are identified as core areas for GI, while other areas with relatively high values (lighter green) indicate a subsidiary GI network. A comparison of the obtained marine GI map with the existing distribution of marine protected areas (MPA) in the region [35] shows that many of the identified core GI areas are already included in the MPA network; however, there are also some spatial divides. For example, several areas identified in GI based on their importance for fish are not included.

The current MPA network in the Baltic Sea covers 12 % of its area [35]. The identified GI core areas as well as subsidiary GI areas could indicate potential sites to be investigated for increasing the coverage of protected areas at least to 30 %, as stated in the EU Biodiversity Strategy 2030. This map could also be used to guide the adjustment of sea use conditions in maritime spatial plans (MSP) in order to improve the level of connectivity between MPAs and support ecosystem based management.

4. Discussion

4.1. Applying the GI concept to the marine environment

This paper presents a concept for the mapping of marine GI and tests the approach at the pan-Baltic scale. The approach allows to aggregate various spatial data layers on nature values in order to identify areas of high ecological value and ecosystem service supply potential, thereby forming a basis for transparent, data-driven mapping of marine GI. As such, the current study is a pioneering attempt to apply a systematic GI concept at the scale of a large marine ecosystem. A huge body of

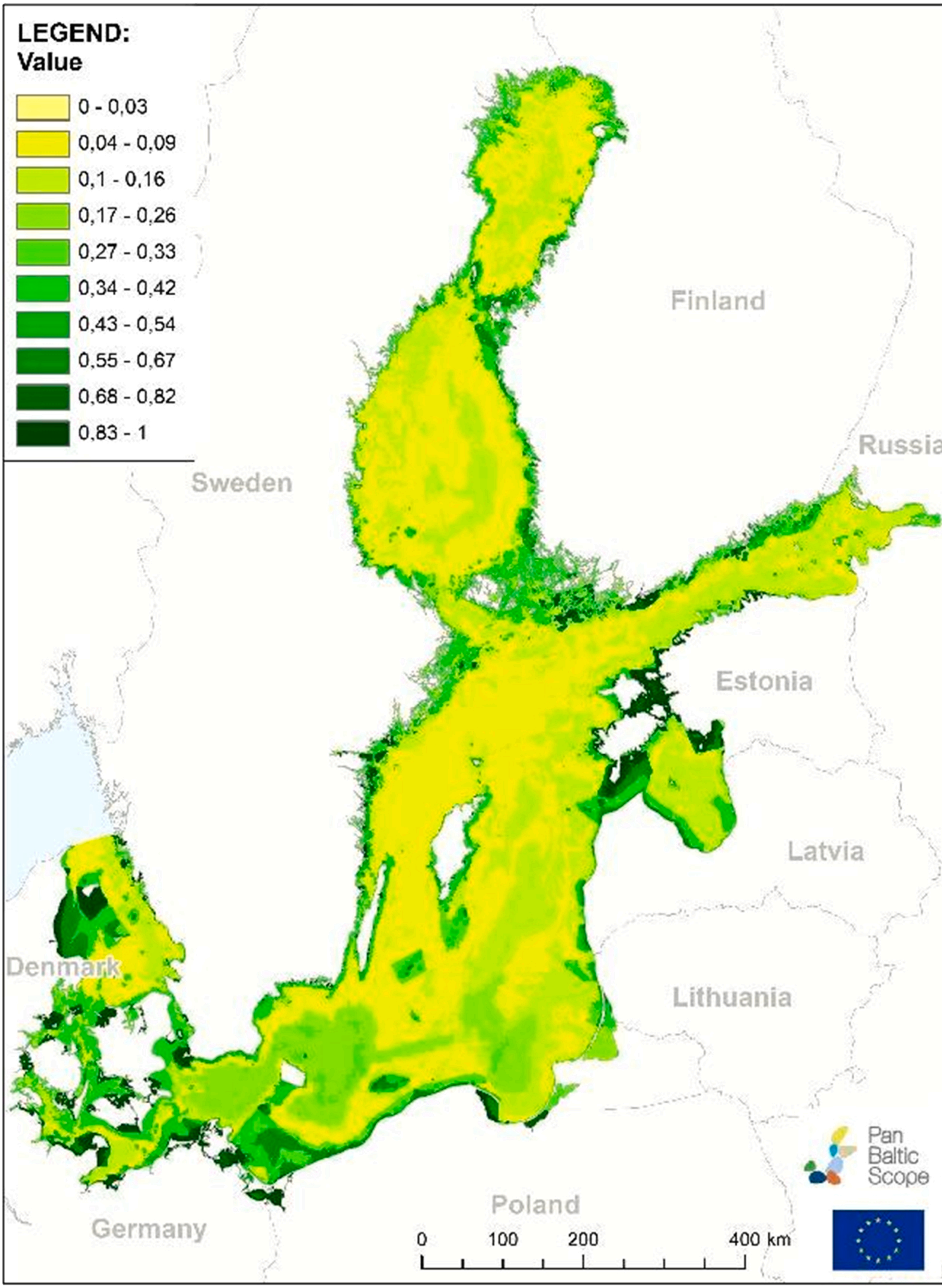

Fig. 7. The aggregated maps of ecological value of all ecosystem component groups.

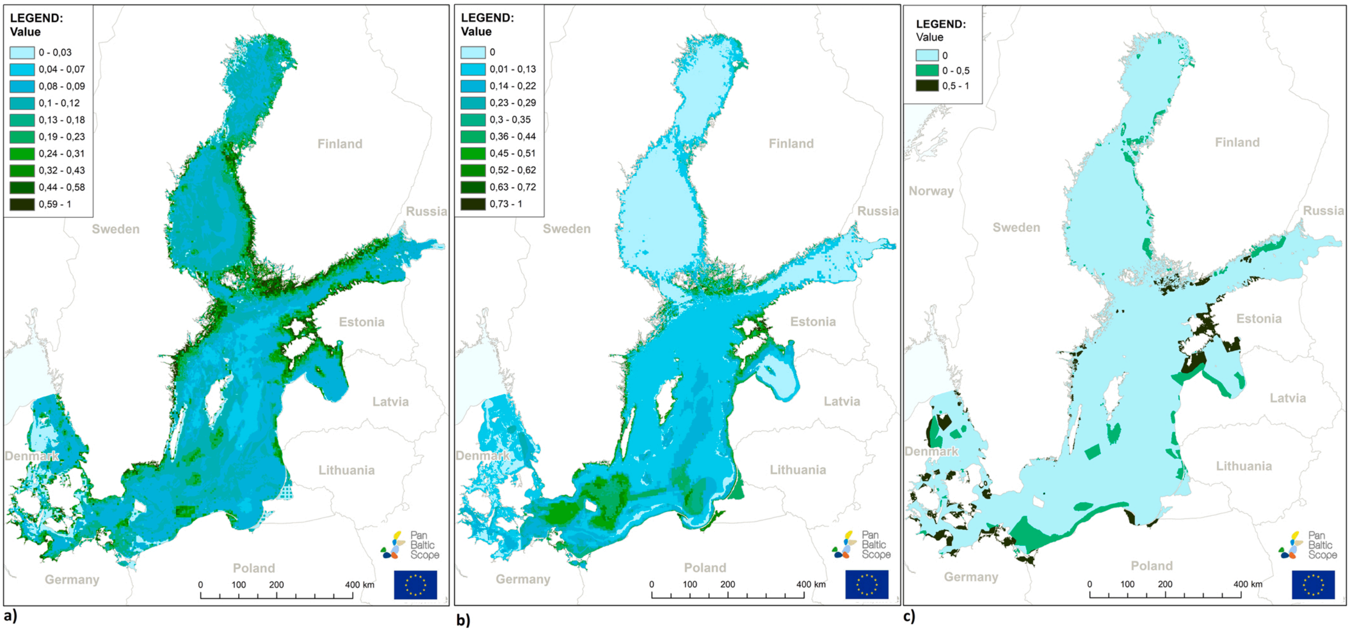

Fig. 8. Aggregate maps of ecological value of all broad ecosystem component groups: a) benthic habitats; b) fish; c) birds.

previous research on the mapping of marine ecosystem features and ecosystem services over the world has provided results based on a variety of methods and levels of precision. Recent developments in the Baltic Sea region were summarised by Inácio et al. [39], who showed that out of 34 peer-reviewed articles on ecosystem service mapping published between 2000 and 2020, none was providing a comprehensive set of ecosystem service maps for the entire sea basin. Even less experience has so far been gained on aggregating spatial data on nature values and ecosystem service supply for the mapping of marine GI. However, a novel approach in this direction was demonstrated by Barbosa et al. [4], through transboundary Green and Blue Infrastructure mapping within the Intercontinental Biosphere Reserve of the Mediterranean in Andalusia (Spain) and Morocco, which covers both marine and terrestrial areas. The advancement presented in the current pan-Baltic study builds on the integration of existing knowledge on the Baltic Sea ecosystem and coherent regional datasets at the scale of the entire marine region. The presented approach provides a basis for further in-depth analysis of the functioning and connectivity of marine ecosystems, as well as to support cross-border ecosystem-based management of marine waters.

Regional marine GI mapping is expected to enhance the ecosystem-based approach in MSP by improving the knowledge base about the roles and connectedness of different ecosystem components, and by supporting the development of cross-border spatial planning solutions. Application of the GI concept in MSP can particularly improve the connectivity and functioning of MPA networks by avoiding habitat fragmentation or blockage of migration routes in ecologically valuable landscapes. Ultimately, GI mapping contributes to a holistic way of the functioning of ecosystems and delivers this knowledge in a meaningful and understandable way for policy and decision makers.

The developed interpretation of marine GI is based on definition provided by the European Commission [23], where GI is described as a strategically planned network of natural or semi-natural areas that provides a wide range of ecosystem services. Estreguil et al. [20] suggested that GI mapping can be based on two complementary approaches – physical mapping of GI-forming components (including protected areas or other valuable nature areas) and mapping of areas delivering multiple ecosystem services. In the presented approach a key source of data to depict valuable nature areas was pan-Baltic maps of marine ecosystem components, instead of, for example, only relying on existing networks of MPAs. This approach allows to base the GI assessment on a broad range of marine ecosystem characteristics (e.g. structural and functional elements, rare and sensitive species, or other features that can define the functioning and resilience of marine ecosystems), as well as to include the most recent reliable regional datasets. In contrast, although the MPA network includes some core areas of the GI, it is designated for the protection of a limited set of species and habitats. More importantly, the selection of MPAs is often restricted by knowledge and data available at the time of site selection as well as priorities in legislation, and therefore are rarely sufficient to conduct appropriate functional or ecological interpretation of ecosystems.

The presented approach is particularly well suited for regional application due to its simplicity, transparency, and potential to make use of data sets of different types. In the Baltic Sea region, regionally agreed spatial data sets are openly provided by HELCOM over its Maps and Data Services. The regional GI mapping allows to create a coherent transboundary view on the location of valuable nature assets and ES supply at the marine regional scale. Such results cannot be reached e.g. by simply compiling different national GI maps, as different countries typically use different and mostly incompatible methodologies.

However, the approach can be practically applied at any scale for which coherent data sets are available with suitable precision and resolution. For example, the regional evaluation could be complemented by more in-depth analyses at the sub-regional scale. This could be needed, as the regional data might not always be of sufficient detail to support management decisions on the national or local level. In some cases, more detailed GI mapping might additionally be required, e.g. for aspects that are not supported by spatial data. Examples of approaches, which could be aligned nationally, are the 'MOSAIC' method for local GI mapping which has been developed in Sweden by the Swedish Agency for Marine and Water Management [31]. Swedish MSP has also developed and considered GI based on best available data and included areas of high nature values for particular consideration in the plans. In Latvia, national scale mapping of marine ecosystem services was carried out based on an assessment of the relative importance of ecosystem components and functions to ecosystem service supply [2]. Importantly, the presented approach is easily adaptable to incorporate new information, when better and more detailed maps at the pan-Baltic scale become available over time.

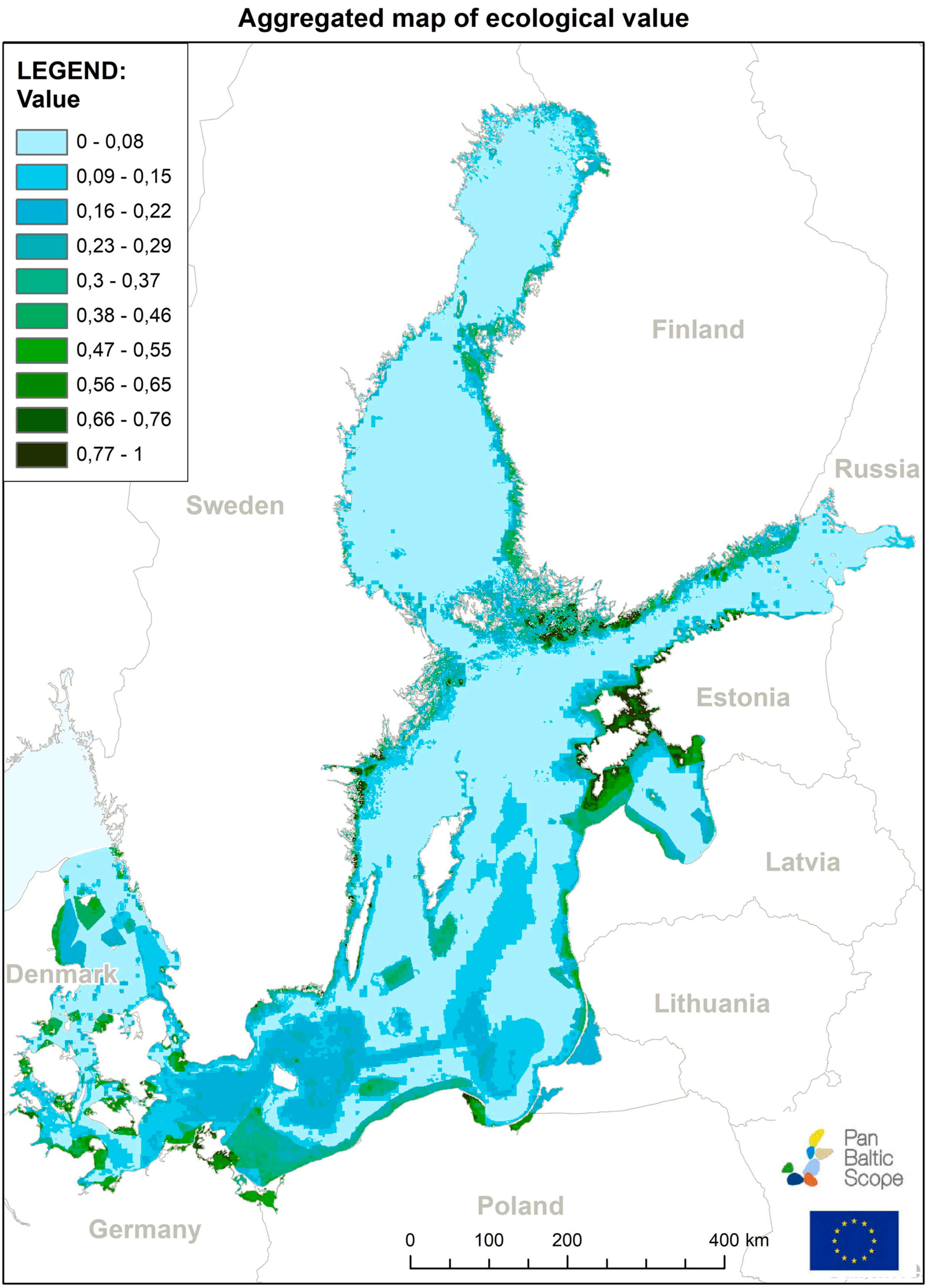

Fig. 9. The aggregated map of ecological value of all ecosystem component groups.

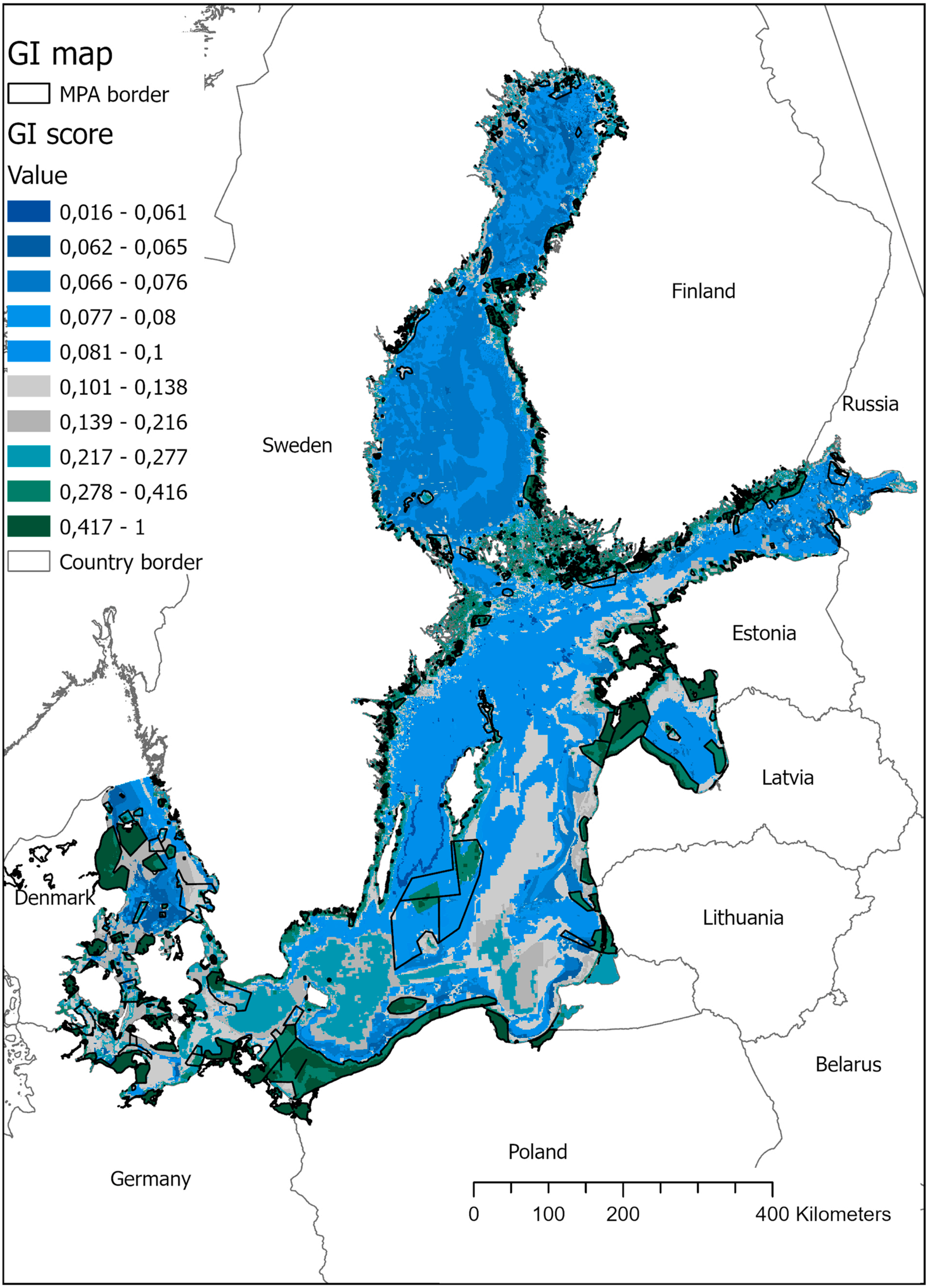

Fig. 10. Final aggregated map of marine green infrastructure shown together with the delineation of existing MPAs in the Baltic Sea. Green colour indicates the top 30 % areas of highest ecological value and ecosystem service potential in the region (the most valuable areas are presented as dark green, other highly valuable areas as lighter green).

4.2. Contribution of the GI concept to MSP

Marine GI mapping is of direct relevance to support implementation of the ecosystem-based approach (EBA) in MSP. Mapping and consideration of marine GI relates to several key elements of EBA, as defined for the Baltic Sea in regional guidelines for the implementation of ecosystem-based approach in MSP, published in 2015 by the HELCOM-VASAB MSP working group [36]. It can contribute to a knowledge base and relational understanding of links between ecological and socio-economic systems, as well as support implementation of precautionary principle, mitigation, participation, and communication [59].

In practice the results of marine GI mapping can feed into different stages of the MSP process, including: i) the scoping stage - helping to define the key objectives of the MSP with respect to nature assets essential for maintaining marine ecosystem health and human well-being; ii) developing stage - explicitly considering aspects highlighted by the GI mapping in national MSP solutions to avoid negative impacts of marine developments on ecologically essential areas; iii) assessment stage - using GI mapping in the assessment of alternative scenarios in Strategic Environmental Assessments of the MSP, to assess potential single as well as cumulative impacts of the plan on marine ecosystem values and ecosystem service supply; iv) implementation stage – applying GI maps in environmental impact assessments of investment projects; as well as v) follow-up stage – monitoring changes in ecosystem conditions in marine GI areas, and the impacts of MSP and other policy actions [55].

Non-binding requirements for the preservation of GI might be easier to integrate in MSPs with advisory character (e.g. in Sweden). In the case of legally binding MSPs (e.g. in Germany) the legal regime, data requirements and stakeholder processes are more strict in the weighing and planning process. Here, GI mapping could support planning designations for protection and enhancement of the marine environment by highlighting areas for consideration.

Regional GI mapping can, here, enhance cross-border coordination of sustainable planning solutions. The regional GI map can help identify core areas from the sea basin perspective, for which MSP solutions are required at national or local level, thus supporting implementation of subsidiarity and coherence principle. Finally, the GI concept can help communicate the structural and functional complexity of ecosystems to various stakeholders and sectors, and thereby enable a data-driven dialogue between different interest groups on potentials and limitations for the use of the sea.

4.3. Contribution of GI concept for enhancement of MPA network

One of the primary functions of marine GI is to support the maintenance of biodiversity. Protected areas, in the EU including the Natura 2000 network, form core areas of GI in this regard. Nevertheless, GI extends beyond designated protected areas, hence ensuring the connectivity and functionality of the entire ecological network. Hence, mapping of marine GI may contribute to conservation both by identifying areas of high ecological value, which might qualify for full protection, and by indicating areas which may be relevant to consider for other types of protection (such as potential OECMs), thereby also enabling to improve the connectivity of the MPA network. Marine GI mapping results can also help to recognise areas where certain restrictions to or regulation of human activities could be warranted. For example, MSP solutions could aim to avoid habitat fragmentation or blockage of migration routes in ecologically valuable landscapes, as also demonstrated by Barbosa et al. [4], who applied Green and Blue Infrastructure design to support conservation management of freshwater, coastal and marine ecosystems.

4.4. Limitations and further research needs

The credibility of the obtained GI mapping results mostly depends on data availability and the accuracy of applied data sets, which is still insufficient in many marine regions. In the present study, some marine ecosystem components had to be omitted due to issues with data availability or data quality. The presented approach, however, suggests a hierarchical and transparent way of making use of existing available datasets under such preconditions. Another data related limitation is that the outcomes of the mapping are largely influenced by the indicators, and methods, used to identify ecological values and ecosystem service supply. Thus, a clear documentation of metadata and the detailed steps to calculate GI are prerequisites for quality assurance of any GI assessments.

Identified limitations to the presented approach, which should be addressed in future studies on marine GI, include:

1. The connectivity of ecological networks is an essential parameter for assessment of GI [47], which was not addressed in the present GI mapping. Connectivity analysis can be either structural (based on the characteristics of landscape/seascape) or species-specific (linked to environmental conditions that enable species to spread between sites). In the Baltic Sea, the connectivity aspect is commonly recognised for highly mobile species such as fish, birds and mammals, while it is more often neglected for benthic species groups, e.g. macroalgae, bivalves and crustaceans, which are essential components to describe functional connectivity in marine ecosystems. This is mostly due to large knowledge gaps on the autecology of foundation and keystone species, however, the general knowledge base is growing [3,8,41,45].
2. The presented study assesses the potential of ecosystem services based on the occurrence of marine ecosystem components. However, the GI mapping should ideally also encompass information on areal densities of species, as well as species-specific variability in the intensity of functions and processes underlying the concerned ecosystem service supply. The latter is often related to variability in environmental conditions that define the functioning of ecosystems, thereby resulting in regional specificities of ES supply [15]. Hence, the here applied qualitative, expert knowledge-based approach limits the reliability of the results to certain extent. Further developed approaches to map marine ecosystem service supply should be more based on quantitative approaches, including various modelling techniques as suggested by Inácio et al. [39], to link available marine monitoring data with indicators used for quantifying ecosystem services.
3. A related aspect is to consider changes in ecosystem services supply, and potentially in ecological value, due to variability in environmental and habitat conditions. A truly sustainable approach for GI mapping should address potential variability in GI due to changes in pressures from human uses, climate change or other factors [14,15]. It was not realistic to assess the condition of mapped ecosystem components at the spatial resolution of the current study, or using expert judgement only. In order to include information on the expected condition of nature values, the presented approach would need to be further integrated with data on the spatial extents and intensities of different human pressures, the expected effects of each of these pressures on different nature values, and these analyses should ideally also be followed by monitoring to validate the results. Ultimately, marine GI mapping results could be linked to cumulative impact assessment as was piloted by Bergström et al. [7]. Several spatial decision support systems are being developed that have a capability of performing cumulative impact analyses [17] and synergies could be searched for developments in this direction. Another limiting factor is variability in data coverage, which entails a risk of both underestimating and overestimating the relative importance of different impacts at a more local scale. At the regional scale, human pressures affect biota everywhere in the Baltic Sea, but are the most intense in the southwestern parts, near the coastline and close to urban areas [33], indicating that these areas as priorities for

developing a closer understanding of cumulative impacts from human pressures on GI.

4. Assessment of GI functionality should incorporate relationships between ecosystem service supply and demand. The value of services are not constant; for example, recreational services can be higher near densely populated areas [64]. The value of a service may also vary depending on its availability in ecosystem; in case the ecosystem component is rare and important, this could be translated into a higher value, although in such a case the possibility of changes in demand over time would also need to be considered.
5. Further discussion would be required on criteria for identifying the ecological value of ecosystem components. The presented study applied the criteria used for identification of ecologically or biologically significant marine areas (EBSAs) developed within the framework of the UN Convention on Biological Diversity (CBD). However, depending on local conditions or conservation objectives, there might be more relevant criteria to include. Here, different network analyses could be promising, to study changes in ecological processes and determine underlying actors (e.g. species, habitats) and mechanisms of changes [62,67]. However, such analyses are very knowledge and data-demanding and not yet feasible to be carried out for a wide range of ecosystem components at the pan-Baltic scale.

5. Conclusions

A pioneering application of the green (or blue) infrastructure concept in the marine realm was tested at the scale of a large marine region. The proposed methodology for marine GI mapping includes qualitative valuation of marine ecosystem components with respect to their relevance for selected ecological value criteria and ecosystem services, a hierarchical aggregation approach to the production of maps on ecological value and ecosystem service potential, respectively, and finally - merging of these to highlight core areas for marine GI.

The mapping results indicate that highest ecological value and ecosystem service potential are often observed in areas rich in islands, shallow bays and straits, which represent a wide range of environmental gradients hosting a diverse range of benthic habitats as well as bird and fish species.

Mapping of marine GI has great potential for enhancing the ecosystem-based approach in MSP. It can also identify potential areas of high ecological and ecosystem service value, which could contribute to increased connectivity of the MPA network or be identified as other effective area-based conservation measures, supporting implementation of the EU Biodiversity Strategy 2030 target to protect at least 30 % of the sea. It is suggested that further development of the marine GI concept be supported by practical case studies on its operationalisation in MSP, environmental management, and nature conservation.

The study demonstrates marine GI mapping in the Baltic Sea region, which is relatively rich in coherent spatial data on the distribution of ecosystem components across the entire region. The transferability of the presented approach to other marine regions, in Europe or beyond, depends on the availability of harmonised spatial datasets at the addressed scale. Enhanced and coordinated transboundary mapping of nature values would allow to export the study method to other marine regions, as well, and ultimately carry out a similar assessment at the pan-European scale.

CRediT authorship contribution statement

Anda Ruskule: Conceptualization, Methodology, Writing – Original draft. **Jonne Kotta**: Conceptualization, Methodology, Writing – review & editing. **Champa Rani Saha**: Visualization, Writing – original draft. **Philipp Arndt**: Conceptualization, Writing – review & editing. **Didzis Ustups**: Conceptualization, Investigation. **Solvita Strāķe**: Conceptualization. **Lena Bergström**: Conceptualization, Methodology, Writing – review & editing, Visualization.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2022.105374.

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