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Seabed landscapes of the Baltic Sea: Geological characterization of the seabed environment with spatial analysis techniques

Anu Kaskela

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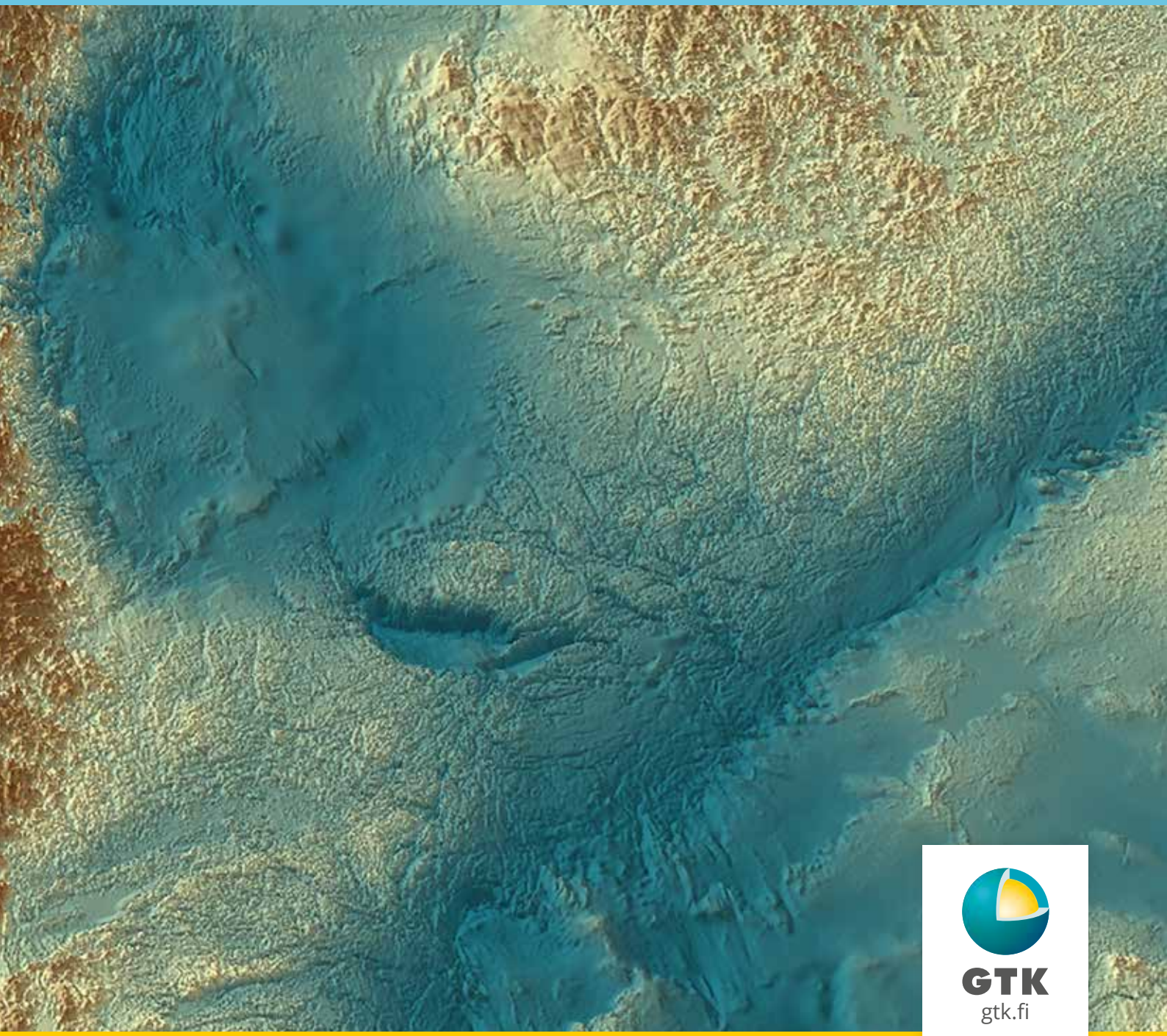

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Geological characterization of the seabed environment with spatial analysis techniques

by

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ACADEMIC DISSERTATION

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ABSTRACT

Marine ecosystems provide a wide range of ecosystem services to human society, including supporting, regulating, cultural, and provisioning services. The concept of Blue Growth even considers marine areas as potential drivers of the economy. However, despite the long tradition of ocean exploration, the realization of Blue Growth and effective marine spatial planning often suffer from incomplete and scattered marine data over large areas.

This dissertation presents a GIS-based approach to analyzing and characterizing the geologic seabed environment of the Baltic Sea. It combines scattered geospatial data to produce spatial representations of the Baltic Sea in terms of the seabed geomorphic features, marine landscapes, and geodiversity. The broad scales of the analyses reflect the scale of the available datasets and the needs of transnational ecosystem-based management.

Spatial analysis techniques enabled the identification of coherent geomorphic features and quantification of geodiversity patterns over the entire Baltic Sea region, within the limits of the input data resolution. Based on the results, the overall geological landscape of the Baltic Sea is characterized by plains and basins. Other geomorphic features, such as elevations and valleys, are characteristic of certain sub-regions. The seabed geodiversity generally increases from south to north and from the open sea to areas with a high shore density. The crystalline bedrock areas provide more diverse seabed environments than the sedimentary rock areas. Archipelagos, in particular, stand out as seabed areas with high geodiversity. The results underline the significance of the ongoing processes (erosion, sediment transport, and accumulation), the basement rock type, past glaciations, and certain geological events during the last deglaciation in shaping the seabed environment of the Baltic Sea.

The dissertation presents new evidence that the geodiversity of the seafloor influences the distribution of the zoobenthic assemblages of the eastern Gulf of Finland. It is suggested that the high geodiversity and archipelago gradient could directly influence benthic assemblages and biodiversity by providing a multitude of habitats and indirectly by channeling water movement. Additionally, the potential key habitats, rocky reefs, were mapped with good accuracy in seabed areas with limited data, and the features were also recognized to have ecological value. These spatial datasets provide valuable background material for more detailed studies on the rocky reefs and the archipelago areas, as well as for monitoring their status.

The study provides spatial information on the seabed characteristics of the Baltic Sea for scientists, marine spatial planners, and managers. The results emphasize that geodiversity should be acknowledged in the ecosystem-based management of marine areas, because it has intrinsic value, it provides several abiotic ecosystem services, and it is associated with the biodiversity and long-term conservation of the marine environment.

Keywords: marine geology, geodiversity, spatial analysis, geomorphology, seabed, marine landscape, Baltic Sea

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ORIGINAL PUBLICATIONS

ABBREVIATIONS

BPI	Bathymetric position index
BTM	Benthic terrain modeler
EMODnet	European Marine Observation and Data Network
ESBM	Ecosystem-based management
GIA	Glacial isostatic adjustment
GIS	Geographic information system
ICES	International Council for the Exploration of the Sea
LGM	Last Glacial Maximum
LiDAR	Light detection and ranging
MBES	Multibeam echosounder
MPA	Marine protected area
MSP	Marine spatial planning
SSS	Side scan sonar

LIST OF ORIGINAL PUBLICATIONS

This dissertation is based on the material and results originally presented in the following papers, which are referred to in the text by their Roman numerals. The original articles I-IV have been reprinted with the kind permission of the copyright holder, Elsevier Ltd.

I Kaskela, A. M., Kotilainen, A. T., Al-Hamdani, Z., Leth, J. & Reker, J. 2012. Seabed geomorphic features in a glaciated shelf of the Baltic Sea. Estuarine, Coastal and Shelf Science 100, 150–161. ISSN 0272-7714, http://dx.doi.org/10.1016/j.ecss.2012.01.008.

II Kaskela, A. M., Rousi, H., Ronkainen, M., Orlova, M., Babin, A., Gogoberidze, G., Kostamo, K., Kotilainen, A. T., Neevin, I., Ryabchuk, D., Sergeev, A. & Zhamoida, V. 2017. Linkages between benthic assemblages and physical environmental factors: The role of geodiversity in Eastern Gulf of Finland ecosystems. Continental Shelf Research 142, 1-13. ISSN 0278-4343, https://doi.org/10.1016/j.csr.2017.05.013.

III Kaskela, A. M. & Kotilainen, A.T. 2017. Seabed geodiversity in a glaciated shelf area, the Baltic Sea. Geomorphology 295, 419-435. ISSN 0169-555X, http://dx.doi.org/10.1016/j.geomorph.2017.07.014.

IV Rinne, H., Kaskela, A., Downie, A.-L., Tolvanen, H., von Numers, M. & Mattila, J. 2014. Predicting the occurrence of rocky reefs in a heterogeneous archipelago area with limited data. Estuarine, Coastal and Shelf Science 138, 90-100. ISSN 0272-7714, http://dx.doi.org/10.1016/j.ecss.2013.12.025.

THE AUTHOR'S CONTRIBUTIONS

I A. Kaskela had the main responsibility for Paper I, with the support of Prof. A. Kotilainen. A. Kaskela planned the study with the co-authors, participated in compiling and harmonizing the background data and modeled the seabed structures. A. Kaskela wrote the paper and prepared the figures, which were commented on by the co-authors.

II A. Kaskela designed the study for Paper II with the co-authors. She conducted the fieldwork, data production, harmonization, and analysis together with the co-authors. Statistical analyses were performed by H. Rousi, M. Orlova, and M. Ronkainen. Paper II was jointly written by A. Kaskela and H. Rousi, Kaskela being responsible for the geological part and Rousi for the biological part, and the manuscript was commented on by the co-authors.

III A. Kaskela had the main responsibility for planning and carrying out the study for Paper III. A. Kaskela wrote the manuscript, with contributions from A. Kotilainen.

IV A. Kaskela had the main responsibility for the processing of geological data for Paper IV. Kaskela performed the seabed structure analysis and contributed to writing and illustrating the paper. Paper IV is also a part of the PhD dissertation of H. Rinne.

1 INTRODUCTION

The Blue Marble is an iconic picture of Earth taken in 1972 by a crew member of the Apollo 17 spacecraft. The picture reveals Earth as different from other planets. It shows a planet with a complex system of air, water, and land (Wuebbles 2012). Earth is the only planet known to support life. The blue expanse of the oceans makes Earth special. If Earth had orbited closer to the Sun, water would had evaporated, and if any further away, water would had frozen over the course of geologic time (e.g., Hart 1978, 1979, Kasting et al. 1993). The existence of liquid water is often considered as a prerequisite for the origin of life.

Throughout the geological history of Earth, the oceans have changed their size and shape. The current state, with five oceans (the Arctic, Atlantic, Pacific, Indian, and Southern Ocean), dates back about 175 million years to the Jurassic period. Today, more than 70% of Earth's terrain is overlain by seawater: 60% of the Northern and 80% of the Southern Hemisphere. In the future, it is likely that the oceans will cover even larger areas. Global sea level has reportedly risen throughout the 20th century. On the basis of the current climate change scenarios, sea level is estimated to rise due to the thermal expansion of the water and melting of the ice sheets by about 0.5–1 m by 2100 (Church et al. 2013). At present, marine areas, and especially the coastal systems, deliver several ecosystem services, whose economic value has been estimated to amount to more than half of the average global value of annual ecosystem services (Costanza et al. 1997). However, present knowledge of the marine environment is often insufficient for sustainable management. We lack detailed information on seafloor features, and, for example, only about 10–15% of the seafloor has actually been surveyed with oceanographic vessels at 1.5–2 min resolution (Wessel & Chandler 2011).

This dissertation presents an integrated approach to analyzing and characterizing the seabed environment with spatial analysis by combining geological, environmental, and ecological data. Part of this data has been collected and harmonized from already existing sources. Seabed substrates, geomorphological features, and geodiversity provide several abiotic ecosystem services and have intrinsic value. Below, the reasons underlying the ecosystem-based approach to maritime spatial planning are briefly discussed, a few (data) related problems are introduced, and an overview of how marine geological characteristics contribute to maintaining a healthy marine ecosystem is provided.

1.1 Blue Growth

Blue Growth or the Blue Economy is a recent concept adopted by policy makers (e.g., European Commission 2012, UNCSIDS 2014). The concept builds on welfare and resources that society can potentially gain from marine areas. For instance, the European Commission (2014) has regarded marine areas as drivers for the European economy, because they have considerable potential for innovation, jobs, and growth. Blue Growth includes aquaculture, seabed mining, coastal tourism, marine energy, and marine biotechnology.

While interest in using marine resources is growing, all marine areas are already affected by human influence (Halpern et al. 2008). A large proportion of the ocean ecosystem is strongly influenced by multiple drivers, and human impacts have increased in recent years (Halpern et al. 2008, 2015). The anthropogenic influence on marine ecosystems derives, for example, from overfishing, modification of seabed habitats, land-based pollution, climate change, invasive species, and transport accidents such as oil spills (e.g., de Groot 1984, Jackson et al. 2001, Bax et

al. 2003, Halpern et al. 2008, Molnar et al. 2008, Doney et al. 2012, Coughlan et al. 2015, Helle et al. 2016). Continental shelves are among the marine areas with the highest predicted cumulative human impact, although they cover less than 10% of marine environments (Halpern et al. 2008). Shallow coastal waters, where sunlight is able to penetrate and rivers transport nutrients, are among the richest in marine life in terms of their biomass (Wei et al. 2010). Furthermore, a large proportion of the human population, e.g., almost half of Europeans lives in coastal areas with a marine influence (Douvere 2008). According to Gray (1997), the best way to conserve marine diversity is to conserve habitat and landscape diversity in coastal areas.

In order to maintain and potentially amend marine ecosystems, Blue Growth includes the concept of sustainable development, which aims at meeting the needs of the present without compromising the ability of future generations to meet their needs (WCED 1987).

1.2 Ecosystem-based management of marine areas

How are we able to acquire further economic growth from marine areas and simultaneously support sustainable development? Marine spatial planning (MSP) seeks to address this question. MSP is a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that are usually specified through a political process (Ehler & Douvere 2009). It aims to take into account future interests as well as the current situation.

The environmental problems mentioned in the previous chapter partly result from the fragmentation of ocean governance systems. In recent years, marine policy has shifted from the management of individual sectoral activities towards ecosystem-based management (ESBM) (Crowder & Norse 2008). ESBM is as an interdisciplinary approach to MSP, which balances ecological, social, and governance principles at appropriate temporal and spatial scales in a distinct geographical area to achieve the sustainable use of the resources (Long et al. 2015). It emphasizes spaces instead of (single) species, and focuses on conserving the ecosystem structure, functioning, and key processes. The process has developed from the conservation efforts of the Great Barrier Reef more than 30 years ago into a global initiative, which is implemented in several sea areas from Europe and America to Asia (e.g., Day 2002, Li 2006, European Parliament 2008).

To be able to implement ESBM, one should know the marine ecosystem in question. For instance, the spatial zonation of activities and the establishment of interconnected networks of marine protected areas (MPAs) call for the inclusion of a spatial element in management (e.g., Rinne 2014). In many cases, the realization of Blue Growth and ESBM suffer from incomplete and scattered marine data, although there has been progress in data compilation in recent years (e.g., Ruckelshaus et al. 2008, European Commission 2014, Shucksmith et al. 2014, Zaucha 2014, Ministry for the Environment and Statistics New Zealand 2016).

1.3 Marine areas are the great unknown

Ecosystems comprise both abiotic and biotic environments and their interactions. As a consequence, ESBM requires data from various perspectives, including the ecosystem as well as the economy and society (Collie et al. 2013). Marine environmental data of this type are often inconsistent in terms of both their spatial coverage and collection methodologies.

1.3.1 Data gaps

Full-coverage spatial data on the seabed are challenging and costly to obtain, and only 5–10% of the world's seafloor has consequently been mapped with the equivalent resolution to similar studies on land (Wright & Heyman 2008 and references therein). For example, the General Bathymetric Chart of the Oceans, GEBCO_2014, covers the Earth with a 30 arc sec grid, but only ~18% of the grid cells over the oceans are constrained by measured data or preprepared grids that may contain some interpolated values (Weatherall et al. 2015). Moreover, about 60% of the seafloor has been mapped at a bin size of 0.5° x 0.5°, and the 50% mark was reached in 1979 (Wessel & Chandler 2011). The increase in explo-

ration coverage of new seafloor areas has slowed down since then. Apparently, there was a transition to more purpose-driven investigation from the general exploration in the 1970s, which led to a decrease in data acquisition for previously unexplored areas (Wessel & Chandler 2011). A recent example of this is that the search for the missing Malaysian Airlines flight MH370 represents the largest continuous high-resolution acoustic mapping effort for the Indian Ocean (Picard et al. 2016).

It has been estimated that it would take about 900 ship years to obtain complete multibeam coverage of the world's oceans (Weatherall et al. 2015). Satellites also provide data, e.g., gravity models, on marine areas, but their resolution is poorer than with sonars, and the latest gravity model of the seafloor enables sea-floor features to be resolved to about 6 kilometers (Sandwell et al. 2014, Witze 2014). The turbid near-shore areas are also problematic to survey, as they are too shallow for an efficient bathymetric survey but too deep for a land-based survey, and thus often appear as unmapped patches called "white ribbon" zones (e.g., Kotilainen & Kaskela 2017).

Nevertheless, despite the above-mentioned challenges, the physical environmental parameters are generally easier to survey across wide areas than to obtain a full coverage set of ecological samples (Post 2008, Harris 2012). There are large gaps in the marine species record, and it has even been argued that it is impossible to map the true species biodiversity of the oceans (Harris & Baker 2012). The ecological data coverage is often low and irregular, and thus inappropriate for broad-scale MSP efforts (Tulloch et al. 2013, Collie et al. 2013, Stamoulis & Delevaux 2015). Technological advances in statistical analysis and geographical information systems (GIS) have created new approaches to integrate inconsistent geological and biological data and to map and model the marine environment. For instance, the potential coverage of a habitat can be derived from the association between environmental data and biological samples (see e.g., review by Brown et al. 2011).

1.3.2 Scattered unharmonious data

In addition to actual data gaps, marine data sets can be difficult to obtain because they are scattered around different organizations. Moreover, they might not be thematically solid. In many cases, data on the European seabed substrate are produced on the basis of national standards, and the grain-size classification schemes and data interpretation methods vary between countries, for example (EMODnet Geology 2016). Besides, the existing marine data are not necessarily at an adequate scale for specific MSP purposes. This is highlighted by a recent estimate that, to date, approximately 60% of the seabed substrates of the European seas have been mapped at the scale of 1:1 000 000 and 20% at the scale of 1:250 000 or in more detail (EMODnet Geology 2016). The respective figures for the Baltic Sea are 100% and 33%.

Several transnational efforts have been established to overcome data-sharing problems during recent years (e.g., Al-Hamdani et al. 2007, Meiner 2010, 2013, Stevenson 2012, EMODnet Geology 2016). These projects have aimed to combine and harmonize existing datasets or data patches into continuous basin-wide data products. Papers I–III provided examples of how such harmonized multisource datasets have been used to study seafloor characteristics over broad transnational marine areas.

1.4 Scale

ESBM should acknowledge the thematic scale along with the spatial scale (Cogan et al. 2009). Ecosystems occur at various scales, from ocean environments to certain sea basins, and from specific habitats such as seamounts to seafloors with complex micro-topography (Crowder & Norse 2008). The scale should enable the most significant drivers and threats to the ecosystem in question to be explained (Levin et al. 2009). ESBM strategies usually take the scale into account by adopting a hierarchical approach to define the planning units (e.g., Greene et al. 1999, Roff & Taylor 2000, Roff et al. 2003, Connor et al. 2004, Madden & Grossman 2007, Spalding et al. 2007, HELCOM 2013a).

In this dissertation, the spatial scale is used in connection with the resolution and extent of the study, broad-scale referring to large areas with low-resolution data and fine scale (or detailed scale) to local studies with high-resolution data.

Additionally, seabed characteristics have been described based on an approach that focuses on geomorphology and geomorphic features as mappable habitats (Greene et al. 1999, Harris & Baker 2012): megahabitats present large geomorphic seabed features, 1–10 km in size, nested within major physiographic provinces; mesohabitats are geomorphic features from tens of meters to 1 km in size, and include glacial moraines, gas-escape pock marks, mass wasting deposits, and bedrock outcrops; macrohabitats are 1–10 m in size and include seafloor materials such as boulders and sediment waves; microhabitats are centimeters or less in size, such as sediment grains or small cracks and crevices in a solid (rock) substrate. The mega-/mesohabitat-scale studies of Papers I and III enabled a comparison between Baltic sub basins/regions, and the more detailed meso-/macrohabitat-scale studies presented in Papers II and IV enabled the detection of specific seafloor features and landscapes at the community level.

1.5 Geological knowledge in characterizing seabed ecosystems

1.5.1 Seabed substrates and geomorphic features

Seabed surface substrates are one of the primary parameters in defining benthic habitats of the Baltic Sea, along with bottom topography, biotic features, hydrography, wave exposure, and spatiotemporal variability (Snickars et al. 2014). Generally, classification schemes for marine environment recognize hard, soft, and mixed substrates as being key habitat-determining factors (e.g., Davies et al. 2004, Beaman & Harris 2007, Greene et al. 2007, Last et al. 2010). A coarse substrate is often inhabited by suspension feeders such as mollusks, and deposit feeders inhabit muddy basins (Beaman & Harris 2007, Post et al. 2011, Rousi et al. 2011). Sheltered sedimentation basins might be species-poor habitats, as they often suffer from anoxia due to limited water exchange (Laine 2003, Laine et al. 2007).

Certain geomorphic features have been included in marine classification schemes, because they play a part in defining the distribution of the benthic biota and biodiversity both in deep sea and shelf environments (e.g., Greene et al. 2007, Harris et al. 2008, Madden et al. 2009, Mortensen et al. 2009a, Last et al. 2010, Buhl-Mortensen et al. 2012, Harris & Baker 2012). Seabed geomorphology takes into account the form and hardness of the seabed (Harris 2012). Seabed geomorphic features vary in size and include features such as canyons, ridges, sandbanks, basins, moraines, and fjords. For example, the spatial variability of benthic communities of East Antarctica is primarily influenced by changes in broad-scale seabed morphology, which partly controls sedimentation patterns, current flow, and the supply of organic matter, among others (Post et al. 2011). The commercially valuable adult rockfish has also been shown to prefer elevated and fractured tectonic and glacial habitats to smoothed bedrock (Greene et al. 2011). The elevated and rugged features impact current flow by causing turbulence, which concentrates nutrients and thus provides the potential for food. Rough terrains with angular boulders and spaces between them offer refugia and good habitats. However, a preference for physically homogeneous habitats has been noted in temperate seagrass fish assemblages (Staveley et al. 2016).

The Habitats and Birds directives (Council Directive 92/43/EEC and Directive 2009/147/EC, respectively) of the European Union include the protection of marine habitats and species. The directives define the formation of an ecological network of protected sites encompassing the terrestrial and marine habitats occurring in Europe (Natura 2000 network). Annex I of the Habitats Directive lists habitats important to biodiversity protection, and defines some habitats based on geomorphological criteria and assigns biodiversity values accordingly (European Commission, 2013). For example, according to the Annex I habitat description, reefs are formations of hard compact biogenic or geogenic substrata on solid and soft bottoms, which arise from the sea floor in the sublittoral and littoral zone, and they may support a zonation of benthic communities (European Commission, 2013). A key species on the rocky reefs of the Baltic Sea is the perennial brown alga *Fucus vesiculosus* L., which serves as an important food source for many invertebrates (Engkvist et al. 2000, Wikström & Kautsky 2007) and may provide a refuge for invertebrate and fish species (e.g., Kautsky et al. 1992). Paper IV

of this dissertation focuses on the reefs formed by hard substrata.

1.5.2 Marine landscapes

The marine landscape (also referred to as 'seascape' or 'benthoscape') approach is one tool that can contribute to marine management. Marine landscapes are combinations of ecologically determined hydrographic, bathymetric, and geological datasets that characterize potential broad habitat distribution patterns. If the required abiotic datasets exist, the approach provides a cost-effective method for characterizing seafloor conditions and potential habitats on a broad scale. The approach informs conservation efforts that seek to optimize biodiversity (rather than a particular species) in a given area. The International Council for the Exploration of the Sea (ICES) specifies that the term 'marine landscape' is similar to the term 'habitat' in that it refers to an area of integrated landforms and biota, but covers a broader spatial area. Marine landscapes were first outlined in Canada (Roff & Taylor 2000) and have since been identified in several marine areas (Connor et al. 2006, Al-Hamdani et al. 2007, Whiteway et al. 2007, Harris & Whiteway 2009, Verfaillie et al. 2009, Galparsoro et al. 2010, Brown et al. 2012).

Marine landscapes have been characterized by top-down approaches that include a hierarchical classification of hydrological and geological parameters (e.g., Roff & Taylor 2000, Connor et al. 2006, Al-Hamdani et al. 2007) or by bottom-up approaches that include a multivariate statistical analysis of environmental samples (e.g., Verfaillie et al. 2009, Huang et al. 2011). The top-down approach is typically used to establish a general understanding of a broad area, while the bottom-up approach provides more detailed characterization of different component spaces (Shumchenia & King 2010, LaFrance et al. 2014). The top-down approach was implemented in Paper I and bottom-up in Paper II.

Some marine landscape approaches and the ones presented in Papers I and II have emphasized physical elements of the seabed, including geomorphology, seabed heterogeneity, and texture, in broad-scale habitat mapping (e.g., Connor et al. 2006, Al-Hamdani et al. 2007, Shaw et al. 2014). The landscape consists of physical elements, landforms such as hills and basins, as well as living elements including flora and fauna. The physical landscape is a result of internal processes such as tectonics and external processes, including weathering and erosion. These marine landscape approaches are useful for identifying broad seafloor features such as canyons and rocky reefs (Brown et al. 2011). They also aim to present a holistic view of the seafloor and to incorporate an understanding of the past and ongoing geological processes that have shaped the seafloor (Shaw et al. 2014).

The marine landscape approaches presented in Papers I and II aimed at characterizing seabed conditions. Paper I focused more on seabed geomorphic features, which were considered as adding a geomorphological link to the marine landscape approach. Paper II developed the marine landscape approach by analyzing the relationships between abiotic variables and benthic assemblages. Thus, the benthos was included in the analyses, and the marine landscapes derived in Paper II were called benthic marine landscapes. Additionally, the term 'seabed landscape' has been used in this thesis. This refers to the physical landscape of the seabed and includes geomorphic features, substrates, and geodiversity.

1.5.3 Geodiversity

Besides constituting the physical framework for biodiversity, abiotic nature provides abiotic ecosystem services and has an ecosystem value of its own (Gray et al. 2013). The term 'geodiversity' has been used in parallel with biodiversity to promote a more integrated management of nature (a shift from the traditional biocentric focus) and to emphasize that nature consists of both biotic and abiotic components (Gray 2005). Geodiversity takes into account the natural range of geological, geomorphological, and soil features, as well as their assemblages, relationships, properties, interpretations, and systems (Gray 2004).

Geodiversity provides resources for economic development, tourism, recreation, and outdoor activities, and knowledge that aids society to adapt to climate change and to mitigate its consequences through improved understanding of natural processes, among others (Gordon et al. 2012). Knowledge of the distribution of geodiversity supports spatial planning, the sustainable use of resources, and the defining of priority

areas for conservation (Pellitero et al. 2011, Gray et al. 2013, Melelli 2014). The seafloor is a target of several anthropogenic activities, including aggregate extraction, trawling, and marine construction (e.g., pipelines and plants for marine energy), and the resulting impacts on the integrity of the features may vary, depending on the character and vulnerability of the feature, as well as the nature of the activity (Burek et al. 2013).

Geoconservation, which is the conservation of geological and geomorphological features, was earlier largely ignored in the marine environment, but awareness of the value of submarine geodiversity has grown in recent years (Burek et al. 2013). Examples include the Kvarken archipelago, which is included in UNESCO's list of World Heritage sites due to its geological value. It is an exemplary area with a changing landscape, where an active geoprocess, isostatic land uplift, leads to a continuous succession of moraines from the seafloor to land (Breilin et al. 2004, 2005, Reijonen 2004, Kotilainen et al. 2012, Kotilainen & Kaskela 2017).

Geodiversity might also serve as a proxy for biodiversity. Abiotic heterogeneity has been noted to reflect the abundance of varying habitats, spatial variation in resources, and thus biodiversity (e.g., Burnett et al. 1998, Nichols et al. 1998, Dufour et al. 2006, Parks & Mulligan 2010, Hjort et al. 2012, Stein et al. 2014). It has even been speculated that threatened species richness could be associated with high geodiversity values (Tukiainen et al. 2016).

The distribution of geodiversity is often analyzed with GIS methods. For example, geodiversity can be assessed by summing the number of different elements that constitute geodiversity (Hjort & Luoto 2010, Pereira et al. 2013, Silva et al. 2015) or by producing an overlay analysis of categorical geological, morphoclimatic, and morphometric data, which can be further used to calculate diversity indices typical of landscape studies (e.g., Shannon and Simpson diversity) (Benito-Calvo et al. 2009, Argyriou et al. 2016). Some studies have applied a geodiversity index that takes into account geomorphology, hydrology, and soils, as well as roughness (Serrano & Ruiz-Flaño 2007, Serrano et al. 2009, Hjort & Luoto 2010, Pellitero et al. 2011, Melelli 2014, Pellitero et al. 2015, Manosso & de Nóbrega 2016). Additionally, the physical complexity of the seabed has been described with parameters such as the slope, rugosity, and roughness (Kostylev et al. 2005, McArthur et al. 2010, LaFrance et al. 2014). A high geodiversity reflects a deformed terrain with structural and lithological complexity, deeply incised regions, eroded reliefs, and heterogeneous abiotic conditions, including both erosion and accumulation, among others (Benito-Calvo et al. 2009, Hjort & Luoto 2010, Pellitero et al. 2015, Manosso & de Nóbrega 2016) during geological time.

1.6 Research objectives and hypothesis

This dissertation study aimed to develop spatial models and visual representations of the physical seabed environment for scientists, marine spatial planners and managers, and to advance ecosystem-based planning of the Baltic Sea. The intention of the study was to develop an overview of the geological features of the seabed and landscape of the area with spatial analysis techniques and to investigate the underlying reasons for the characteristics.

The specific objectives of the research were:

- To define the physical environment of Baltic Sea seabed by identifying geomorphic features with spatial analysis methods (PI);
- To analyze the relationships between abiotic characteristics and benthic assemblages of the eastern Gulf of Finland, taking into account the geological heterogeneity of the area (PII);
- To quantify and analyze the geodiversity patterns of the Baltic Sea, as well as to identify relationships between geodiversity and environmental factors (PIII);
- To develop a methodology to map the occurrences of geomorphologically defined key habitats, rocky reefs, in a geographically complex area, the Archipelago Sea, using the best available data (PIV).

The dissertation consists of a synopsis and four papers, which are referred to by the Roman numerals I–IV. The methodology and data used in the papers are briefly described in section 2, and the main results in section 3.

2 STUDY AREA

The focus of this dissertation is the seabed environment of the Baltic Sea. Papers I and III together consider the whole basin, as Paper II is focused on the eastern Gulf of Finland and Paper IV on the Archipelago Sea (Fig. 1).

2.1 Baltic Sea

The Baltic Sea is located on a continental shelf and it is one of the largest inland seas in the world. It is a shallow sea with an average depth of about 55 m. The Baltic Sea consists of several sub-regions (e.g., Arkona Basin, Bornholm Basin, Eastern and Western Gotland Basins, Gulf of Finland, Archipelago Sea, Bothnian Sea, Kvarken, Bothnian Bay), each having unique geomorphic and hydrographic characteristics (e.g., Fonselius 1996, Ojaveer & Kalejs 2008, HELCOM 2013b) (Fig. 1).

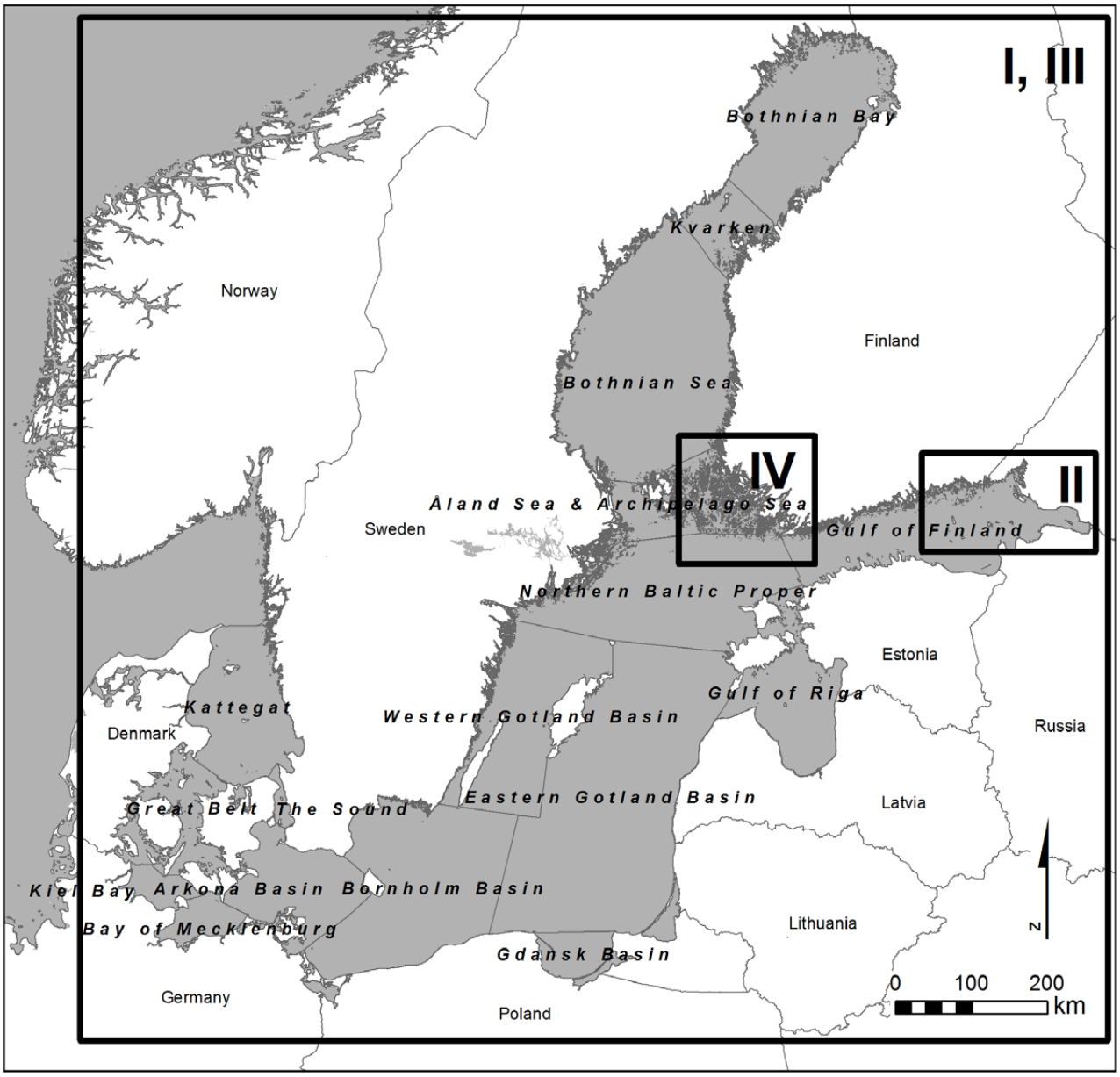

Fig. 1. The Baltic Sea and the study areas of the papers included in the thesis. The study areas are outlined with black boxes and the papers are referred to in Roman numerals. Dataset origins: coastline - European Environmental Agency 2013, sub-regions - HELCOM 2013b.

It has limited water exchange with the North Sea through the Danish Straits, and combined with a large river runoff, this has resulted in brackish water conditions with a salinity gradient typical of estuaries. The Baltic Sea is practically tideless, and the present sea-level fluctuations of the area are mainly controlled by air pressure and winds. The northern Baltic Sea freezes yearly. The biotic part of the Baltic Sea ecosystem is a mixture of limnic and marine species. It is a species-poor environment with benthic species richness decreasing along the gradient of decreasing salinity from south to north.

The bedrock of the Baltic Sea consists of Paleoproterozoic crystalline basement rocks that crop out locally along the western, northern, and northeastern coasts. Sedimentary rock can be found in the southern areas of the Baltic Sea and the Gulf of Finland, as well as in tectonic depressions in the central Bothnian Sea and the Bothnian Bay (Winterhalter et al. 1981, Koistinen et al. 2001). Several ancient tectonic lineaments and fracture zones divide the bedrock into blocks, which are also evident in the seafloor (e.g., Härme 1961, Tuominen et al. 1973, Winterhalter et al. 1981). The main factors that have contributed to the geological characteristics of the Baltic seafloor include the pre-glacial bedrock surface, glacial erosion, and deposition, as well as post-glacial sedimentary processes (Winterhalter et al. 1981).

The Baltic Sea has undergone several glacial erosion and glacio-aquatic sedimentation periods during the past 3 million years (Mangerud et al. 1996, Hughes et al. 2016). During the Last Glacial Maximum (LGM), approximately 30–20 ka BP, the global sea level was more than 120 m lower than today, and large parts of the current shelf seafloors were either dry land or covered by ice (e.g., Clark & Mix 2002, Clark et al. 2009, Lambeck et al. 2014). At that time, the Baltic Sea basin was completely covered by an ice sheet, and by about 10 ka BP, the entire basin was deglaciated (Svendsen et al. 2004, Stroeven et al. 2016). The melting of the ice sheets raised the global sea level and triggered glacio-isostatic rebound locally, which is still ongoing. The interactions of these controls resulted in an alternation of lacustrine and brackish-water phases of the Baltic Sea history during and after the deglaciation (Baltic Ice Lake 17.0–11.7 ka BP, Yoldia Sea 11.7–10.7 ka BP, Ancylus Lake 10.7–9.8 ka BP, Initial Littorina Sea 9.8–8.5 ka BP, Litorina Sea 8.5– ka BP (Björck 1995, Andrén et al. 2011, Stroeven et al. 2016). Moreover, the process has not ended: the current climate change scenarios estimate that the sea level will rise between 0.5–1 m globally by 2100 (Church et al. 2013). As noted earlier, the Baltic Sea is an area of ongoing glacial isostatic adjustment (GIA) with the land uplift rate varying from the -1 mm/y in the south to 9 mm/y in the Bothnian Bay (Ekman 1996, Kakkuri 2012). Ongoing GIA partly compensates for the local sea-level rise in most of the Baltic Sea region, and the mid-range scenario of global sea-level rise equates to a relative sea-level rise of 0.60 m near Hamburg and a relative sea-level fall of 0.35 m in the Bothnian Bay (Grinsted 2015). Consequently, as the shoreline has moved through the geological history of the shelves, relict coastal deposits such as boulder fields are found below water. In addition, glaciers have carved valleys and eroded and redeposited material. Glacial deposits such as till and moraine occur on the seafloor of formerly glaciated areas (e.g., Todd & Kostylev 2011, Shaw et al. 2014, Greenwood et al. 2015, Dowdeswell et al. 2016).

The Baltic Sea is one of the most degraded marine areas in the world (Lotze et al. 2006). It has been subjected to anthropogenic use for centuries, resulting in impoverished marine resources (HELCOM 2007). In addition, climate change is challenging the ecosystem. Projected changes in the sea surface temperature, freshwater discharge, duration of sea ice, and salinity will have probable impacts on biological processes and biota (e.g., distribution and seasonal succession) in the Baltic Sea (Viitasalo et al. 2015). To survive these challenges, this sensitive water area needs oversight and efficient management.

2.2 Eastern Gulf of Finland

The Gulf of Finland represents a mosaic of different bathymetric, hydrological, and geological environments characterized by pronounced gradients in salinity, oxygen, and temperature. It is divided into a deeper and marine-influenced western section and a shallower eastern section

that includes higher proportions of freshwater (Pitkänen et al. 2001). The Neva River, which debouches into the area at St. Petersburg, is the most voluminous source of freshwater discharge into the Baltic Sea (Leppäranta & Myrberg 2009). Till deposits, moraines and eskers are typical seabed features of the (northern) Gulf of Finland (Häkkinen & Åker 1991).

2.3 Archipelago Sea

Archipelagos are a particular feature of the central and northern part of the Baltic Sea (Niemelä et al. 2015). They present very dynamic seafloor conditions, where seafloor properties and processes change within very short distances. The Archipelago Sea forms a transition zone with gradients from the coast to the open sea. The water properties of the area are influenced by several factors: the adjacent main basins of the Baltic Sea (the Gulf of Finland, Gulf of Bothnia, and Baltic Proper), the fluvial discharges and the division into numerous sub-basins, and the wide amplitudes of seasonal cycles (Suominen 2015). The resistant Precambrian crystalline rocks are often exposed in the outer Archipelago Sea, while the innermost parts are sheltered and include softer sediments. The seabed substrate distribution within the area is very patchy, with rock outcrops, till, gravel and sand, and clays of different ages.

3 MATERIAL AND METHODS

All of the papers of this thesis utilized data in geographical information system (GIS) format, as well as spatial analysis methods available in the ArcMap environment, unless otherwise stated.

3.1 Spatial scale

The GIS datasets represented broad spatial scales with a grid size reflecting the extent of the study area: 200 m x 200 m/250 m x 250 m in the Baltic-wide analysis (Papers I and III), 100 m x 100 m in the eastern Gulf of Finland (Paper II), and 25 m x 25 m in the Archipelago Sea (Paper IV).

Paper I used the term "small scale" in reference to the broad physical structures of the seafloor and the other papers used the term "broad scale" for the similar features. The term small scale was used because cartographically it implies low-resolution maps (e.g., 1:1 000 000 – the resulting fraction is small). However, it was noted that the usage of the term small scale was confusing, because it is sometimes (especially in general language) used in the context of detailed local-scale maps. Therefore, the other papers used the terms broad scale for low-resolution maps and fine scale for high-resolution maps.

3.2 Datasets

The seabed substrate and bathymetry were the main datasets used in all papers. Therefore, the focus is on describing these two parameters and their derivatives. Other data (e.g., coastline, salinity, Secchi depth, bedrock, deglaciation) were used according to the context of the study, and the reader is referred to the original papers for further information.

3.2.1 Seabed substrate data

Marine geological mapping provides spatial data on seabed substrate properties, their distribution, and geomorphology. The data usually derive from either manual interpretation or (semi-)automatic interpolation of seismo-acoustic data, including single-beam echo sounder, seismic profiler and sidescan sonar (SSS), and multibeam echosounder (MBES) data, and sediment samples (e.g., Hughes Clarke et al. 1996, Coggan et al. 2007, van Lancker et al. 2013, Jakobsson et al. 2016). The mapping strategies depend on the survey interests, sea basin characteristics, and national mapping traditions. For example, in Finland, marine seabed substrate maps are produced based on seismo-acoustic surveys and seabed sampling. First, seismo-acoustic profiles are interpreted based on the acoustic properties

of the (sub-)surface material (e.g., porosity, bulk density). Then, the interpreted profiles are transformed into so-called substrate ribbons and exported into a mapping program (GIS). The distribution of the seabed substrates is manually outlined from the substrate ribbons and sediment samples with the help of side-scan sonar mosaics and water depth information. Water depth can be measured with MBES that collects high resolution bathymetric information, for example. Traditionally, marine geologists have produced discrete maps of seabed substrates and structures to provide data on marine resources, geotechnical properties, and geological events. In this dissertation, the aim was to study seabed surface substrates that also characterize benthic habitats.

The studies of Papers I, II, and III used transnational broad-scale substrate datasets (< 1:500 000) from several EU projects (e.g., BALANCE, TOPCONS, EMODnet Geology). The general process for compiling the seabed substrate maps within these projects involved several steps. First, the (national) information was sourced and then harmonized according to a classification system agreed by the partners. These large datasets were pooled from various sources representing different survey methodologies and varying mapping strategies (e.g., Al-Hamdani et al. 2007, Al-Hamdani & Reker 2007, Kaskela et al. 2014, EMODnet Geology 2016). Harmonization was implemented by the national partners, and they generalized the maps to the target scale, again following agreed criteria. Finally, the responsible partner compiled the national datasets/maps. The author has participated in the harmonization and compilation of these data. Additionally, Paper II included fieldwork to provide detailed surface substrate information from the key areas.

Paper IV was restricted to Finnish waters. Thus, the seabed substrate data were derived from the national marine geological mapping program of the Geological Survey of Finland (GTK). The Finnish marine geological mapping program produces 1:20 000 data with ca. 60% acoustic coverage of the seafloor (the distance between acoustic-seismic survey lines is about 500 m).

3.2.2 Bathymetry

Generally, bathymetry data were derived from external data sources. The author participated in developing the bathymetry models used in Papers I and II.

The bathymetry models included in Papers I and III were compiled from existing datasets in neighboring countries. Paper I utilized a dataset from Baltic co-operation and Paper III from European co-operation (Al-Hamdani et al. 2007, Al-Hamdani & Reker 2007, EMODnet Bathymetry Consortium 2016).

Papers II and IV included interpolations from point datasets and contour lines, among others. The interpolations were produced using the ArcMap "Topo to raster" algorithm (ArcGIS Desktop 2016). The bathymetry model included in Paper II was interpolated based on multibeam data from the key areas, and the larger study area was covered with depth data points, coastline and contour lines available either from the National Land Survey of Finland Topographic Database or at VSEGEI (A.P. Karpinsky Russian Geological Research Institute) (Kaskela et al. 2013). The IOW (Das Leibniz-Institut für Ostseeforschung Warnemünde) Baltic Sea bathymetry model was used if no other depth point data were available (Seifert et al. 2001). Paper IV used the National Land Survey of Finland Topographic Database as primary input data for the model, and further offshore the IOW Baltic Sea bathymetry dataset was used.

3.3 Spatial analysis techniques

Spatial analysis techniques were applied in identifying seabed structures (Papers I–IV), developing the marine landscape approach (Papers I, II), and analyzing seabed geodiversity (Papers II, III) at varying scales (Fig. 2).

3.3.1 Seabed structures and topographical characteristics

The science of quantitative terrain analysis, which combines mathematics, earth sciences, engineering, and computer science, is called geomorphometry (Pike et al. 2008). Sometimes,

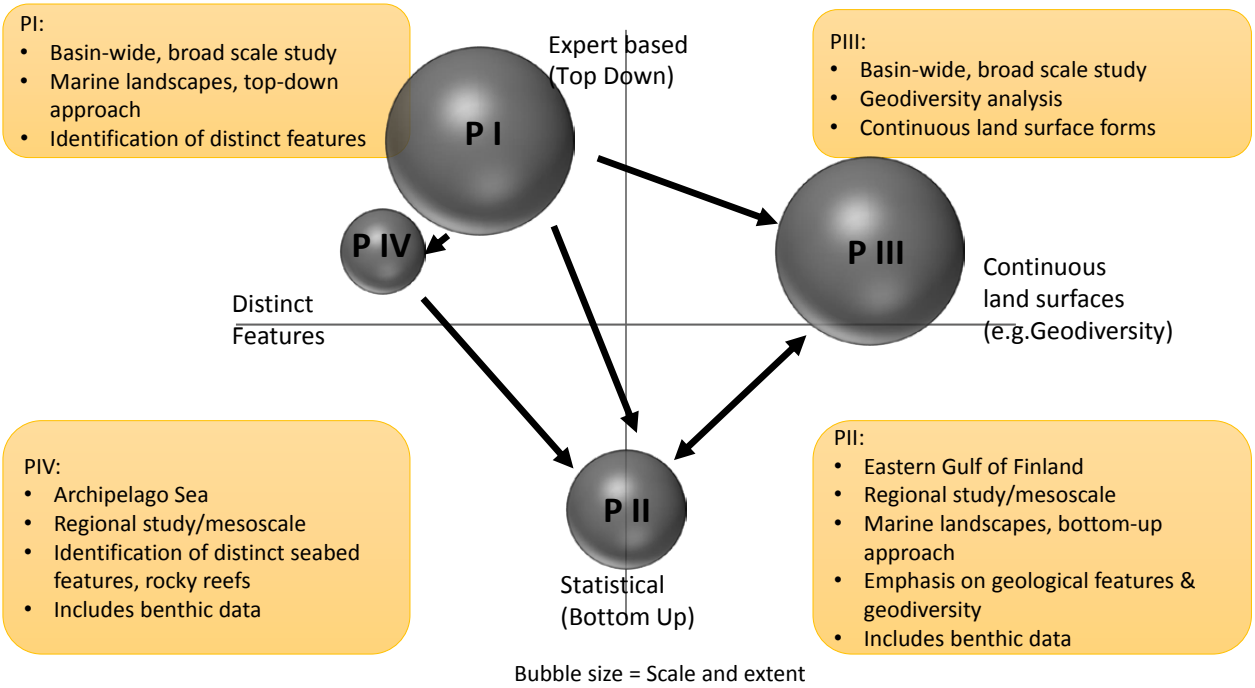

Fig. 2. Characterization of the papers on the basis of their extent, scale of the study, and objectives.

geomorphometrical applications include a distinction between landforms and land surface forms (Evans 2012). Landforms are bounded segments of the land surface and can be discontinuous. Land surface forms are continuous and include the whole globe. Paper IV includes features that can be defined as landforms, Paper III considers geodiversity that can be regarded as a land surface form, and Papers I and II include both types.

Slope, aspect, and curvature are first-order derivatives of bathymetry. Roughness (the standard deviation of slope) is a second-order derivative. These variables were considered to infer material properties and geomorphological, hydrological, and ecological processes in both terrestrial and marine areas (e.g., McKean & Roering 2004, Glenn et al. 2006, Grohmann et al. 2011, Erikstad et al. 2013, Smith 2014). The continuous grids of these variables were applied in Paper II to analyze linkages between the seabed environment and benthic assemblages. Additionally, slope was included in Papers I, III, and IV, and roughness was used in the context of geodiversity in Paper III.

Here, the ArcMap extension Benthic Terrain Modeler (BTM) was used in modeling broad-scale seafloor structures from bathymetry grids (Wright et al. 2012). The tool has been applied in connection with several seabed geology and habitat studies (e.g., Lundblad et al. 2006, Wilson et al. 2007, Diesing et al. 2009, Buhl-Mortensen, et al. 2012, Jerosch et al. 2016). BTM calculates bathymetric position index (BPI) values with a neighborhood analysis function from a bathymetry model. The BPI value denotes whether a pixel is situated either higher (positive values) or lower (negative values) than its surroundings, and the values can be further classified into distinct structures, e.g., basins, crests, or narrow crests. Continuous BPI grids with varying neighborhoods were applied in Paper II and the derived distinct seabed structures were included in the analyses presented in Papers I, III, and IV. In Papers I and IV, the optimal BPI neighborhoods to identify relevant seabed structures were determined by generating several BPI grids with varying neighborhood sizes, which were compared with substrate data and well-known features to find the best fit.

Paper IV aimed at developing a methodology for identifying potential key habitats using the best, but limited, data available on bathymetry and geology. Rocky reefs are defined in the An-

nex I of the Habitats Directive (European Council Directive 92/43/EEC) as formations of hard compact biogenic or geogenic substrata, which arise from the seafloor in the sublittoral and littoral zone; hence, they are defined in geological terms. Paper IV included the following phases: identification of elevated structures with BTM, comparison of elevated structures with substrate data (where available), and establishing of a link between elevations and exposed rock in order to project the occurrences of rocky elevations to areas without substrate information. The conservation value of a reef is related to species diversity, and the structures were therefore ecologically evaluated by modeling the distribution of four key species typical of reefs. The occurrences of rocky reefs were validated using dive transects.

3.3.2 Determining Marine Landscapes

Marine landscapes were investigated in Papers I and II.

Paper I presented an example of a top-down approach. The objective was to produce a coherent spatial dataset on the distribution of seabed geomorphic features over the entire Baltic Sea. As stated in the Introduction, some benthic species and their assemblages favor certain geomorphic features and can be used as a proxies of the benthic biota and biodiversity (e.g., de Forges et al. 2000, Post 2008, Mortensen et al. 2009a, b, McArthur et al. 2010, Huang et al. 2011, Greene et al. 2011, Post et al. 2011, Harris & Baker 2012 and references therein). In addition, seabed geomorphic features reflect conspicuous physical elements that are traditionally considered as elements constituting the landscape. In Paper I, the marine landscapes were determined by identifying seabed structures with BTM and performing an overlay analysis to combine the derived structures with seabed substrates and photic zones. The scale of the analysis correlated with mega- and mesohabitat scales.

Paper II included a bottom-up approach to identify benthic marine landscapes in geologically complex areas of the eastern Gulf of Finland at a spatial scale of 1:500 000. The study included benthic sampling and full-coverage acoustic surveys of Finnish and Russian key areas at an approximate scale of 1:5 000. The purpose was to construct a detailed picture of depth, substrate type, and zoobenthic composition. Altogether, 218 zoobenthic samples were collected and analyzed. Organisms were identified to the species level (where possible) and statistical analysis was conducted on the spatial distributions of 23 zoobenthic taxa. In addition, a set of video clips was studied from the Finnish key areas to include information on the benthic organisms inhabiting the coarse-grained substrates. The zoobenthic samples and video observations were analyzed separately. The statistical analyses were performed using Plymouth Routines in Multivariate Ecological Research (PRIMER) (Clarke 1993). The BEST and LINKTREE routines were used to analyze the relationships between abiotic variables and benthic assemblages and to identify thresholds (Clarke et al. 2008) that were used to span the benthic marine landscapes to cover the general study area of the eastern Gulf of Finland. Paper I revealed that the eastern Gulf of Finland includes a diverse seabed environment. Thus, the abiotic dataset examined in Paper II included variables describing the coastal environment, geodiversity, geological features, and multiple analysis neighborhoods, among others.

3.3.3 Geodiversity

Paper III applied selected geodiversity methods developed for terrestrial studies to the seabed environment. The broad-scale geodiversity of the Baltic Sea was quantified in a GIS environment with three measures: richness, patchiness, and the geodiversity index. Patch richness (i.e. variability) measures the number of different types or combinations, patchiness the number of individual patches over a certain neighborhood, and the geodiversity index combines richness and structural complexity into a single variable. The measures were analyzed on the basis of geological datasets, i.e. bedrock, seabed substrate, and the distribution of structures in the GIS environment. The geological datasets represented spatial scales from 1 to 2 million, and their thematic resolutions represented similar scales with five categories. The geodiversity patterns were analyzed against potential drivers describing glacial influence and post-glacial sedimentation and erosion conditions with Spearman's rank correlation.

4 RESULTS

Paper I. Seabed geomorphic features in a glaciated shelf of the Baltic Sea.

Paper I aimed to characterize the seabed landscape of the Baltic Sea according to the geomorphic features. The seabed geomorphic features were identified by analyzing and modeling bathymetric, seabed substrate, and photic depth datasets, which were compiled from countries neighboring the Baltic Sea. The scale of the analysis correlated with mega- and mesohabitat scales. On this basis, a total of 18 seabed geomorphic features were mapped over the Baltic Sea basin. The seabed geomorphic features included plains, basins, sea valleys and holes, sea troughs, elevations, and slopes with differing combinations of substrate and euphotic conditions. Sediment accumulation areas cover approximately one-third of the seafloor.

One of the advantages of the study was that it enabled a comparison between sub-regions of the Baltic Sea. The results demonstrate that the Baltic Sea sub-regions differ from each other in the landscape characteristics of the seabed. At the Baltic scale, plains and basins were the most ubiquitous seabed features, while other features such as elevations and sea valleys were more localized.

The seabed geomorphic features were considered useful in confronting challenges regarding the physical characterization of the shared marine environment, as in the EU Marine Strategy Directive (Directive 2008/56/EC). Knowledge of the distribution of the geomorphic features could aid in identifying some key habitats, a topic that was further discussed in Paper IV. Paper I also included a first approximation of the distribution of geodiversity in the Baltic Sea. The geodiversity of the Baltic Sea was the focus of Paper III, and the link between geodiversity and benthic habitats was further investigated in Paper II.

Paper II. Linkages between benthic assemblages and physical environmental factors: The role of geodiversity in the eastern Gulf of Finland ecosystems.

Paper II analyzed the role of geological features and geodiversity in determining the composition of benthic assemblages in geologically complex coastal areas of the eastern Gulf of Finland in the northern Baltic Sea. It included geological and biological fieldwork in carefully selected key areas and statistical analysis to examine the relationships between abiotic characteristics and benthic assemblages. Statistical analyses identified correlations between benthic data and abiotic variables, but correlations were not consistent with respect to zoobenthic grabs and video observations. It was considered that differences were due to the observation methods and the lower coverage area of the video data. The ratio of Secchi depth to water depth showed a strong correlation with species distributions observed in video recordings ($\rho = 0.56$), whereas variables describing broad-scale geodiversity and the archipelago gradient (the abundance of islands, ratio of land and sea area) correlated with zoobenthic sample data (generally $\rho > 0.30$). The abiotic variables that were analyzed with several neighborhoods showed that the correlation with benthic assemblages increased with radii.

A model including the Secchi depth and terrain roughness explained the greatest proportion of spatial variation in zoobenthic sample data ($\rho = 0.69$). On the basis of these two variables, nine benthic marine landscapes, which contained distinct benthic assemblages, were identified. The results revealed that the landscapes found in topographically complex seabed areas generally possessed higher species diversity than flatter areas. The most complex landscapes were located in the in the vicinity of islands in the central part of the eastern Gulf of Finland.

Paper II suggested that geodiversity, which was represented by roughness, and the archipelago gradient directly influence benthic assemblages and biodiversity by providing a multitude of habitats and indirectly influence them by channeling the movement of water. It also demonstrated that broad-scale geodiversity should be considered in regional habitat mapping, maritime spatial planning, and conservation policies.

Paper III. Seabed geodiversity in a glaciated shelf area, the Baltic Sea.

Paper III followed up Paper I in studying the seabed geodiversity of the Baltic Sea. While Paper I focused on certain geomorphic features, Paper III analyzed broad-scale geodiversity patterns on the basis of three parameters: richness, patchiness, and the geodiversity index. The geodiversity patterns were also analyzed against potential drivers describing the glacial influence and post-glacial sedimentation and erosion conditions.

The study revealed distinct variation in geodiversity patterns between sub-regions, supporting the results of Paper I. Particularly archipelagos located in crystalline rock showed high geodiversity values. Generally, the resistant crystalline rock areas displayed higher geodiversity values than the more permeable sedimentary rock areas. The three geodiversity parameters exhibited very similar trends in sedimentary rock areas, but were more dispersed in crystalline rocks. The differences between patchiness and richness were especially noticeable, both in spatial distribution and correlation values. Besides crystalline bedrock, geodiversity correlated with roughness, slope, the land uplift rate, deglaciation, shore density, and distance to the coast.

Extensive archipelagos with dense occurrences of rocky islands and reefs are characteristic of the Baltic Sea. This was observed as high shore density values in crystalline rock areas. The archipelagos present dynamic seafloor conditions, where seafloor properties and processes change within very short distances.

Paper III emphasized that geodiversity should be considered in the ecosystem management of marine areas, because it has intrinsic value and it also provides several abiotic ecosystem services.

Paper IV. Predicting the occurrence of rocky reefs in a heterogeneous archipelago area with limited data.

Paper IV presented spatial estimations of the occurrences of specific geological features, rocky reefs, which are also included in Annex I of the Habitats Directive (European Council Directive 92/43/EEC). Annex I lists features that are important in biodiversity protection and should be maintained (or restored) to a favorable conservation status and form an ecological network of protected areas, the Natura 2000 network.

The study focused on the Archipelago Sea, where rocky reefs and the associated algal communities and blue mussel beds are vital in maintaining biodiversity. It was documented that there are rocky islands and reefs within the area, as it was also shown by Papers I and III. However, the spatial distribution of the reefs was not so well known, and the past establishment of the Natura 2000 network was partly based on insufficient knowledge of their occurrence. For example, the seabed substrate data (~1:20 000) provided by the national marine geological mapping program covered less than half of the area.

The idea behind Paper IV was to identify rocky reefs from the available bathymetry and substrate data by modifying the approach developed in Paper I and to validate these reefs with biological data. On this basis, 55 out of 68 (81%) of the potential reefs that were ground truthed were confirmed to be reefs, and the number of predicted key species occurring correlated significantly with the number of species observed. Nevertheless, the ground truthing revealed zonation within the substrate content, with bedrock and boulders gradating into fine-grained material towards the bottom of the structure. This implied that the rocky reef model might exaggerate their areal extent or the identified formations could actually be reef complexes with undulating surfaces.

5 DISCUSSION

This dissertation study has demonstrated a GIS-based approach to visualize the geological environment of the seafloor and to compare sub-regional characteristics. It has combined sparse knowledge and used it to produce spatial representations of the Baltic Sea in terms of both seabed geomorphic features and geodiversity (Papers I, III, IV). The numerical GIS approach enabled the determination of coherent geological features over the entire Baltic Sea basin and in specific sub-regions within the limits of the input data resolution. Potential key habitats were extrapolated from the existing sources in areas without high-resolution data, and they were also recognized as having ecological value (Paper IV). Additionally, new evidence was presented linking geodiversity and biodiversity by showing that geodiversity influenced the distribution of zoobenthic assemblages (Paper II).

5.1 Validity of spatial analysis techniques

The benefits of a GIS-based approach include transparency, reproducibility, and objectivity (e.g., Paper I). Transparency and reproducibility were supported in all papers by presenting the numerical definitions in use. In fact, Paper III reproduced part of the geomorphic analysis presented in Paper I, because new datasets on bathymetry and seabed substrates had been released between the studies. It was encouraging that although the datasets had been updated, the results remained approximately the same. This also validated the results to some extent. In this context, objectivity means that the features were identified following the same principles over the research area, i.e. the features were commensurate. These "Baltic Sea-based" definitions might not capture all relevant geomorphic features in other shelf sea areas, and they should be adjusted to suit different seas. For example, both Paper I and the global analysis of geomorphic features (Harris et al. 2014) applied the definitions provided by the International Hydrographic Organization, but the identification methods were different. Despite the objectivity of the methods, the set of variables included in the analyses were partly a subjective choice led by the research interests and available data. The presented studies emphasized geological characteristics. In cases, the inclusion of some other parameters, such as oxygen or wave energy, could have increased the ecological validity of the results (e.g., Papers I, II).

An increase in the availability of digital bathymetric data has fueled marine geomorphometry in the last decade (LeCours et al. 2016). This dissertation has provided insights into the potential of geomorphometric methods for deriving new information on seabed characteristics based on low resolution, broad-scale datasets. Paper I tested BTM, which is an ArcMAP toolbox designed for the identification of seabed structures from bathymetry data. BTM proved to be a valuable tool, and it was considered to provide more information on seabed features than bathymetry data alone, or bathymetry and slope data combined. It was also easy to use and thus it was utilized in all the papers. BTM enabled the modeling of potential geomorphic habitats, rocky reefs, with good accuracy in areas without high-resolution seabed mapping data (Paper IV). BTM has been widely used in other benthic studies, including studies on a broad scale (e.g., Buhl-Mortensen et al. 2012, Jerosch et al. 2016).

The topographic complexity of the seabed was analyzed with roughness, calculated as the standard deviation of the slope (Grohmann et al. 2011). Paper II demonstrated that roughness had zoobenthic value, and Paper III highlighted its correlation with geodiversity.

The broad-scale distribution of geodiversity was investigated based on the distribution of seabed geomorphic features and geodiversity parameters: patchiness, richness, and the geodiversity index (Paper I, III). The geomorphic feature analysis provided information on general distribution patterns, as well as on rarity, whereas the geodiversity parameters themselves do not provide any information on rarity but focus on the abundance and number of features (Benito-Calvo et al. 2009, Paper I, III). The geodiversity parameters were mutually correlated in sedimentary rock areas, but not in crystalline rock areas with high topographical complexity (Paper III). Paper III highlighted that

topographical/structural heterogeneity should be taken into account in geodiversity analyses, as richness (the number of different types) itself does not inform about terrain variability. Moreover, one should ensure that the analysis neighborhood is appropriate for the area (Paper III). It was interpreted that the broad analysis neighborhood was perhaps too coarse to establish linkages between geodiversity and effective processes in a fragmented seabed environment. The radius (20 km) reflected the results of Paper II.

5.2 Datasets

Papers I, II, and III exploited transnational broad-scale datasets (1:500 000 - 1:1 000 000) compiled and harmonized from different sources. The thematic and spatial resolution of the dataset influences the quantification of landscape patterns (Jelinski & Wu 1996, Buyantuyev & Wu 2007, Pellitero et al. 2015). The papers investigated broad-scale geological patterns that provide physical information on the seabed landscapes and habitats of the Baltic Sea. The geological datasets represented the spatial scales of mega- to mesohabitats. The thematic resolutions aimed to capture the main elements that define the landscape characteristics. Despite the efforts to compile the data uniformly, the accuracy and confidence levels may vary across the datasets, because the data were collected using different survey methodologies, among other factors (e.g., Al-Hamdani et al. 2007, Al-Hamdani & Reker 2007, Kaskela et al. 2014, EMODnet Geology 2016).

Some of the available datasets, especially from the deeper open sea areas, were relatively old or had poor resolution (Papers I, III). Modern reliable data were mostly available for the shallow coastal areas or areas with economic value. It is very likely that high-resolution multibeam bathymetry data, which are not yet available for the whole Baltic Sea, will reveal new, more detailed information on the geological features of the seabed in the future (e.g., Greenwood et al. 2015, Dowdeswell et al. 2016). Additionally, airborne topographic light detection and ranging (LiDAR), as well as aerial and satellite images, provide opportunities to map the shallow areas (e.g., Chust et al. 2008, Kotilainen & Kaskela 2017).

There were indications that the resolutions of the spatial data and scale of the investigation were in cases too broad for accurate analyses. For instance, in places, the reefs were not as large as estimated (Paper IV), and the correlations between geodiversity and environmental data were low in the most diverse environment (Paper III). Nevertheless, the broad-scale datasets used in the papers represented the best available data at the time of the study and were considered adequate for the analyses. It is expected that the high-resolution data will increase the level of detail at the local scale, but not so much at the broad scale applied here.

It was emphasized in the Introduction that marine surveys are nowadays increasingly conducted as case studies with different research interests. It is time consuming and costly to survey the seabed. Therefore, it would be essential that frameworks for data collection and possibilities for international and multidisciplinary data sharing from different surveys would be supported, which would enable scientists and society to take full advantage of the data. For example, the research presented in Paper II placed a considerable amount of effort (e.g., workshops, guidelines, researcher exchange) into conducting surveys in Finnish and Russian waters following the same principles to enable data comparability, but despite this, the different methodologies (e.g., devices) might still have introduced uncertainties in the results. Metadata and confidence estimates are an important addition to actual data, especially for multi-source datasets. It is also a challenge for the future to develop confidence estimates for data products derived from several multi-source datasets (e.g., Foster-Smith et al. 2007, Reijonen et al. 2008). One problem in combining spatial datasets is positioning inaccuracies between datasets or positioning shifts (Reijonen et al. 2008, Papers I and III). Here, the geomorphic features were identified and validated by comparing features with well-known occurrences (Papers I, IV), similarly to Harris et al. (2014), and by using ecological data (Paper IV).

It was observed that different ground-truthing methods led to biased results and impacted on validation (Paper II, IV). Differences in the biodiversity level and benthic species content

have been discovered due to the sampling gear (e.g., Reijonen et al. 2008, Mortensen et al. 2009b, Buhl-Mortensen et al. 2012, Flannery & Przeslawski 2015 and references therein; Puro 2015, Papers III and IV). Therefore, it is important to consider that ground truthing (e.g., dive transect, video observations, grabs) meets the objectives of the study. For example, grab samples focus on soft sediment habitats, while video observations enable the observation of coarse and hard seafloor habitats; the former enable study of the infauna/sediment column, while the latter provide a visual image from a bird's (~fish)-eye view and enable the identification of the epifauna (e.g., Flannery & Przeslawski 2015 and references therein). The accuracy measure (e.g., AUC), reflecting the recorded species observations against the predictions, does not detect these types of limitations or biases of the derived models (Paper IV). It is recommended to use multiple gear types to examine general biodiversity patterns (Buhl-Mortensen et al. 2012, Flannery & Przeslawski 2015).

5.3 Seabed landscape characteristics of the Baltic Sea

The continental shelves are submarine continuations of the continents, extending from the shoreline to the continental slope. The seabed substrate distribution on the shelf is controlled by complex interactions between bedrock geology, the tectonic setting, glaciation history, sediment supply and erosion, bed stress, and slope (Reineck & Singh 1980). Tides, ice, wind-generated waves, and currents are generally the main sources of energy for eroding and transporting the marine sediments of the shelf seas at present.

The studies presented are in line with other studies stating that glaciated shelf areas are shaped by bedrock composition, glacial impact, and post-glacial processes (e.g., Winterhalter et al. 1981, Josenhans & Zevenhuizen 1990, Beaman & Harris 2003, Todd & Kostylev 2011, Shaw et al. 2014). The analyses confirmed that the underlying basement significantly impacts on the geodiversity level of the seabed on a broad scale (Papers I, III). The high geodiversity areas were located in Precambrian crystalline basement, while the more homogeneous open sea and southern areas are mainly located on sedimentary rocks. Sand covers large areas of the southern Baltic, where sedimentary rocks provide sources for sand. On average, one-third of the Baltic seafloor can be regarded as a sediment accumulation area. The crystalline bedrock areas include approximately 25% of the seafloor of the Baltic Sea, and they occur especially in the northern area. Differences in the resistance to erosion of various rock types (due to hardness, lithology, and cleavage), glacial scouring, and fault intensity all contribute to the rugged topography in crystalline basement rock areas.

During the LGM, the global sea level was more than 120 m lower than today, and parts of the current sea areas were either dry land or glaciated (e.g., Clark & Mix 2002, Clark et al. 2009, Lambeck et al. 2014). Due to glacial activity and fluctuation in the shoreline position, glacial deposits such as till and moraine, as well as coastal deposits such as boulder fields, are found on the seafloor of the formerly glaciated areas (e.g., Todd & Kostylev 2011, Shaw et al. 2014, Greenwood et al. 2015, Dowdeswell et al. 2016). In relation to this, Paper I showed that moraines can be found throughout the Baltic Sea, and the areal coverage of exposed moraines increased towards the north. Additionally, some sea valley systems coincided with fault lines, glacial outlets, and ancient rivers.

Paper III confirmed that the geodiversity of the Baltic Sea reflects the glacial influence. It was interesting that the geodiversity did not appear to reflect so much the extent or duration of glaciation, but sudden events during deglaciation. When geodiversity levels were compared with deglaciation patterns, peaks that correlated with the openings of the sea connections and sea-level lowerings were noticed. Sediment deformations related to the sea-level changes have been identified in limited seabed areas, which have been interpreted as debrites triggered by rapid base-level lowerings (Hyttinen et al. 2011). Paleoseismic events, which were most likely activated when the ice sheet was retreating from a certain area and bedrock stresses were released through lineaments and fracture zones (Kotilainen & Hutri 2004, Hutri et al. 2007), might have impacted on the seabed environment. Based on the results, it appears that these abrupt

geological events have had a significant impact on the seabed environment that is still evident in the vicinity of the edge of the ice sheet. Moreover, the glacial influence continues to affect the seafloor processes of the Baltic Sea even today, because glacial-isostatic uplift continuously raises new material into shallower areas of active erosion (Ekman 1996, Kakkuri 2012).

Besides bedrock and glacial impact, geodiversity was associated with roughness, slope, the land uplift rate, distance to the coast and shore density. Coastal areas are energetic and active environments where various processes modify the seabed, resulting in high seafloor diversity. In particular, the areas with a high shore density, the archipelagos, are very heterogeneous. These contrast with open sea areas, which are typically more flat and stable areas (and located on sedimentary rocks). For instance, the Arkona Sea, the Bornholm Sea, and the Gulf of Riga have homogeneous seafloor environments with plains, basins, and elevations covering the majority of these sub-regions (Papers I, III). The correlation with roughness and slope was self-evident, because generally high values indicate a dynamic environment with areas of erosion and sedimentation that take place within short distances. The significance of these variables was further explained by the fact that they reflect the structural aspects of the bedrock itself, which are due to long-term pre-glacial and glacial processes. Additionally, basal roughness might be linked with the former ice stream flow and basement properties.

The dissertation study demonstrated that the Baltic Sea sub-regions differ from each other in their geological/landscape characteristics, although some sub-regions are more similar than others (Papers I and III). Generally, the southern sub-regions resemble each other in their geological features, but diverge from the northern areas, while the northern areas are alike. As noted above, geodiversity in the Baltic Sea is noted to increase towards the north and from open sea to high shore density areas (Paper III).

One could attempt to delineate sub-regions based on the seabed landscape/geological characteristics presented in Papers I and III. Where would the thresholds be? Both papers support separating crystalline bedrock areas from sedimentary rock areas, the latter being more homogeneous in terms of geodiversity. Coastal areas and especially archipelagos could also be delineated from open sea areas. Archipelagos serve as high geodiversity regions and include a variety of seabed geomorphic features. Besides, they are also areas with potential rocky reef occurrences, which are among the key habitats. The Baltic Sea is a generally shallow and flat seabed area, supported by the statistic that plains cover about 50% of the seafloor. Thus, deep areas with steep slopes such as the Åland Sea, High Coast, the area south of Stockholm, and the Swedish coast around the Sound represent exceptional environments that have also been linked with geodiversity. In addition, (coastal) areas with clusters of sea valleys and troughs, which often serve as water passages and transport nutrients, should be separated as specific seafloor environments. Complex substrate elevations are characteristic of the northern Baltic Sea, and especially in Kvarken area, with intensive isostatic up-lift continuously exposing new areas to erosion and revealing glacial deposits such as till and moraines (Reijonen 2004, Kotilainen et al. 2012, Kotilainen & Kaskela 2017). Furthermore, a correlation between a land-uplift rate above 2 mm/y and geodiversity was observed (Paper III). The results promote the lineation of the uplift zone occurring in the northern Baltic Sea. Isostatic uplift enables continuous succession from the seabed to the coastal area, and the shallow areas in the uplift zone are consequently generally younger than in the central and southern Baltic Sea. No relationship between geodiversity and water depth was observed, although geodiversity was generally lower in areas deeper than 80 m, which are also below the permanent halocline. This and other studies support the separation of areas deeper than 80 m from shallower areas (Winterhalter et al. 1981, Kohonen & Winterhalter 1999, Myrberg et al. 2006).

In Paper III, it is noted that three geodiversity parameters showed more analogous patterns in sedimentary rock areas than in crystalline rock areas. The correlations were also weaker in crystalline rock areas. Generally, crystalline rocks were identified to include higher geodiversity than sedimentary rocks. The broad scale of the study (the neighborhood of the analyses and low resolution data) probably prevented the capture of associations between geodiversity and environmental variables in the most fragmented seabed areas. Therefore, the scale of future

analyses should consider the geodiversity of the seabed environment.

5.3.1 Archipelagos

Vast archipelagos are a particular feature of the central and northern part of the Baltic Sea (Niemelä et al. 2015). The Stockholm Archipelago and Archipelago Sea contain tens of thousands of islands and are probably among the largest archipelagos in the world. Based on Papers I and IV, elevations with rock are characteristic of the archipelagos and coincide with Precambrian basement rocks, which have suffered glacial scouring and over-deepening of pre-existing drainage channels. At present, the most resistant materials, mainly granites and gneisses, stand out as elevated structures forming islands and rocky reefs, and material in between has been eroded, thus forming submarine channels. The elongated deep-sea troughs characteristic of the Åland Sea and the Archipelago Sea partly coincide with fault lines and thrust zones, and serve as important water passages that connect the Baltic Proper with the Gulf of Bothnia (Winterhalter et al. 1981, Koistinen et al. 1996). Additionally, Papers I and IV showed that glacial deposits, such as eskers and moraines, are typical of the Gulf of Finland and the northernmost archipelagos, or of specific zones within the Archipelago Sea. Elevations of sand are typical of the submarine area around the Salpausselkä formation (Paper IV), and moraine formations such as De Geer moraines characterize the both terrestrial and submarine landscape of the Kvarken Archipelago (Breilin et al. 2004, 2005, Reijonen 2004, Kotilainen et al. 2012, Kotilainen & Kaskela 2017).

The archipelagos can be divided into zones that run parallel to the coastline and represent the gradient from coastal areas to more open sea conditions: the sheltered inner archipelago, the middle archipelago and the exposed outer archipelago (e.g., Häyrén 1900, Jaatinen, 1960, Granö et al. 1999). At the simplest, the archipelago zones have been defined based on land to sea ratio. The archipelago zonation has been noted to influence hydrographic properties, terrestrial vegetation, coastal geology, fish, and benthic communities (e.g., von Numers & van der Maarel 1998, Hänninen et al. 2000, 2007, Korvenpää et al. 2003, O'Brien et al. 2003, Vahteri et al. 2009). Nevertheless, it has been proposed that the zoobenthic communities in the archipelago are not delineated by surface boundaries, i.e. the land-to-sea ratio, but by depth and factors related to it (O'Brien et al. 2003). In addition, the transitional patterns of water properties from the inner to the outer archipelago (Archipelago Sea) are in cases prone to anomalies. For example, temperature and chlorophyll-a have shown geographically divergent seasonal developments (Suominen et al. 2010). Papers II and IV, which focused on the archipelago areas of the eastern Gulf of Finland and Archipelago Sea, respectively, support the view that the land-to-sea ratio does not capture the true variability of the seabed environment.

Paper II analyzed benthic assemblages against environmental variables. According to the results, variables describing the archipelago gradient, the abundance of islands, and ratio of land to sea, correlated with zoobenthic sample data. However, the land-to-sea ratio (e.g., archipelago zonation) received lower correlation values ($\rho < 0.40$) than the abundance of islands ($\rho > 0.40$). In contrast to the archipelago gradient, the number of islands did not take account of the size of the islands, and small skerries had the same weighting as larger ones. The results also revealed a strong correlation between benthic assemblages and seabed roughness. The influence of both roughness and the archipelago gradient appeared to increase with the spatial scale. These broad spatial scales were probably partly related to certain functional processes such as water circulation, sediment transport, or zoobenthic behavior. This was supported by the fact that salinity co-varied with depth, roughness, and island abundance. It was explained that numerous islands and the complexity of the seabed could form a submarine labyrinth, controlling water movement and hydrographical conditions. Geomorphic features and the physical complexity of the seabed generate transport channels and submarine sills that could result in the formation of sheltered bays with limited flushing and occasional anoxic conditions. Generally, oxygen deficiency is related to deeper areas, but within the archipelago environments, seasonal anoxia or even decades-long anoxic conditions have been recorded from shallow depths (O'Brien et al. 2003, Virtasalo et al. 2005, Vallius 2006, Koti-

lainen et al. 2007, Lukkari et al. 2009, Vallius et al. 2011). Oxygen depletion is among the greatest pressures affecting the achievement of a good environmental status of the benthic habitats of the Baltic Sea (Korpinen et al. 2013).

Paper IV included the modeling of specific geomorphic features, namely, rocky reefs, in the Archipelago Sea. Generally, the main material of elevated structures within the study area consisted of rock and boulders, indicating energetic seafloor conditions. Potential reefs were primarily concentrated in the exposed outer archipelago, and they often extended above the surfaces, forming skerries. Thus, what was observed on the sea surface did not represent a true image of the seabed area. Examining the reef distribution presented in Figure 4 of Paper IV, it can be seen that rocky reefs already form a submarine labyrinth in the outer archipelago, and the small skerries are actually crests of larger rocky elevations, which will grow into larger islets and islands due to land uplift.

The research presented promotes further studies on the inclusion of seabed characteristics into archipelago zonation and benthic analyses. Archipelagos of the Baltic Sea are sensitive environments with high geodiversity. They provide several ecosystem services, with the Stockholm Archipelago, for example, being of major significance as a recreational area (Sandström et al. 2000). The functionality of the sensitive archipelagos should be preserved and spatial knowledge of the basins sensitive to anoxia could assist in the effective management of the archipelagos, for example.

5.4 Associations between geological characteristics and benthic assemblages

Relationships between organisms and environmental variables are scale dependent (e.g., Zajac et al. 2003, Post 2008, Williams et al. 2010, Last et al. 2010, Buhl-Mortensen et al. 2012, Zajac et al. 2013). It is known that the seabed substrate strongly influences zoobenthic communities on local and regional spatial scales within the Baltic Sea (e.g., Rousi et al. 2011, Snickars et al. 2014, Weigel et al. 2015). Certain geomorphic features also define the distribution of the benthic biota and biodiversity (e.g., Harris & Baker 2012 and references therein, Paper IV), and abiotic aspects of the habitat complexity influence the benthic communities (e.g., Kostylev et al. 2001, Olenin & Daunys 2004, McArthur et al. 2010, Shumchenia & King 2010, Harris & Baker 2012b, Buhl-Mortensen et al. 2012, LaFrance et al. 2014). Abiotic heterogeneity reflects the abundance of varying habitats, spatial variation in resources, and thus biodiversity (e.g., Burnett et al. 1998, Nichols et al. 1998, Dufour et al. 2006, Parks & Mulligan 2010, Stein et al. 2014, Paper II). The geodiversity parameters roughness, substrate variability, and substrate patchiness, which also describe abiotic heterogeneity, have been correlated with benthic assemblages on the marine landscape scale (e.g., LaFrance et al. 2014, Paper II). Results suggest that geodiversity influences benthic assemblages on broad spatial scales, whereas seabed substrates and geomorphic features affect benthic assemblages at more local scales (Paper II, Paper IV).

The correlation between geodiversity and biodiversity is not necessarily one-to-one. Paper III observed that the most complex landscape did not include the highest biodiversity. As mentioned earlier, it was explained that topographic complexity could result in complex hydrological systems that limit circulation and lead to hypoxic/anoxic conditions. It is also possible that the upper ranges of physical complexity reflect habitat fragmentation rather than habitat heterogeneity (as explained by Tews et al. 2004). Seabed geodiversity results in greater habitat complexity, but biodiversity also depends on the health of the seabed environment and active processes.

Paper IV was successful in assigning ecological value to potential rocky reefs. It also noted that rocky habitats on large complex reefs reaching the surface several times resulted in a higher species number than those in more isolated reefs. These large reefs were probably better connected to each other, in contrast to smaller elevations separated by deeper trenches, emphasizing the importance of connectivity.

The results support further studies on seabed geodiversity, connectivity, and biodiversity in order to promote a functional network of marine protected areas.

5.5 Results in the context of ESBM and other uses

Effective transnational marine spatial planning requires extensive knowledge of the environmental characteristics of the region in question (e.g., Collie et al. 2013). It is relevant to ask how it is possible to describe the marine ecosystems with insufficient datasets. It is highly unlikely that all marine areas will be surveyed with a detailed resolution in the coming decades (e.g., Weatherall et al. 2015). In ESBM, it has been considered that some species are more important than others to maintain the function and resilience of the marine ecosystem, and that it is logical to conserve the ones we know are important (Crowder & Norse 2008). Similar to this, scientists should strive to recognize the most important features that support the functioning of marine ecosystems in the long term.

Analyses of seabed geomorphic features and geodiversity provide consistent information on the physical marine environment (Papers I–IV) and deliver background data for ESBM and for European directives such as the Habitats Directive (Directive 92/43/EEC), the Water Framework Directive (Directive 2000/60/EC), the Marine Strategy Framework Directive (Directive 2008/56/EC), and the Maritime Spatial Planning Directive (Directive 2014/89/EU). It should be noted, however, that this dissertation aimed to characterize broad-scale characteristics of the seafloor, which are useful for management at a national or international level. The results should not be used in local-scale management or for the conservation of a particular threatened species or iconic feature.

Conservation of ecosystem structure and functioning is one of the main principles of the ESBM (Pirot et al. 2000, Secretariat of the Convention on Biological Diversity 2004). Ecosystems are not stable but adapt to changes in the surrounding environment (Pirot et al. 2000, Secretariat of the Convention on Biological Diversity 2004, Long et al. 2015). Oceans have changed their size and shape throughout geological history; during glaciations, the sea level has lowered and in interglacials the sea level has been elevated. High sea-level conditions, such as at present, have only occurred for about 12% of the time during the past 150,000 years (Harris & Baker 2012). The advance and retreat of ice sheets have been central to the development of the benthic environments occurring across the shelf environments, and many relict glacial features form unique benthic habitats (e.g., Post et al. 2011, Todd & Kostylev 2011, Harris 2012 and references therein, Shaw et al. 2014). The same is valid for the Baltic Sea (Winterhalter et al. 1981, Papers I and III). All species living on the continental shelf at present are colonists that have arrived in the last 10,000 years or less (Harris 2012). The ecological age of the Baltic Sea dates back about 8000 years, and several uninhabited ecological niches are still available (Bonsdorff 2006). Moreover, the current climate change scenarios estimate a relative sea-level rise of around of 0.60 m near Hamburg and a relative sea-level fall of 0.35 m in the Bothnian Bay by 2100 (Grinsted 2015). Baltic-scale variations in sea-level change are due to the local compensation of GIA.

Recognition of the inevitability of change is critically important to the ESBM (Pirot et al. 2000, Secretariat of the Convention on Biological Diversity 2004). It has been recommended that conservation sites should include a range of environments, allowing organisms to adjust to changing environmental conditions (Hunter et al. 1988). The conservation of geological features and geodiversity might support the long-term protection of natural succession, biological processes, and biodiversity, because geological features are more stable in time than biological communities (Hunter et al. 1988, Nichols et al. 1998, Anderson & Ferree 2010, Beier & Brost 2010, Parks & Mulligan 2010, Hjort et al. 2012, Gill et al. 2015, Paper I, Paper III). Erosion and deposition generally influence geodiversity on very long time scales, even though abrupt events such as major storms, changes in drainage or human-induced perturbations may alter the benthic environment on short time scales (Nuorteva & Kankaanpää 2016, Paper III). Areas that represent the diversity of the current abiotic conditions probably encompass a broad enough range of environments to allow organisms to adjust their local distribution in response to long-term environmental change (e.g., Hunter et al. 1988, Nichols et al. 1998).

Furthermore, spatial data on geodiversity and geomorphic features can be applied to identify the most important areas for future studies and to recommend which types of environments

need more protection. Geomorphic knowledge can help identify the critical life habitats and advance the application of ESBM to the design of marine reserve networks (e.g., Halpern et al. 2008, Wright & Heyman 2008, Harris 2012). For example, the rocky reefs defined in Paper IV provide spatial data the Habitats Directive, which calls for the creation of a network of special areas of conservation, i.e. the Natura 2000 network. Other potential applications of marine geomorphological mapping in ESBM include wave energy modeling, renewable energy exploitation, determining essential fish habitats and habitat suitability for economically-important species, fishing resources, dredged sediment disposal management, the valuation of ecosystem goods and services, the development of biological quality indices, land–sea exchange modeling, and human activity sensitivity maps (Galparsoro et al. 2010 and references therein).

ESBM should acknowledge the influence of the functional links between geodiversity and biodiversity (Gray et al. 2013). High geodiversity areas can be used to target surveys to optimal areas with the maximum diversity of habitats to inform on the dynamics of the seafloor environment (Paper I, Paper II, Paper III). It is suggested that on the mesoscale, a high degree of seabed geodiversity may override the influence of specific seabed features in determining zoobenthic assemblages (Paper II). Areas with high geodiversity are also candidates for a MPA within a region, allowing perhaps the maximum biodiversity to be protected within the smallest possible area (Harris et al. 2008, Harris & Whiteway 2009). Generally, maps of seabed landscapes or high seafloor complexity can be used to direct certain anthropogenic activities such as underwater constructions, sand extraction, and aquaculture to the most suitable areas and to develop guidelines/frameworks for the monitoring of environmental impacts (e.g., Inger et al. 2009, Punt et al. 2009, Handley et al. 2014, Ucinowicz et al. 2014). It is likely that detailed surveys are needed to fully describe conditions over fragmented landscapes, whereas less detailed surveys might be sufficient over homogeneous, flat landscapes (see e.g., van Son et al. 2015).

Often, ecosystem studies primarily address the biotic parts or treat abiotic characteristics only as complementing biodiversity (e.g., see Foley et al. 2010 and references therein). Nevertheless, the ecosystem consists of both its biotic and abiotic parts and their interactions. Geodiversity is not just a complement of biodiversity, but a fundamental part of natural diversity (Serrano & Ruiz-Flanõ 2007). Geodiversity has intrinsic value and it provides abiotic ecosystem services (Gray 2011, Gray et al. 2013). It provides resources that can help society to adapt to climate change and to mitigate its consequences through an improved understanding of natural processes, among others (Gordon et al. 2012). Geodiversity should be integrated as a scientific tool together with biodiversity to obtain territorial understanding and land management information (Serrano & Ruiz-Flaño 2007, Paper III).

Spatial information on important ecosystem features is critical in conservation and marine spatial planning. Papers I and III have confirmed that the seabed landscape characteristics of the Baltic Sea vary between locations, and that they reflect the bedrock type, glacial history, and ongoing geological processes. The maps presented in Paper IV serve as a valuable background for the more detailed mapping of the species diversity on reefs, as well as for monitoring their ecological status. The results of Paper II were conveyed to decision makers in charge of the maritime spatial planning process of the Kymenlaakso area, and as a consequence, an area of high geodiversity has now been acknowledged in the maritime spatial plan of the Finnish eastern Gulf of Finland (Kymenlaakson Liitto 2014).

It is also notable that marine maps do not just serve scientific knowledge and ESBM, but additionally promote public engagement with the marine environment (e.g., Cogan et al. 2009). The underwater world is largely invisible, and submarine maps, such as those included in this dissertation, can be used to raise awareness and communicate the status of the marine ecosystem to the general public. Similarly to the Blue Marble and the other images from space, submarine maps are among the tools for visualizing the unseen.

6 CONCLUSIONS

The seabed of the Baltic Sea is primarily characterized by various plains and basins. Elevations and features such as valleys, holes, and troughs are locally concentrated. Sand occurs in the southern Baltic Sea and Bothnian Bay. The coverage of exposed moraines increases towards the north. Sediment accumulation areas cover approximately one-third of the Baltic seafloor.

The seabed geodiversity of the Baltic Sea varies between sub-regions. The seabed geodiversity of the Baltic Sea generally increases from south to north and from open sea to areas with a high shore density. Crystalline bedrock areas provide more diverse seabed environments than sedimentary rock areas. The associations between environmental parameters and geodiversity were lower in crystalline rock areas than in sedimentary rocks, which indicates a need for higher data resolution and a shorter analysis neighborhood in these areas.

Archipelagos stood out as seabed areas with high geodiversity. The results suggest that the numerous islands, rocky reefs and complexity of the seabed might form a submarine labyrinth, which already controls water movement and hydrographical conditions in the outer archipelago.

Differences in the geomorphic content and geodiversity levels of the Baltic sub-regions are due to the basement rock type, glacial history, and ongoing processes. Geodiversity was especially related to roughness, shore density, and glacier-derived processes. The results suggest that geodiversity is not related to the extent or the duration of the ice sheet, but to certain geological events during the last deglaciation.

Geological features and geodiversity were examined in relation to benthic assemblages to determine the benthic marine landscapes of the eastern Gulf of Finland. The results indicate that at broad spatial scales, geodiversity overrides the influence of the seabed substrate and geomorphology. The landscapes found in topographically complex seabed areas possessed higher species diversity than more homogeneous areas. High geodiversity and archipelago gradient might directly influence the benthic assemblages and biodiversity by providing a multitude of habitats and indirectly by channeling water movement.

Key habitat features, rocky reefs, were identified in a complex archipelago area in the northern Baltic Sea using the best, although limited, data currently available. Rocky reefs were defined with geomorphic terms. The study demonstrated that potential key habitats can be extrapolated from the existing sources in areas without high resolution data with good accuracy and ecological validity.

The results provide spatial information for scientists, marine spatial planners, and managers on the seabed characteristics of the Baltic Sea based on geological data. Geodiversity should be acknowledged in the ecosystem-based management of marine areas, because it has intrinsic value, it provides several abiotic ecosystem services, and is associated with the biodiversity and long-term conservation of the marine environment.

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TERMINOLOGY

Abiotic ecosystem service. Ecosystem services that are related to geodiversity can be termed 'abiotic ecosystem services'. These include regulating (e.g. terrestrial processes including the rock cycle and carbon cycle), provisioning (e.g. minerals, construction materials), supporting (e.g. habitats), and cultural services (e.g. geotourism, knowledge). (Gray 2011, Gray et al. 2013).

Ancylus Lake. Ancylus Lake was a stage in the history of the Baltic Sea. It was a freshwater stage, which took place around 10.7–9.8 ka BP.

Baltic Ice Lake. The Baltic Ice Lake refers to a freshwater lake that gradually formed in the Baltic Sea basin during the last deglaciation. The Baltic Ice Lake dates back to around 17.0–11.7 ka BP.

Bathymetric position index (BPI) (also topographic position index, TPI). The bathymetric position index is a second-order derivative of bathymetry. The BPI is derived as a measure of where a certain georeferenced location, with a defined elevation, is relative to the general landscape. The derivation involves evaluating elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined neighborhood. (Lundblad et al. 2006, Wright et al. 2012).

Benthic terrain modeler (BTM). Benthic Terrain Modeler is an ArcGIS extension that was developed by the NOAA Coastal Services Center's GIS Integration and Development program in cooperation with the Oregon State University Davey Jones Locker Seafloor Mapping/Marine GIS Lab. The extension analyzes the benthic terrain from input (multibeam) bathymetry in ESRI's GRID (raster) format and allows users to create grids of the slope, bathymetric position index, and rugosity from an input data set. (Wright et al. 2012).

Biodiversity. Biodiversity refers to the variability among living organisms from all sources, including, *inter alia*, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part: this includes diversity within species, between species, and of ecosystems (United Nations 1992).

Blue growth. The Blue Growth Strategy was adopted by the European Commission in 2012. It is a long-term strategy to support sustainable growth in the marine and maritime sectors as a whole. (European Commission 2012).

Echosounder. (Single-beam) An echosounder uses sound waves to measure water depth and sometimes also the properties of the soft sediments below the seafloor. The time interval between the emission and return of a pulse is recorded, which is then used to determine the depth of water and/or thickness of sediment units under the survey track line. Single-beam echosounders use high-frequency sound waves. For example, GTK's echosounder, which also detects sediment properties, uses a frequency of 28 kHz. Echosounder data can be processed to provide a visual profile of the seabed sediments/sedimentary units.

Ecosystem. An ecosystem comprises all the living organisms in an area, and the way in which they influence each other and the environment.

Ecosystem-based management (ESBM). Ecosystem-based management is as an interdisciplinary approach to marine spatial planning, which balances ecological, social, and governance principles at appropriate temporal and spatial scales in a distinct geographical area to achieve the sustainable use of the resources (Long et al. 2015).

Ecosystem service. Ecosystem services are the benefits provided by ecosystems, which include provisioning (e.g. food and water), regulating (e.g. regulation of climate), cultural (e.g. recreation), and supporting services (e.g. nutrient cycling) (Millennium Ecosystem Assessment 2005).

EMODnet. The European Marine Observation and Data Network (EMODnet) consists of organizations assembling marine data, products, and metadata to make them more available to public and private users relying on quality-assured, standardized, and harmonized marine data which are interoperable and free of restrictions on use. For further information, see: http://www.emodnet.eu/.

Geoconservation. Geoconservation can be defined as action taken with the intent of conserving and enhancing geological and geomorphological features, processes, sites, and specimens (Burek & Prosser 2008).

Geodiversity. Geodiversity takes into account the natural range of geological, geomorphological, and soil features, as well as their assemblages, relationships, properties, interpretations, and systems (Gray 2004).

Geodiversity index. The geodiversity index aims to assess the level of geodiversity. It relates the variety of physical elements with the roughness and surface of the previously established geomorphological units according to the following formula: Gd Eg R / Ln S, where Gd = geodiversity Index, Eg = number of different physical elements in the unit, R = coefficient of roughness of the unit, S = surface of the

unit (km^2), and Ln = neperian (in cases replaced by natural) logarithm. (Serrano & Ruiz-Flaño 2007, Hjort & Luoto 2010).

Geographic information system (GIS). A geographic information system refers to a computer system that stores, organizes, and analyses data that relate to the position, area, or size of objects.

Geomorphometry. The science of quantitative terrain analysis, which combines mathematics, earth sciences, engineering, and computer science, is called geomorphometry (Pike et al. 2008).

Glacial isostatic adjustment (GIA). Glacial isostatic adjustment describes the ongoing adjustment process of the earth once burdened by ice sheets.

Last Glacial Maximum (LGM). The Last Glacial Maximum refers to the period during the latest glacial when the global ice sheets reached their maximum integrated volume.

Litorina Sea. Litorina Sea is a brackish-water stage of the Baltic Sea, which started around 8.5 ka BP and has transformed into the current Baltic Sea.

Marine landscape (also seascape, benthoscape). Marine landscapes are combinations of ecologically determined hydrographic, bathymetric, and geological datasets that characterize potential broad habitat distribution patterns (Roff & Taylor 2000). The approach informs conservation efforts that seek to optimize biodiversity (rather than a particular species) in a given area. The International Council for the Exploration of the Sea (ICES) specifies that the term 'marine landscape' is similar to the term 'habitat' in that it refers to an area of integrated landforms and biota, but covers a broader spatial area.

Marine protected area (MPA). A marine protected area is any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment (Kelleher 1999).

Marine spatial planning (MSP) (also maritime spatial planning). Marine spatial planning is a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that are usually specified through a political process (Ehler & Douvere 2009).

Multibeam echosounder (MBES). Multibeam echosounders collect bathymetric soundings in a swath perpendicular to the ship track by electronically forming a series of transmit and receive beams in the transducer hardware which measure the depth to the seafloor in discrete angular increments or sectors across the swath (Hughes-Clarke et al. 1996).

Patchiness. Within this dissertation, patchiness refers to a geodiversity parameter that analyses the number of individual geological patches over a certain neighborhood.

Richness. Within this dissertation richness refers to a geodiversity parameter, which analyses the variability of the different geological feature types over a certain neighborhood.

Seabed landscape. Within this dissertation, seabed landscape refers to the physical landscape of the seabed and includes geomorphic features, substrates, and geodiversity.

Seismic profiler. Seismic profiles provide data on seafloor sub-bottom properties. The system includes an acoustic wave generating seismic source and one or more receivers of the reflected signal. Seismic profilers use low frequency acoustic waves (e.g. GTK's ELMA has frequency range of 250–1300 Hz), which also penetrate coarser material of the seafloor. Seismic profiling includes the following phases: first, the acoustic waves are emitted from the source to the seabed; then, the transmitted acoustic waves are reflected from boundaries between various layers with different acoustic properties (e.g. geological units); and finally, the energy reflected back from the solid seabed layers is received by hydrophones and the data are processed so that a visual profile of the seabed geological units can be created.

Side scan sonar (SSS). Side scan sonar creates an image of the surface properties of the seafloor and provides information on the distribution of the surficial substrate. It is accomplished by towing a sonar device that scans the seafloor by emitting fan-shaped acoustic energy pulses down and later receives the returned acoustic pulses. The intensity of the acoustic reflections from the seafloor depends on the material. For example, hard areas such as rock reflect more sound and have a stronger return signal than softer materials. The typical frequencies of side scan sonars range from 100 to 500 kHz.

Sustainable development. Sustainable development aims at meeting the needs of the present without compromising the ability of future generations to meet their needs (WCED 1987).

Yoldia Sea. Yoldia Sea was a brackish water stage of the Baltic Sea subsequent to the Baltic Ice Lake. It occurred around 11.7–10.7 ka BP.

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The realization of effective marine spatial planning often suffers from incomplete and scattered marine data over large areas. However, technological advances in statistical analysis and geographic information systems (GIS) have enabled the development of new applications to map the marine environment based on pre-existing spatial data. This PhD thesis is comprised of a synopsis and four original papers that present a GIS-based approach to analyzing and characterizing the geological seabed environment of the Baltic Sea. It combines scattered data to produce spatial representations of the Baltic Sea in terms of the seabed geomorphic features, marine landscapes, and geodiversity. Additionally, potential key habitats, rocky reefs, were extrapolated from the existing sources with good accuracy and ecological validity.

The results deepen our understanding of the geological characteristics of the Baltic Sea and provide spatial information on the seabed for scientists, marine spatial planners, and managers. The overall geological landscape of the Baltic Sea is characterized by plains and basins, and other geomorphic features, such as elevations and valleys, are characteristic of certain sub-regions. The seabed geodiversity generally increases from south to north and from the open sea to areas with a high shore density. Differences in the geomorphic content and geodiversity of the Baltic sub-regions are due to the basement rock type, glacial history, and ongoing processes. A high geodiversity and archipelago gradient might directly influence the benthic assemblages and biodiversity by providing a multitude of habitats and indirectly by channeling water movement. The results emphasize that seabed geological features and geodiversity should be acknowledged in marine spatial planning, because they have intrinsic value and they provide several abiotic ecosystem services, among others.

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