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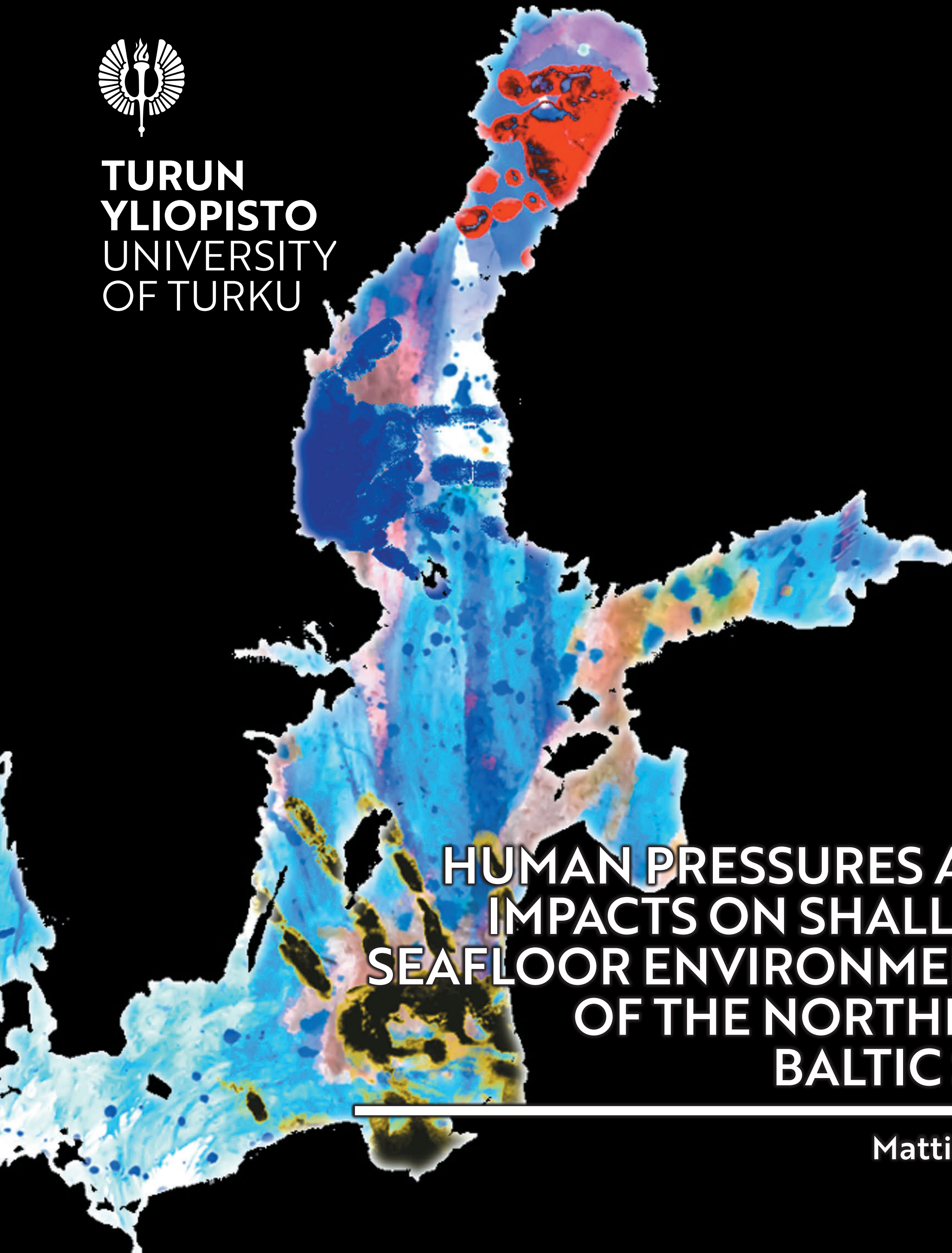

HUMAN PRESSURES AND IMPACTS ON SHALLOW SEAFLOOR ENVIRONMENTS OF THE NORTHERN BALTIC SEA

Matti Sahla

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ABSTRACT

Unsustainable use of coastal resources and space has resulted in global degradation of marine environments. Stopping adverse development requires improved understanding of how different human activities affect nature. International treaties and national legislation have been established to stop widespread environmental deterioration, but targeted local actions are still needed. Comprehensive planning processes such as marine spatial planning (MSP) and integrated coastal zone management (ICZM), promote sustainable development of coastal regions and additionally require evaluation of human influence on the marine environment.

In this thesis, I examine human pressures and impacts on the shallow seafloor environments of the northern Baltic Sea. The general aim of this work is to improve the quality of location-based human pressure and impact evaluations on marine environments. The work contributes to developing environmentally conscious coastal planning by improving knowledge and introducing new methodological solutions for pressure and impact evaluations. A great variety of spatial data has been used in this work, ranging from LiDAR point clouds to species-specific monitoring data. The analysis processes in the research utilizes and combines methodologies of scenario assessments, spatial modeling and statistical examination with a geographical approach.

The results of this study display the possibilities and uncertainties of detailed remote sensing data, categorized biotope data and different modeling approaches when evaluating human pressures and impacts on shallow seafloor environments. This thesis also discusses the possibilities for utilizing open source data on benthic environments and human activities to support sustainable planning decisions. The work also reveals large-scale degradation of benthic keystone species *Fucus* spp. in the Finnish coastal areas using modeling and species monitoring data. The main findings of this thesis provide new geographical insights on human pressure and impact evaluations that can promote sustainable planning decisions in coastal regions.

KEYWORDS: human pressure, human impact, benthic communities, Baltic Sea, marine spatial planning, coastal planning, spatial modeling

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TIIVISTELMÄ

Rannikkoalueiden ja rannikon resurssien kestämätön käyttö on heikentänyt meriympäristöjen tilaa maailmanlaajuisesti. Kehityksen suunnan kääntäminen edellyttää luotettavaa tietoa ihmisen toiminnasta sekä sen vaikutuksista rannikoiden luontoon. Vaikka kansainväliset sopimukset ja kansalliset lait pyrkivät osaltaan estämään luonnon tilan heikkenemistä, niiden lisäksi tarvitaan paikallisia toimia. Esimerkiksi laaja-alaiset rannikoilla tehtävät suunnitteluprosessit, kuten merialuesuunnittelu (MSP) ja rannikkoalueiden yhdennetty käyttö ja hoito (ICZM), tavoittelevat kestävää kehitystä, mutta niiden tulee pohjautua luotettavaan tutkimustietoon.

Tutkin väitöskirjassani ihmistoiminnan aiheuttamia paineita ja niiden vaikutuksia pohjoisen Itämeren mataliin merenpohjaympäristöihin. Tavoitteenani on parantaa näitä ympäristöjä kuvaavien alueellisten ihmistoimintaan kytkeytyvien paine- ja vaikutusarviointien laatua ja siten tukea matalien merenpohjaympäristöjen erityispiirteet huomioivaa rannikkosuunnittelua. Käytän tutkimuksissani monipuolisia paikkatietoaineistoja LiDAR –pistepilvistä yksittäisten lajien seuranta-aineistoihin. Teen monen tyyppisiä maantieteellisiä analyyseja hyödyntäen ja yhdistellen erilaisia skenaariomenetelmiä, alueellisia paikkatietomalleja ja tilastollisia menetelmiä.

Tutkimukseni tulokset osoittavat yhtäältä yksityiskohtaisten kaukokartoitus-aineistojen, luokiteltujen biotooppiaineistojen ja erilaisten mallinnusmenetelmien arvon keskeisinä merenpohjien tilaa käsittelevän tiedon lähteinä, mutta tuovat esille myös niiden käyttöön liittyviä epävarmuuksia. Työssä tarkastelen erityisesti, miten avoimia tietolähteitä voidaan hyödyntää rannikon kestävän käytön suunnittelussa. Käytän myös mallinnusmenetelmiä ja lajitasoista seurantatietoa osoittaakseni rakkohaurujen (Fucus spp.) taantuneen laaja-alaisesti Suomen rannikkoalueilla. Väitöskirjani keskeisenä tuloksena on, että maantieteellinen lähestymistapa ja alueellinen työskentelymenetelmä vahvistavat rannikkoalueiden kestävää käyttöä ja suunnittelua tukevaa tietopohjaa.

ASIASANAT: ihmistoiminnan paine, ihmistoiminnan vaikutus, merenpohjan yhteisöt, Itämeri, merialuesuunnittelu, rannikkosuunnittelu, levinneisyysmallinnus

Acknowledgements

Making this thesis has been a path of continuous learning. Many of the papers in this work have started from wildly branching ideas and ended up with still too many analysis paths. If I could go back in time and leave myself a note when I was starting the process, it would probably say “Keep it simple, stupid!”. Although the PhD process was not a straightforward path, I´m glad I chose it. Unlike most of PhD students, I have not been working with research funds or conducted the research within a research organization. Writing mainly outside working hours, or during “coffee breaks”, has brought some challenges, but also helped to maintain perspective on what kind of research is relevant outside the academic community. Many of the analysis in this thesis have been sparked by ongoing work related to marine protection and marine spatial planning in Parks & Wildlife Finland.

I would like to express deep gratitude to my supervisors Professor Risto Kalliola and Adjunct Professor Harri Tolvanen for their consisted support and encouragement. Risto taught me what it means to plan and conduct professional research and how to critically evaluate my findings. Harri provided his solid expertise and good comments to drive this thesis forward. Many thanks also to Harri and Risto for the input as co-authors in the papers. I would also like to sincerely thank my other co-authors Michael Haldin, Ari Ruuskanen, Lasse Kurvinen, Henna Rinne, Minna Boström and Charlotta Björklund for making this thesis possible. Jan Ekebom deserves special thanks for hiring me as an internee at Parks & Wildlife Finland and getting me involved into the world of marine protection.

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Table of Contents

Abbreviations

BRT	Boosted Regression Trees
COG	Corrected Observation Gradient
EADM	Expert Assisted Distribution Modeling
EIA	Environmental Impact Assessment
EU	European Union
EQR	Ecological Quality Ratio
GAM	Generalized Additive Modeling
HELCOM	Helsinki Commission
HUB	HELCOM Underwater biotope and habitat classification system
ICZM	Integrated Coastal Zone Management
MSP	Marine Spatial Planning
MSPD	Maritime Spatial Planning Directive (Directive 2014/89/EU)
MSFD	Marine Strategy Framework Directive (Directive 2008/56/EC)
SDM	Species Distribution Modeling
TBT	Tributyltin
WFD	Water Framework Directive
Z_{eu}	Euphotic depth

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Sahla M, Kalliola R, Haldin M. 2016. Role of benthic habitat distribution data in coastal water wind turbine site selection. [a]Ocean & Coastal Management, 124: 78-83. https://doi.org/10.1016/j.ocecoaman.2016.02.010

II Sahla M, Kalliola R. 2018. Reliability of local scale human pressure modeling at the seafloor of the Baltic Sea. [b]Coastal Management, 46(1): 40-57. https://doi.org/10.1080/08920753.2018.1405329

III Sahla M, Tolvanen H, Ruuskanen A, Kurvinen L. 2020. Assessing long term change of Fucus spp. communities in the northern Baltic Sea using monitoring data and spatial modeling. [a]Estuarine, Coastal and Shelf Science, 245: 107023. https://doi.org/10.1016/j.ecss.2020.107023

IV Rinne H, Boström M, Björklund C, Sahla M. 2021. Functionality of HELCOM HUB classification in describing variation in rocky shore communities of the northern Baltic Sea. [a]Estuarine, Coastal and Shelf Science, 249: 107044. https://doi.org/10.1016/j.ecss.2020.107044

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Author´s contribution

	I	II	III	IV
Original idea	MS, RK	MS	MS	HR
Data preparation	MS	MS	MS, AR	MB, CB, MS
Analysis planning	MS, RK	MS, RK	MS, AR	HR
Analysis	MS	MS	MS, AR	HR, MB, CB
Writing	MS, RK, MH	MS, RK	MS, HT, AR, LK	HR, MB, CB MS

MS=Matti Sahla, RK=Risto Kalliola, MH=Michael Haldin, HT=Harri Tolvanen, AR=Ari Ruuskanen, LK=Lasse Kurvinen, HR=Henna Rinne, MB=Minna Boström, CB=Charlotta Björklund

1 Introduction

Coastal seas have globally experienced notable environmental degradation due to unsustainable use of the resources and space above and below the surface (Millenium Ecosystem Assessment 2005). Especially coastal industries, fishing, construction and transportation have impacted heavily on marine biodiversity in seas all over the world (e.g. Breitburg & Riedel 2005; Crain et al. 2009). Worldwide phenomena, such as global warming, acidification of the seas and atmospheric spread of harmful substances have caused changes even in the most remote areas (CBD 2014; IPCC 2018; EMEP 2018).

Rising concern for the state of the marine environment has emerged in the latter half of 20th century, resulting in actions for the establishment of marine protected areas and international agreements regulating the use of marine space (e.g. UNCLOS 1982; Minamata Convention 2013; Leadley et al. 2014). Establishment of marine protected areas have led to positive developments on a local scale, whereas international treaties have succeeded in restricting some of the most harmful activities at sea and in coastal regions. However, comprehensive planning for the use of marine space has been scarce until the 1990´s policy development for Integrated Coastal Zone Management (ICZM) and the more recent boom of Marine Spatial Planning (MSP). The ICZM and MSP processes aim for sustainable and cost-efficient utilization of marine space (e.g. Post & Lundin 1996; Ehler & Douvere 2009). These comprehensive planning approaches have created an increasing demand for information describing human activities and environmental values in the marine areas.

Information on where human activities cause environmental degradation can help sustainable planning choices and site selection for coastal activities. Most of the anthropogenic impacts on marine environments are still insufficiently understood, and causalities of especially simultaneous activities are rarely considered in the coastal planning processes. Detailed planning requires new methodological solutions, improved spatial accuracy and assessment of prevailing uncertainties in the pressure evaluation processes.

The general aim of this thesis is to improve the spatial assessment of human impacts and pressures in marine environments. The papers included in this work contribute to developing environmentally conscious coastal planning and site selection. The work also aims to strengthen planning and site selection processes by increasing information on the spatial distribution of important benthic communities. Methods for geographical evaluation of future, current and historical pressures and impacts have been further developed during this work. The studies present multiple differing approaches for evaluating human-induced pressures and impacts on a local scale. The information requirements and uncertainties of the assessments are also examined. The work reveals a variety of vast potential pressures and impacts on benthic environments and manages to quantify large-scale deterioration in the state of underwater nature.

The main research objectives of this thesis are:

1) To derive new insights into the spatiotemporal evaluation of human-induced pressures and impacts on marine environments (Papers I, II, III).
2) To assess how data availability and properties can affect human pressure evaluations and offshore planning (Papers I, II, III, IV).
3) To quantify the changes of keystone species *Fucus* spp. caused by long term reduction of seafloor light availability (Paper III).
4) To evaluate the usability of modeled species distribution data when assessing the state of the marine environments (Papers I, III).

In the thesis papers, the scope of the research proceeds from assessing potential future pressures (I), to an evaluation of current pressures and impacts (II), followed by quantification of large-scale changes caused by past human activities (III) (see Figure 1). Paper IV focuses on evaluating categorized environmental information that has been utilized in impact evaluations.

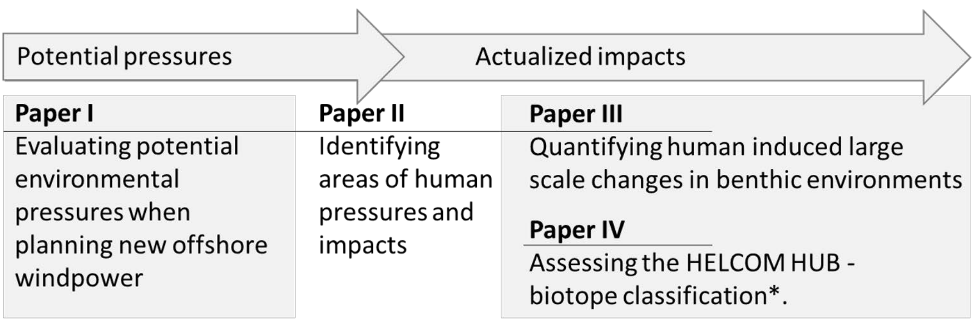

Figure 1. Overview of the general themes in Papers I-IV. *Data categorized with HELCOM HUB -biotope classification was used in Paper III.

Paper I investigates how the quality of available environmental data can affect the perceived suitability of different sites for offshore wind power placement. The outcomes of three hypothetical planning schemes with dissimilar input data on depth and *Fucus* spp. distribution are assessed. The input data is used to define suitable sites for shallow water wind turbine placement and the sites are evaluated with detailed data on *Fucus* spp. occurrence. The paper presents how placement of turbines in different depth classes influence the potential disturbance of *Fucus* spp. communities. The work also displays how new added turbines cause accumulated disturbance of *Fucus* spp. habitats in different input data scenarios.

Paper II examines the usability of cumulative human pressure modeling in the shallow seafloor and complex shoreline conditions in the northern Baltic Sea. The paper aims to reveal the most crucial informational needs of the modeling process by identifying how different pressure and environmental data affect the modeling outcomes. Cumulative human pressure modeling output is also evaluated in comparison with seafloor monitoring data.

Paper III aims to assess long term changes in *Fucus* spp. communities in Finnish coastal areas using monitoring data and spatial modeling. The paper presents how human-induced reduction in light availability on the seafloor has reduced the suitable areas for *Fucus* spp.. The reduction is evaluated with two separate analysis processes conducted with separate datasets. First, the assessment was conducted using measurement data on the lower growth limit of the *Fucus vesiculosus* belt and analyzing the change over time. In the second approach, past and present suitable seafloor areas for *Fucus* spp. biotope were modeled utilizing historical Secchi depth measurement data.

Paper IV evaluates how HELCOM HUB biotope classification manages to describe variation in the rocky shore communities of the Finnish marine area and creates an overview of how dominant biotopes are regionally distributed along the Finnish coasts. The paper displays what kind of components are lost in the classification process. The paper also aims to identify how certain non-dominating biotope classes are distributed within more dominant biotopes. The paper examines the biotope classification utilized in Paper III.

2 Background

2.1 Human activities affecting the sea

2.1.1 Rising concern for the state of the seas

Anthropogenic influences on marine and coastal environments have been involved in widespread public discussions for more than half a century. The case of Minamata in Japan is one of the earliest and most widely known examples of the impacts of coastal activities gaining global attention. In Minamata, industrial discharges of mercury accumulated in the fish and shellfish from the 1930s to the 1960s (McIntyre 1995; Normile 2013). Over these 30 years, a great number of mercury related deaths occurred in the people in the region. In the 1960s, major tanker accidents caused increased awareness of the potential impacts of oil spills on marine environments (Reisch & Mielke 1978). Reoccurring accidents and increased environmental concern created demand for establishing a set of ground rules for using the seas.

The United Nations Convention on the Law of The Sea (UNCLOS 1982) is widely regarded as the foundation for marine protection and management. The treaty came into force in 1994 and it provides a general framework for using sea areas. In addition, some international treaties and legal measures concerning marine pollution and management of living marine resources has been established prior to the1990s (e.g. Spalding et al. 2013). The first steps towards widespread and concrete actions for environmentally sustainable management of marine resources were taken in 1992 with the formulation of the ICZM concept during the Earth Summit of Rio de Janeiro (United Nations 1992). Later the UN continued the work with the following concept of MSP. In 2009, the UN published its manual “Marine Spatial Planning: a step-by-step approach toward ecosystem-based management” (Ehler & Douvere 2009). The European Union (EU) adopted directives such as “The Marine Strategy Framework Directive” (MSFD) (European Union 2008) and “Maritime Spatial Planning Directive” (MSPD) (European Union 2014) that provide legal frameworks for more efficient protection of marine areas and the planning of sustainable use of marine space at a EU level. The international guidelines have been followed by national legislations on marine spatial planning.

Demands for utilizing marine space often result in conflicts with the natural marine environment (Ehler 2018). Marine spatial planning (or maritime spatial planning), has been introduced as a public process to determine the suitable use of marine areas. MSP aims to find suitable locations for different uses of marine space and coastal activities. Information on where different activities cause harm to marine environments is essential for environmentally conscious planning. Spatial methods for assessing human induced pressures and impacts have been actively developed and utilized for more than a decade (e.g. Halpern et al. 2008; Korpinen et al. 2012).

2.1.2 Human pressures and impacts

Human pressures in coastal areas are caused by human activities that have potential to inflict environmental degradation (e.g. Halpern et al. 2008; Korpinen et al. 2012; Andersen et al. 2015). Human activities refer to concrete actions, such as coastal construction or agricultural practices, whereas pressures indicate the type of potential harm they cause (e.g. noise or input of nutrients). Human impacts are caused when pressures occur near sensitive environments and the state of the environment is degraded.

Pressures can vary from global threats to local issues. Large scale pressures such as global warming and acidification of the world's seas cannot be addressed by local planning alone. Local planning and regulation can, however, address some widespread pressures such as input of excess nutrients from land and overexploitation of fish stocks. Increased nutrient concentrations and overfishing have caused notable environmental degradation in the Baltic Sea region especially during the past 50 years (e.g. Laamanen et al., 2004; Torn et al. 2006; Elmgren et al. 2015; Andersen et al. 2017; HELCOM 2018). Local measures and planning can also mitigate the effects of common coastal activities such as shipping and dredging.

One human activity can cause multiple pressures (e.g. HELCOM 2018). For example, shipping traffic can simultaneously cause noise, disturb soft seafloor sediments and transport invasive species to new areas. Pressure categorizations can help to assess how multiple simultaneous activities affect the nature. In the Baltic Sea region, many actors such as the Baltic Marine Environment Protection Commission (HELCOM) and many countries surrounding the Baltic Sea follow the EU´s pressure categorization established in the Marine Strategy Framework Directive (European Union 2008, Annex III). The pressure grouping in the directive has been updated since the 2008 as the work with identifying relevant pressures has progressed. The pressure groups include adverse effects that are mainly related to eutrophication, contaminants, changes in the seabed, sound, hydrological changes, introduction of non-indigenous species, fishing, hunting and litter.

The impacts that human pressures cause depend on the pressure intensity and the biological component (environment type, species or species groups) at the site. Intensity, for example, can refer to noise levels that are reduced when increasing distance to a shipping lane. High levels of noise on the other hand do not have a similar effect on plant communities and animals at the same location. When conducting impact evaluation and modeling, differences in how pressure types affect biological components can be quantified by "weighting coefficients" (Korpinen et al. 2012). In impact modeling, weighting is applied to the analysis using information concerning the spatial extents of pressures and biological components. Impacts occur in areas where pressures and sensitive biological components co-exist.

Work to comprehensively map marine human pressures and impacts on a global scale was introduced to the scientific community by Halpern et al. (2008). Since then pressure studies have mainly been conducted on regional levels (e.g. Halpern et al. 2009; Selkoe et al. 2009; Ban et al. 2010; Korpinen et al. 2012; Clark et al. 2016; Khamis et al. 2019; Reker et al. 2019).

2.2 Environments of the shallow seafloor in the Baltic Sea

2.2.1 Physical features and water column characteristics

Topographic features and chemical properties below the surface influences to benthic species distribution and the severity of certain human pressures. Topographical traits can often indicate where depth and exposure conditions are suitable for sensitive seafloor communities to occur and where human activities are most likely to cause severe impacts (e.g. Zawada et al. 2010; Hansen & Snickars 2014). Benthic topography also influences the spatial distribution of seafloor substrates by contributing to water movements. When considering spatial distribution of benthic species, seafloor depth is perhaps the most relevant individual environmental parameter as it influences multiple other conditions on the seafloor, such as light availability, salinity, temperature and wave exposure (e.g. She et al. 2007; Bekkby et al. 2008; Reissmann et al. 2009; Luhtala & Tolvanen 2013; Le Fur et al. 2018).

Suitable chemical properties of the water, including e.g. salinity, nutrient levels, oxygen availability and acidity are essential for most seafloor communities and often define their spatial distribution (e.g. McQuaid & Branch 1984; Granéli et al. 1990; Eilola et al. 2009; Carstensen et al. 2014). Salinity is one of the most notable factors affecting regional species composition in vast brackish water systems. In the Baltic Sea salinity causes gradual shifts from marine species dominance to brackish and fresh water species (e.g. Viitasalo et al. 2017). On the northern Baltic Sea, the Kvarken region acts as a border zone for many brackish water species groups such as *Fucus* spp., *Mytilus* and many red algae communities that cannot occupy the low salinity regions in the north (Viitasalo et al. 2017). Similar transition can be found in the Gulf of Finland where salinity decreases gradually towards the East.

Most of the notable chemical features in the coastal waters of Finland are measured frequently on specific selected locations. The collected data is often reflecting the local situation and evaluation on a national or regional scale requires further GIS processing such as interpolation, modeling or combined processing with remote sensing data.

2.2.2 Depth and substrate

Human activities often concentrate on shallow coastal sites that are also valuable for marine environment especially when assessing species diversity and biological production. Detailed information on seafloor depth and topography can help to identify locations with the highest environmental values in order to evade unnecessary damage when planning new activities. Data precision and availability, however, varies greatly in the Baltic Sea region.

Navigational charts are one of the most common source of publicly available depth information in the Baltic Sea coastal areas and the data are often utilized in biological modeling processes and marine spatial planning. One characteristic trait of the data is that the measurements along navigational lines are relatively accurate for safety reasons, but depth markings outside shipping lanes can be sparse and less reliable. The available depth information is usually transformed from point and line formats to spatially comprehensive raster data for further processing and visualization purposes. The transformation is usually done by interpolation methods that estimates the depths of uncharted areas using surrounding measurements.

More accurate depth information exists in certain regions. However, detailed mapping information of vast seabed areas are constrained by military restrictions in many Baltic Sea countries. Methodological limitations also affect the available data. Large research vessels can conduct detailed mapping of the seafloor, but the campaigns can be conducted only in relatively deep waters.

From an environmental perspective, aerial mapping methods are interesting because they can easily cover shallow and rocky areas that would be difficult to reach and navigate by boats. LiDAR mapping methods in coastal areas utilize laser scanning to measure depth (e.g. Banic et al. 1986; Irish & White 1998). The instruments often utilize red and green pulses of laser to measure distance. Red laser cannot penetrate water and is reflected from the surface while the Green pulse penetrates clear water and is reflected back from the seafloor. The difference between the red and green pulses can be used to calculate water depth. However, LiDAR measurements rely on the transparency of the water and cannot often be applied in turbid waters such as estuaries. For shallow areas that are biologically the most interesting, LiDAR mapping has also proven to be useful for substrate detection (Tulldahl & Wiksröm 2012; Kotilainen & Kaskela 2017). Availability of LiDAR data is currently limited to specific areas.

In addition to directly depth related features, species occurrence on the seafloor is highly dependent on the available seafloor substrate. Mosaic-like variation of seafloor substrate is common in the shallow waters of the northern Baltic Sea, creating opportunities for a diverse underwater nature. In deeper waters the proportion of soft sediments increase (e.g. Lappalainen et al. 2019).

The seafloor in the Baltic Sea can be roughly divided into hard and soft substrates. Hard substrate types are often divided into subclasses separating the bedrock and seafloors with differing grain- or boulder sizes (e.g. VELMU 2019). Some of the most notable keystone species in the Baltic Sea such as bladderwrack (*Fucus vesiculosus* (L.)) and blue mussel (*Mytilus trossulus* (L.)) rely on the availability of hard substrates. When categorizing soft sediments, the sandy substrates, clay and muddy seafloors can be divided into separate subclasses. Infaunal species and rooted plants depend on soft sediment availability with species specific preferences in relation to the sediment type. As an example, eelgrass (*Zostera marina* (L.)) depends on sandy seafloor areas, whereas the common reed (*Phragmites australis* (L.) can often be found in muddy estuaries (e.g. Leinikki et al. 2004; Viitasalo et al. 2017).

Moreover, accurate substrate data is often subject to military restrictions and methodological limitations on comprehensive mapping prevail. However, some substrate maps have been publicly released but with reduced accuracy. For example, the Geological Survey of Finland has published substrate maps of the Finnish seafloor areas at scales of 1:1 000 000 and 1:100 000. The lower resolution product covers all finish marine areas and the higher resolution map contains many vast areas that have been subject to intensive mapping campaigns. In addition, substrate likelihood can be modeled to increase the performance of species distribution modeling in large scale evaluations.

2.2.3 Light availability at the seafloor

A wide range of human activities cause changes in coastal water transparency and seafloor light availability (e.g. Sipelgas 2009; Savage et al. 2010) resulting in problems for primary production. Often the decreasing water transparency has been connected to the increasing amounts of phytoplankton and eutrophication (Lewis et al. 1988; Karydis 2009; Fleming-Lehtinen & Laamanen 2012; Snoeijs-Leijonmalm et al. 2017). As light availability defines where photosynthesizing benthic plant communities can occur (e.g. Gattuso et al. 2006; Luhtala et al. 2016), evaluating changes in water transparency is essential for comprehensive human pressure and impact assessments. Information for change detection in the Baltic Sea has been collated in previous studies (e.g. Fleming-Lehtinen & Laamanen 2012) and these can be utilized to define past light conditions on the seafloor (Tolvanen et al. 2013).

The optical properties of water are highly dependent on temporal change (e.g. Luhtala et al. 2013). Large parts of the shallow seafloors can be occasionally aphotic, darkened for example by the occurrence of sediment plumes from estuaries or algal growth in the water mass. Water transparency can be measured by accurate electronic devices, but often the most abundant information and the longest time series are recorded as Secchi depth measurements (e.g. Fleming-Lehtinen & Laamanen 2012). Secchi measurements are conducted by lowering a white disk into the water and observing at which depth the disk is no longer visible. Secchi measurements provide point type of data that can be further processed into spatially comprehensive data, but often have limited view on the temporal changes in the water transparency. Satellite measurement data can also be used to detect water turbidity, which can be transformed to describe Secchi depths with comprehensive spatial coverage and frequent time series.

The relation of Secchi depth and bathymetric data can be used as a coarse estimate to describe how euphotic and aphotic seafloors are geographically distributed (Tolvanen et al. 2013). In Finnish coastal areas, the limit of the euphotic depth (Z_{eu}) has been measured, on average, at 2.85 times the Secchi depth (Luhtala & Tolvanen 2013).

2.2.4 Underwater habitats

For human impact evaluations, it is essential to know where sensitive environments and sites with high biodiversity occur. However, detailed information on mixed distribution patterns, gradual shifts and small variations in species occurrence cannot be directly utilized in large scale evaluation and planning processes. Categorizations of the underwater nature help to reduce complex information into manageable units for spatial planning and status evaluations. There are two main classification systems used for Finnish underwater habitats; Natura 2000 habitat classification and HELCOM Underwater biotope and habitat classification (HELCOM HUB). Natura 2000 habitat classification (Anon 2013) was formulated on the basis of the European Union’s Habitat Directive (European Union 1992) that focuses on the conservation of natural habitats and of wild fauna and flora. The classification system was created as a part of the establishment of a common framework for the protection of natural habitats, and it contains many of the most notable terrestrial and marine habitats found in Europe. The classification includes a number of the habitat types found in Finnish coastal marine environments such as lagoons, reefs, estuaries and sandy dunes. The Natura 2000 habitat classification contains broad scale habitat complexes delineated primarily by their physical features.

HELCOM HUB classification was established to create a common understanding of Baltic Sea underwater habitats, biotopes and communities (HELCOM 2013). The classification contains six levels with information on vertical zones, substrate, community type and dominant species group. The species group - level makes HUB especially interesting for human pressure evaluations as all species do not react similarly to different pressures. Compared to the Natura 2000 classification HELCOM HUB contains more information, and therefore also requires more detailed mapping data.

Many of the Baltic Sea habitats and habitat complexes are in a poor state (e.g. HELCOM 2018; Kontula & Raunio 2019). The habitats along Finnish coasts have been assessed in a report "Threatened Habitat Types in Finland 2018" by Kontula & Raunio (2019) that utilized HELCOM HUB biotope classification. In the assessment, 42 Baltic Sea marine habitats were evaluated and 10 of them were classified as "Threatened" (VU-EN), 4 as "Near Threatened" (NT), 14 as "Least Concern" (LC) and 14 of the habitat types did not have sufficient data to conduct the analysis. Habitats characterized by *Fucus* spp., red algae, *Unionidae*, *Monoporeia affinis* and/or *Pontoporeia femorata* and coastal estuaries were classified as Endangered (EN). In these habitats, the characteristic communities have been considerably degraded. Most of the changes can with high confidence be traced to anthropogenic pressures. Development of *Fucus* spp. is especially concerning as it is one of the most important keystone species groups in the Finnish benthic environments. Degradation of Fucus can reflect negative developments in the coastal environments and in many other species groups (e.g. Bäck & Ruuskanen 2000; Torn et al. 2006; Schories et al. 2009).

2.2.5 Spatial distribution of benthic communities

Reliable information for spatial distribution of benthic organisms is crucial for successful impact evaluations of the seafloor. Detailed species level information on benthic macro organisms in the northern Baltic Sea is most often gathered by diving (visual inspection) or taking bottom samples (see VELMU 2019). Video equipment from boats can be mainly used to detect macrovegetation on species group levels. Detailed information of seafloor communities represent a very spatially restricted area, whereas remote sensing methods can provide a comprehensive overview. Remote sensing such as satellite images, aerial images and LiDAR data have limited possibilities to identify benthic organisms on the seafloor, but they can be used to detect habitat types and patches of large plant species. Modeling can be used to extend the available mapping information by indicating the potential suitability of seafloor areas for certain species or species groups.

Field inventories have most often been conducted with a "drop video" method in Finnish coastal areas. In this method a video recorder is lowered down from a boat near the seafloor so that visual identification of objects can be conducted. An inventory of the recorded material is made for visible species, substrate and other seafloor traits (VELMU 2019). The drop video method can rapidly provide an overview but lacks the possibility for close inspection and taking physical samples. Therefore, the inventories made by drop video are often accurate only for large-sized organisms and on a species group level.

Diving inventories are a more accurate way of acquiring species data but the methods are relatively time demanding. The diver identifies species visually and takes samples for later examination if identification is uncertain (VELMU 2019). In drop video and diving -methods, coverage of the species or species groups on the seafloor is documented. Species specific inventory dives are made for certain purposes, such as monitoring the lower growth limit of *Fucus* spp..

Using video and diving inventory data can be problematic as they can only provide point type of information on limited areas. Remote sensing methods such as LiDAR scanning can provide an accurate way of mapping vast seafloor structures in shallow localities but the methods lack precision for species identification (e.g Cottin et al. 2009; Tulldahl & Wikström 2012; Marcello et al. 2018). Data provided with video or diving methods can be utilized with e.g. LiDAR data to identify certain structures as habitats or patches of certain species groups (e.g. Tulldahl & Wiksröm 2012). Visible patches of vegetation for large species such as the common reed (*Phragmites australis* (L.)) can also be mapped with satellite data or aerial photographs (e.g. Bourgeau-Chavez et al. 2013).

Species distribution modeling (SDM) is a useful way to predict the distribution of benthic species or species groups on large scale with relatively low costs. Models can provide an overview of the most suitable areas for seafloor communities by using information on environmental conditions and observed species occurrence (e.g. Reiss et al. 2011; Virtanen et al. 2019). Data on environmental conditions such as depth, light availability or salinity is used to indicate the type of physical environment, where species have been observed. Suitable areas can be predicted by a range of different modeling methods such as GAM (Generalized Additive Modeling), RF (Random Forest), EADM (Expert Assisted Distribution Modeling) or BRT (Boosted Regression Trees) (e.g. Peterson & Herkül 2019; Sahla et al. 2020). The different methods have differing technical solutions and workflow, but the main process is the same: Empirical observation data are used to determine how the environmental gradients or their combinations affect the species distribution. This information is utilized to display the most suitable areas for the occurrence of species or species group in question.

3 Material and Methods

3.1 Study area

All the papers in this thesis focus on the marine areas of Finnish coasts in the northern Baltic Sea (Figure 2). The analysis in Paper I was conducted in Rönnskärr archipelago in the Quark region. Paper II focused on the Archipelago Sea in South-West Finland. Papers III and IV covered all Finnish marine areas.

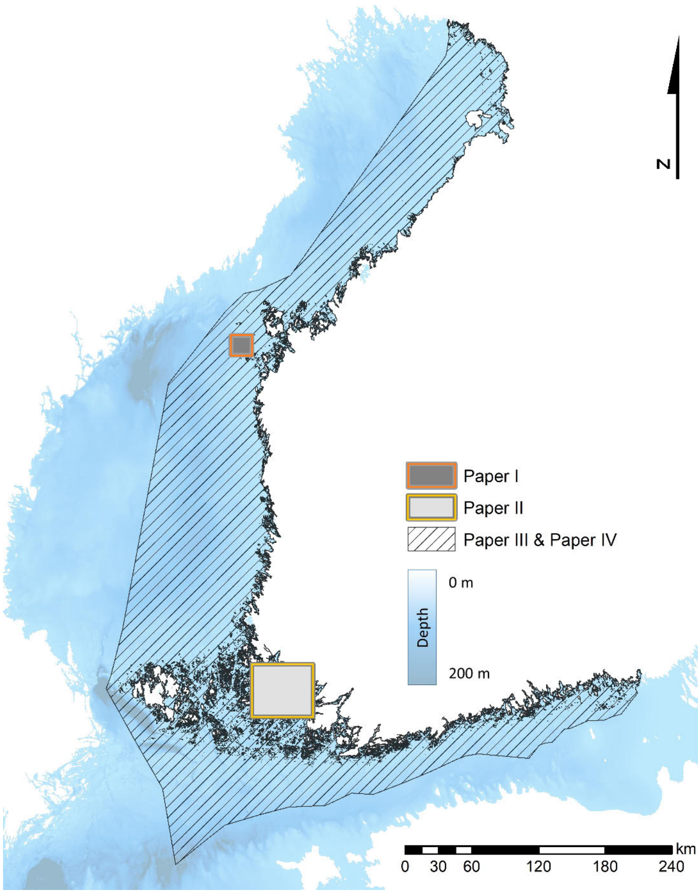

Figure 2. Study areas of the papers included in this thesis.

The Baltic Sea region is under intensive human use, as the world's second largest brackish water basin includes around 85 million inhabitants within its watershed (HELCOM 2018). The limited level of water exchange makes the Baltic Sea especially vulnerable to threats originating from the land areas. Eutrophication in the region has been evident for decades and levels of contaminants are elevated in many areas (Laamanen et al. 2004; Torn et al. 2006; Andersen et al. 2017; HELCOM 2018). High nutrient concentrations and lowered water transparency near the mainland are a prevailing sign of intensive land use in the Baltic Seas watersheds. Local pressures caused by various activities are common throughout the whole region (Figure 3).

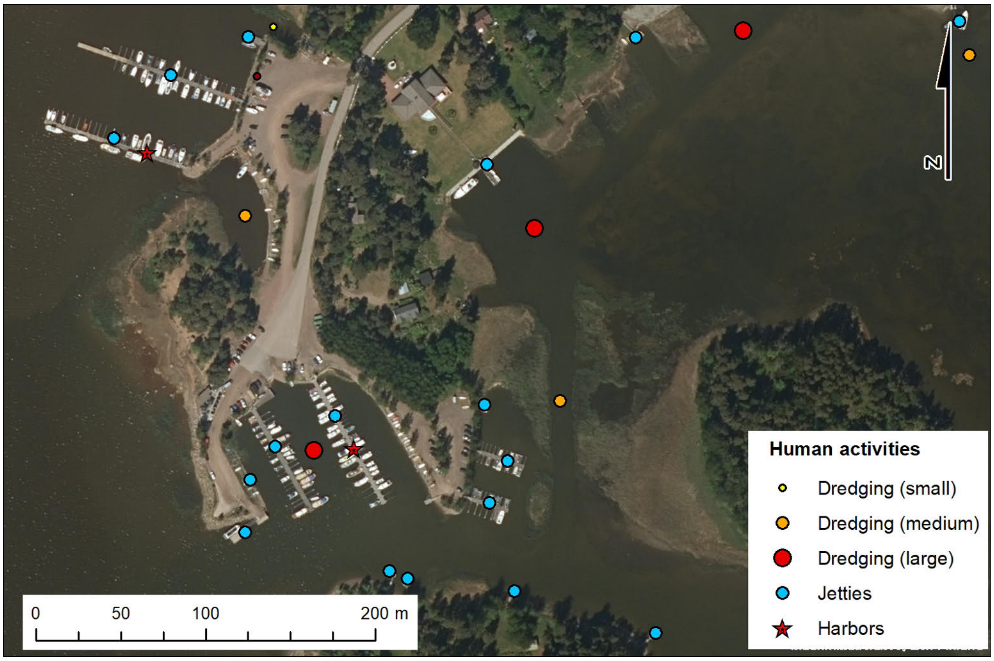

Figure 3. Common human activities are often visible in aerial images in the Northern Baltic Sea. Location: Lökören, Pyhtää, Finland. Human activity mapping data © Parks & Wildlife Finland (Sahla et al. 2020b). Aerial image © National Land Survey of Finland.

Finland has a long and diverse coastline, where visible signs of human presence are frequent. The most common indication of human activities are jetties that often mark the location of nearby settlements (e.g. Sahla et al. 2020b). Access for recreational boating is often maintained by dredging that has considerably altered the Finnish coastline. Another common sign of human presence in the area are large vessels such as passenger ships and tankers that utilize navigational routes in Finnish waters (e.g. Viitasalo et al. 2017). Visible signs of eutrophication such as algal blooms and abundant annual filamentous algae are common throughout the coastal regions, indicating intensive land use and agricultural practices in the drainage areas. Generally, human activities along the Finnish coast are most frequent close to the mainland and near the largest population centers (e.g. Sahla et al. 2020b).

Human activities shape the Finnish underwater environments, but also a variety of physical gradients have created strong regionality in species composition (Viitasalo et al. 2017; Paper IV). Regional diversity is particularly maintained by a shift in salinity from around 6.5 PSU to almost fresh water in the Bothnian Bay and in the Eastern Gulf of Finland. The availability of different substrates has also created regional characteristics, with vast sand areas in the North, and increasing availability of hard seafloors towards the south. The seafloor near the mainland and large islands often have soft sediments available in the photic zone, whereas in the outer regions soft sediments are deposited in deeper areas (e.g. Viitasalo et al. 2017; Paper IV). Sediment particles and dissolved organic matter from the watersheds often lower the water transparency near the coast and especially in estuarine areas, whereas in the outer sea the transparency often increases. The northern parts of the Finnish marine areas are relatively shallow with gentle depth gradients. Towards the south the seafloor has a gradual shift to deeper seafloors and steeper underwater slopes.

Regional differences in salinity, substrate availability, ice cover and length of the vegetation period contribute to the local biodiversity in the Finnish coastal region. These factors together with e.g. light availability on the seafloor and wave exposure influence the local distribution of species. Throughout the Finnish coastal area, the diversity of species and species groups are higher near the mainland and usually decrease towards the open sea conditions (Paper IV, Figure 1). Level of species diversity is highest at a depth range of 0 - 5 meters, and the proportion of faunal species increases in the deeper areas along with the decreasing availability of light. In Kvarken, the Bothnian Sea, the Archipelago Sea and the Åland regions, some plant communities still exist at depths of 15 to 20 m. In the Gulf of Finland and Bothnian Bay, plant communities do not exceed a depth of 15 m. In deeper areas faunal species are dominant and individual plants may occur.

Decreasing salinity in the northern and the eastern parts of the Finnish coasts cause a gradual shift in the rocky bottoms from *Fucus* spp., *Mytilus* and red algae dominated communities to species that are tolerant of low salinities, such as aquatic mosses (Paper IV). Soft sediments throughout the well illuminated parts of the Finnish marine seafloor are often characterized by *Myriophyllum* spp., *Potamogeton* spp., *Chara* spp. and *Ranununculus* spp. species groups (e. g. Viitasalo et al. 2017). On sandy sediments *Zostera marina* is one notable plant species that mainly occurrs in the highest salinity regions predominantly in the Archipelago Sea. Common reed (*Phragmites australis*) is often found in estuarine areas and in sheltered locations with soft sediments. Soft sediments in the region are also often inhabited by small animals such as mussels and larvae. Annual and epiphytic filamentous algae are common throughout the coastal waters and often related to increased nutrient availability. The number of algal species and bottom fauna species are fewer in the Bothnian Bay -region (Viitasalo et al. 2017), but these areas host many threatened species that are rare in other parts of the Finnish coast.

3.2 Geographical data

Research in this thesis is based on spatial data that can be divided into three main categories: Data on 1) Human pressures, 2) Environmental conditions and 3) Benthic communities (Table 1).

1) Human pressure data were utilized in all the papers of this thesis except Paper IV. Paper I focused on assessing potential pressures caused by offshore wind power placement. In Paper II, the cumulative impacts of a wide range of pressures were evaluated, and Paper III concentrated on the human induced change of illumination conditions on the seafloor.
2) Data on environmental conditions were used in all the papers of this thesis. Paper I included bathymetric data and substrate data. In Paper II, depth was utilized in pressure evaluations, Secchi depth was used to calculate light availability on the seafloor, and substrate was used to evaluate potential impacts. Paper III utilized depth, Secchi depth, seafloor exposure and salinity in species distribution modeling (SDM). HUB categorizations in Paper IV were evaluated using depth data, and substrate information was utilized for data selection.
3) Data describing benthic communities were used in all the papers. Papers I, III and IV included VELMU -inventory data and in Papers III and IV - the inventory data was utilized with the HELCOM HUB biotope categorization. Paper I also utilized accurate LiDAR scanning data for the distribution of benthic communities. Paper II relied on substrate categorization based on light availability and bottom fauna samples.

Table 1. Type of data utilized in the thesis.

	Paper I	Paper II	Paper III	Paper IV
Human pressures				
Physical loss		x		
Physical disturbance	x	x		
Underwater sound		x		
Hydrological changes		x		
Contaminants		x		
Eutrophication		x		
Pathogens		x		
Extraction of species		x		
Environmental conditions				
Depth	x	x	x	x
Secchi depth		x	x	
Light availability		x	x	
Substrate	x	x	x	x
Salinity			x	
Exposure			x	
Benthic communities				
VELMU -species inventory data*	x		x	x
Bottom fauna samples		x		
LiDAR mapped communities	x			
HUB biotope categorization			x	x
Substrate categorization by light availability		x		

*Visual inspection by diving or drop video –method.

3.3 Methods

3.3.1 Human pressure and impact assessment

Human pressures and impacts were assessed in Papers I, II and III. In Paper I, the potential environmental pressure of different scenarios for offshore wind turbine site selection were evaluated. A fixed distance of 200 m buffers was utilized to display the *Fucus* spp. communities that would be potentially affected by the construction work or operation of the turbine. The placement was tested in three schemes for data availability. The cumulative effects of increasing the number of turbines at the site was evaluated with different datasets, and the maximum number of turbines were assessed in different depth zones. In addition, accumulation of potentially impacted

Fucus communities was evaluated, when placing the turbines one at a time at the most preferable sites according to each planning scheme.

In Paper II, cumulative human pressure modeling was applied to display current pressure and impact status on the Archipelago Sea. Pressure modeling was conducted utilizing a formula created by Halpern et al. (2008) with slight modifications in order to apply this global scale pressure modeling into local environments (Paper II, formula 1). Pressure modeling included information on human activities that can cause adverse effects on the marine environment. Activities were transformed into pressure layers describing the intensity and spatial extent of different types of adverse effects. Impacts on the environment were estimated using spatial analysis with extent of the pressures and the spatial distribution of different types of seafloor. The results of the impact modeling were evaluated using data on benthic fauna monitoring, oxygen levels on the seafloor and tributyltin (TBT) concentrations.

In Paper III, large-scale environmental impacts caused by past and continuing human activities were evaluated. The evaluation concentrated on identifying the extent of the reduction in suitable seafloor areas for *Fucus* spp. communities due to changes in light availability. The impacts were evaluated with two separate approaches: 1) Measurement approach, that utilized monitoring data on the depth limit of *Fucus vesiculosus* and 2) Modeling approach, that utilized current and historical measurements of Secchi depth to model past and current distribution of favorable seafloor areas for *Fucus* spp. growth.

3.3.2 Evaluating the spatial distribution of benthic communities

Spatial distribution of benthic communities has been evaluated in all the papers of this thesis, using varying methods. In Paper I, information on *Fucus* spp. distribution was utilized to indicate the locations with high biological values on hard seafloors. Distribution of *Fucus* was assessed using underwater inventory data and LiDAR scanning data. Site selection scenarios for offshore wind power utilize inventory data with >25% *Fucus* coverage and classified LiDAR data with patches of >100m^2 continuous *Fucus* coverage. Additionally, scenarios with no inventory data were tested. Site selection was conducted to test the number of available locations in different depth regions, the damage caused by different scenarios and how well different datasets help in avoiding locations close to important *Fucus* sites.

Seafloor type, containing information on substrate and light availability was used as a proxy for the possible type of benthic communities in Paper II. The type of seafloor was used in cumulative human pressure modeling to evaluate where pressures cause impacts on the environment. Light availability was used to indicate where plant communities can exist, and the substrate defines what kind of species can occur on the seafloor. Temporal light availability on the seafloor was considered using the categorizations of: always illuminated seafloor, occasionally illuminated seafloor and dark seafloor areas. Substrates were grouped into soft and hard substrates (Paper II, Figure 2).

In Paper III, the spatial distribution and the lower growth limits of Fucus spp. in the past and present were evaluated. The analysis provides an overview of changes caused by human activities. The spatial extent of *Fucus* spp. was modeled using two separate modeling methods: 1) Generalized Additive Modeling (GAM) and 2) Expert Assisted Distribution Modeling (EADM). Modeling was conducted using relevant environmental variables to display the spatial extent of favorable sites for *Fucus* spp. along the Finnish coast. The change for the lower growth limit of *Fucus vesiculosus* was evaluated utilizing monitoring data and historical records for the maximum growth depth of *Fucus vesiculosus* in specific sites. The measured growth depths were processed to exclude site specific factors affecting the maximum growth depths. The work included location specific examination and evaluation of the overall development of maximum growth limit of *Fucus vesiculosus*.

In Paper IV, Finnish national underwater inventories data were utilized to provide an overview of species groups dominating the seafloor in different regions and depth zones. The study was conducted using a tool developed by the author of this thesis for classifying the Finnish inventory data into HELCOM HUB biotopes. The paper evaluates how the HELCOM HUB categorization manages to present information on relevant species groups and displays the usability of the categorization on a regional scale.

3.3.3 Scenario-based assessments and parallel workflows

In this work, the scenario assessments and parallel workflows have been utilized in Papers I, II and III. The scenarios provide insights into how methodological solutions and the chosen data influence the perceived results in human pressure and impact evaluations. In Paper I, scenarios of different input data were used to guide the site selection of offshore wind power. The paper demonstrates how data availability could support in utilizing marine space with minimal damage and prevent planning in sensitive locations.

In Paper II, different scenarios provide insights into how much the evaluation of the cumulative human impact is affected by the available data and methodological solutions. Testing was conducted mainly by excluding individual pressure datasets, environmental factors and biological components to see how they affect the perceived impacts on the environment.

Paper III utilizes two separate analysis paths with field measurement and modeling approaches. By using separate analysis methods and data, the work aimed to provide reliability to the evaluation of the changes. The modeling section also included separate scenarios with two different modeling methods and two separate input datasets for Secchi depth. The modeling results were also evaluated with three different scenarios of substrate availability.

4 Results and Discussion

4.1 Open source data supports evidence-based site selection of coastal activities

Environmentally sustainable site selection of various coastal activities requires systematic assessment of potential environmental conflicts (e.g. Aguilar-Manjarrez et al. 2017; Kim et al. 2018; Yan et al. 2018). Recent advancements in accurately mapping the seafloor characteristics (e.g. Brown et al. 2011; Wilson et al. 2019; Trzcinska et al. 2020) and coastal anthropogenic pressures (e.g. Holon et al. 2018; Gómez et al. 2019; Montefalcone et al. 2019) have led to improved possibilities in site specific offshore and coastal planning. However, spatial coverage of detailed mapping data is limited and the use is often restricted due to national security policies. As a result, detailed mapping data in the northern Baltic Sea is not expected to be available for public planning processes and site selection in the near future.

Open source data in this work refer to freely available spatial information that is accessible via public web pages. These datasets are essential for public planning processes and preliminary site selection of coastal activities. Usefulness of open source data in evaluating marine environments have been recently studied by Caro et al. (2018), who displayed that data for evaluating coastal environmental status and human activities are widely available in Europe. The work of Papers I, II, III and IV display various beneficial ways of utilizing generally available information when planning new activities offshore or near the coastline. Considering the environmental characteristics, especially those limiting the occurrence of sensitive species, and using information about existing human pressures can help to target planning resources at the most suitable sites. If detailed mapping data is not available, then placement of activities should target the least suitable locations for high biological values utilizing publicly available information on environmental conditions and appropriate spatial analysis methods. The main findings in this thesis promoting more sustainable planning choices by using open source datasets are:

1) <u>Planning activities in deep locations can often reduce impacts on important plant communities.</u> Paper I demonstrates how offshore activities placed in deep sites can help to reduce the risk of harming certain species groups. Placing wind turbines in deep areas with low possibilities for photosynthesis

can help planning even with no biological data (Paper I, Figure 4). According to the results, a depth of 10 – 15 m in the study area had plenty of available locations for turbine placement, and it is deep enough to evade most of the damage to *Fucus* spp. in the Kvarken region. Paper IV also displays consistent results for low risk planning zones in areas with more than 10 m depth. When planning in shallower sites, more caution should be practiced. However, a considerable number of available locations for coastal activities can be found as very often the most abundant vegetation in the Baltic Sea coastal areas are situated at a depth of 0-2 meters (e.g. Piepho 2017). Even though avoiding shallow and well-illuminated locations can help to reduce the risks when planning activities near vulnerable environments, location specific considerations should always be applied in the final site selection; this is because even relatively deep seafloor areas can maintain important animal communities (Paper IV, Figure 1).

2) <u>Regional characterizations of the underwater nature can help to identify vulnerable sites and the most harmful pressure types.</u> All species are not equally sensitive to the pressures that coastal activities cause (e.g. Korpinen & Andersen 2016). Considering regional characteristics and common species can help to plan activities sustainably. Paper IV shows how different species groups are distributed regionally and within different depth regions. The paper provides a map that comprehensively describes the dominant benthic biotopes in different regions and at different depth zones along the Finnish coast (Paper IV, Figure 1). The provided information can help planners to understand what kind of benthic communities should be considered when planning activities in Finnish coastal areas. The work also supports the utilization of the Finnish Red List Assessment (Kontula & Raunio 2019) by providing an overview of the occurrence of most of the assessed Baltic Sea habitats.

3) <u>Available data on environmental conditions can be used to locate potential areas for important benthic communities before site-specific inventories.</u> Depth, salinity, substrate or wave exposure can provide an overview of what kind of species groups are most likely to occur at the site (e.g. Reiss et al. 2011). Data on marine environmental characteristics are widely available as open source data (e.g. Caro et al. 2018) and could be utilized more comprehensively. The use of the data can be further improved by methods of species distribution modeling. Modeling can provide estimation of species distribution in areas where biological inventories have not been conducted. The modeling methods in Paper III could be utilized at early stages of site selection processes in order to provide estimates of vulnerable

areas before inventories or mapping campaigns are organized. In Paper III, we also present a completely new modeling method, Expert Assisted Distribution Modeling (EADM) that is especially suitable for environmental change detection and can be utilized to evaluate impacts of planned activities.

4) Including existing data of human activities in planning processes could reduce some cumulative impacts in coastal areas. Human activities often target specific places such as estuaries with vessel routes to inland or coastal lagoons with shelter for recreational harbors. Therefore, occurrence of co-existing pressures should be limited or at least carefully planned. Paper II displays how existing human pressures and impacts can be evaluated during preliminary site selection for planned activities. In the study, we implemented the methodology of cumulative human pressure modeling for detailed pressure assessment. Previous studies have been on the level of global (Halpern et al. 2008) or regional seas (e.g. Korpinen et al. 2012) with little information suitable for local scale planning. In Paper II, we upgraded the modeling formula to suit local and more detailed spatial studies, taking into consideration local characteristics such as depth and wave exposure.

Open source data should be utilized in regional and municipal planning or when starting large-scale coastal construction or development projects. Increased use of information would be also beneficial for placing small-scale activities and supporting permit processes in coastal areas. A single dredging operation or constructed jetty rarely has any large scale effects on the environment, but a large quantity of activities in sensitive environments can have notable consequences (Figure 4). Available data on human activities (e.g. Sahla et al. 2020b) can be used to evaluate existing pressures and to identify pressure-free zones. Conducting a spatial evaluation of where different habitats could still be kept in their natural conditions are to be highly encouraged, as the process can provide valuable information for focusing further conservation efforts. Moreover, improving the availability of information on potential impacts and best practices for coastal activities can lead to reducing local human pressures in coastal areas.

Figure 4. In the aerial image, dredged sites are visible where the grey areas of Common reed are missing. The sites are often accompanied with a narrow extension of the shoreline created from the dredged sediments. Location: Isosaari, Turku (60.374966, 22.223572). © National Land Survey of Finland.

4.2 LiDAR data supports detailed planning of coastal activities

Detailed mapping information is especially valuable in coastal areas where planning near sensitive environments cannot be avoided (e.g. Orpin 2004; Moufaddal 2005; Roberts 2005). Mapping vast areas with a high level of detail is difficult because methods are either very time consuming or cannot be used on their own for species identification. Detecting species occurrence usually requires on-site inventories such as diving, video inventories or seafloor sampling. These methods are relatively expensive to conduct and usually cover a very limited area. Methods with high coverage such as sidescan-, multibeam- or LiDAR mapping can be used with on site inventory data to identify areas with large plants on the seafloor (e.g. Tulldahl & Wikström 2012).

LiDAR derived data was utilized in Paper I to identify the distribution of *Fucus* spp. in the test area. The distribution data was used in a hypothetical site selection process for offshore wind power to display how accurate data can help to find a greater number of suitable locations and at the same time avoid planning activities in sensitive locations.

LiDAR waveform data contains information for identifying large macrovegetation on the shallow seafloor and can be used to evade most of the impacts on communities of large plant species (Paper I). The main benefits of LiDAR data are the comprehensive spatial coverage in photic parts of the seafloor, that can be used to evaluate the total areal coverage for certain species groups at the mapped site. For targeted species communities LiDAR data can display notable occurrences, that might not all be detected with field inventories (Paper I, Figure 2). LiDAR however has some disadvantages as it cannot be used to map the seafloor in turbid waters, it requires field samples for species identification, and it cannot detect communities of small organisms.

Benthic surveys for environmental impact assessment (EIA) processes in Finnish coastal waters are most often conducted solely by diving at a few selected locations. However, even a relatively dense inventory grid with surveyed locations every 100 m or 50 m might not be enough to identify all the notable areas with biological values (Paper I). Therefore a combination of field sampling and spatially more comprehensive mapping methods should be promoted. Inventories on site can help to identify and detect even small species and mixed communities, whereas LiDAR can provide a good overview for the spatial distribution of different kind of environments.

LiDAR mapping data can also be beneficial for species distribution modeling as it provides detailed information of depth and seafloor structures. This information can be utilized for improving environmental variables used in the modeling processes, and hence also increase the possibilities for identifying important sites for species that cannot be detected with LiDAR. For future studies combining methodologies of Paper I and Paper III could be especially beneficial as LiDAR data can provide solid mapping information for evaluating modeled species distribution, whereas modeling can provide information for site selection in areas where LiDAR data is not available.

The current remote sensing methods cannot replace underwater field inventories, but broad scale mapping can provide various benefits and a new kind of spatial perception for the shallow seafloor environments. Therefore, large-scale mapping projects for promoting environmentally conscious coastal development e.g. on a national scale should be encouraged.

4.3 Cumulative human pressure and impact mapping is resilient to uncertainties

Cumulative human pressure mapping forms a synthesis of the most common factors that can cause environmental degradation (Halpern et al. 2008; Korpinen et al. 2012). Varying availability of data and methodological solutions, however, create uncertainties to the perceived pressure and impact status. When measuring the success of the pressure and impact modeling, good indicators can be difficult to find, as the modeling process strives to display multiple types of environmental degradation simultaneously.

Individual monitoring indicators on the state of the sea such as oxygen levels, sediment toxins and benthic fauna occurrence correspond quite well to the pressure modeling results, but inconsistencies do exist (Paper II, Figure 4). Seafloor oxygen levels might indicate a good status near a shipping lane where frequent propeller thrusts mix the water. In addition, a recently dredged area might show low toxin levels because the surface sediment layers have been removed. The best correlation with pressure assessments was found with benthic fauna monitoring. The results are consistent with the study of Clark et al. (2016) who found weak, but significant correlation between benthic fauna observations and cumulative impact modeling. It is evident, that individual monitored parameters can only reveal partial impacts of the pressures. Correlation between human pressures and benthic quality assessment indexes has been previously studied by e.g. Borja et al. (2015), who found a good performance of biological indicators that describe the ecological response of seafloor communities to human pressures. Testing these indexes in relation to local scale pressure mapping is highly encouraged for future studies.

According to Paper II, overall impact assessment on cumulative human pressure modeling is resilient to most uncertainties in the data. In Paper II, we tested how removing and altering individual human activities or environmental data affected the outcome of the modeling process. Most of the test scenarios caused only minor changes to the overall pressure status. Information that affects multiple components of the assessment were found to be the most crucial parts of the data in large-scale evaluations (Paper II). The spatial extent of ecological components and how pressures are weighted impact heavily the results of cumulative human impact mapping. As an example, equal weighting of how sound affects seafloor algal communities and mobile animal species will generate poor results, even if the data on underwater soundscape would be good. Exclusion of widespread pressures, such as nutrient input, were also found to cause visible changes on extensive areas. However, Paper II indicates that missing individual components will not strongly affect the intensity of the modeled cumulative pressure over a wide area.

Cumulative human pressure modeling was found to be a suitable way of providing information on the overall pressure status on a local scale. However, in order to understand the causalities of environmental problems, individual pressure groups and activities should be assessed separately. Overall success of human pressure and impact modeling is dependent on the used data and how well it can describe the actual adverse effects on the environment. One major source of uncertainty is the lack of sufficient data for actual pressures: available data often contains spatial information on potential pressure sources or human activities but seldom e.g. noise levels of boating, or effects of small scale dredging are measured in a spatially comprehensive manner. Quantifying the pressures that the individual activities cause is still an issue that requires more research.

Another source of uncertainty is the weighting of how severe the impacts of an individual pressure are towards different environment types. Weighting is most often conducted by expert judgement (Korpinen & Andersen 2016), that can provide coarse estimates of the actual adverse effects. Further research is, however, needed to accurately quantify the impacts that different pressures cause. For evaluating impacted environments, methodologies utilized in Papers I and III can be applied in future studies to provide more accurate overview of what species groups are affected by local pressures. Modeling methods of Paper III can be used to assess suitable areas for large variety of biotopes or individual species, whereas LiDAR mapping can be beneficial in providing spatially detailed overview of some of the most important environments in the Finnish coasts.

Even though there is plenty of room for future development, the currently available data and methodologies on evaluating human pressures and impacts can provide a comprehensive overview of what kind of environments are heavily affected by human activities. The evaluation could also support planning of marine protected areas by identifying low pressure zones with nearly natural environmental status. In addition, cumulative human pressure and impact modeling can act as a great tool for visualizing the harmful activities at sea.

4.4 Habitat classifications introduce a tradeoff between usability and precision

Habitat classifications can transform complex data into easily manageable form that can be used to present spatial variation in marine environments (see Paper IV, Figure 1). Strong et al. (2019) found that classification schemes of marine habitats can introduce uncertainties but still found them to be important for promoting sustainable use of marine space. Paper IV focuses on evaluating how selected species groups are represented in Finnish underwater inventory data, using HELCOM HUB biotope classification (HELCOM 2013). Previous studies on HUB classifications display that the scheme succeeds in displaying most of the notable underwater characteristics of the southern Baltic Sea (e.g. Schiele et al. 2014; Schiele et al. 2015). The findings of Paper IV are consistent with previous studies indicating good overall usability for the classification scheme, but also displaying some of the major uncertainties that HUB might produce in the northern Baltic Sea.

Paper IV shows that in the HUB classification system, red algae are rarely the dominating species in Finnish coastal areas as they are divided into several subgroups within the classification system. In HUB classification the occurrences of red algae with over 10 % coverage at the inventory point are most often categorized to a group other than red algae biotopes. In these cases other abundant species such as *Fucus* spp. in the shallow locations (0 – 5 m) and *Mytilus trossulus* in deeper (5 – 20 m) areas are commonly dominating the classification. Dominance of the separate red algae groups rarely occurs on hard seafloor areas as *Fucus* and/or *Mytilus* are often abundant in these localities. To overcome this issue, differing groups of red algae should be treated as one community, as the functionality of the biotope is not tied to an individual red algae group, but all of them fill a similar purpose together.

As habitat and biotope classifications commonly describe the dominating environment types, they are rarely able to represent rare or small species. Therefore, classified data should not be used as the only source of biological information in detailed planning. To avoid environmental degradation, occurrences of rare and especially sensitive species is recommended to be evaluated separately in detailed site selection and planning processes. This should be taken into account when applying biotope classifications to research setting similar to Papers I & II, or when extending the methodology of Paper III for evaluationg other biotopes.

4.5 Decreasing light availability on the seafloor can cause large-scale changes in benthic communities

Large-scale degradation in the environment is often slow and hence difficult to detect without specific monitoring efforts or dedicated assessments (e.g. Hawkins et al. 2003; Knights 2003; Parr et al. 2003). Quantifying changes on species distribution can be supported by utilizing new developments in the modeling field, as well as time series of species monitoring data. This thesis presents evidence for large-scale reduction of keystone species group *Fucus* spp. in the northern Baltic Sea due to the decreasing light availability on the seafloor. The results most likely also reflect notable degradation of many other benthic species groups that rely on sunlight in the region. The findings are consistent with the previous work of Tolvanen et al. (2013), who estimated a 50 % spatial reduction of illuminated seafloor between 1930 - 2007 in the southwest Finland.

Environmental parameters such as Secchi depth can have a long record of measurements in the coastal areas (Fleming-Lehtinen & Laamanen 2012), whereas frequent monitoring of species distribution is rarely as comprehensive. Records of changes in environmental conditions can be used to reflect the changes on species distribution (Hawkins et al. 2003; Ehrlèn & Morris 2015; Paper III). The environmental requirements of species can be evaluated with the current observation data on the species spatial distribution. The known requirements can be utilized to describe past species distribution when historical environmental data is available.

Paper III quantifies the change in *Fucus spp.* dominated benthic communities caused by long term reduction in seafloor light availability. In the study, different modeling scenarios show a consistent trend towards a decreased suitability of the seafloor areas for *Fucus* spp.. Altogether 12 scenarios were processed, utilizing two separate modeling methods, two separate sets of Secchi depth data and light availability data and two separate substrate datasets. The modeling processes with alternative SDM methods and input data generate relatively similar results with an average 44.7% reduction on suitable areas for *Fucus* spp. biotope during a 100 years evaluation period.

Human induced impacts can be directly monitored by observing the changes in species distribution if the relevant data is available. *Fucus vesiculosus* has been frequently monitored as it is one of water framework directives (WFD) national indicator species for monitoring the state of the Finnish coastal sea areas. Assessment of monitoring data for a *Fucus* lower growth limit in Paper III resulted in similar conclusion as the modeling scenarios. Decrease in the lower growth limit of Fucus has followed the decrease in light availability on the seafloor. Sites with old measurements displayed an especially strong reduction in the lower growth limit of *Fucus* when compared to more recent observations. The measurements were converted to display an Ecological Quality Ratio (EQR) that allows the evaluation of sites with different optimal growth depths in a single dataset. Analysis reveals that degradation of *Fucus vesiculosus* habitats have progressed alarmingly towards a collapsed state. As a positive signal, recent monitoring efforts display a more moderate trend for the decreasing lower growth depth for *Fucus*.

Even though the proportion of change can be presented with relatively high confidence, uncertainties prevail when examining the modeled coverage of a suitable seafloor for *Fucus* spp.. Methods such as LiDAR mapping exist for detailed evaluation of *Fucus* distribution (Tulldahl & Wikström 2012; Paper I), but the data is available only in specific locations. With the current data, a precise areal estimate is difficult to provide. Limited availability of good quality substrate data limits the accuracy of species distribution modeling in large-scale studies. Available substrate data covering the whole Finnish coast suggests that the suitable areas for *Fucus* spp. have decreased from around 1000 km^2 to a little less than 600 km^2 during the past 100 years. This estimate, however, lacks the information about the detailed mosaics of different substrates.

Even though the analysis still has room for improvements, the scale and direction of the change remains clear. Paper III displays how reduction in light availability on the seafloor has led to large-scale degradation of *Fucus* spp. dominated communities. The findings support previous works of e.g. Kautsky et al. (1986), Eriksson et al.

(1998) and Torn et al. (2006) in the Baltic Sea region, but also advances the research by adding new elements of geographical evaluation and species distribution modeling for quantifying the environmental change. For future studies datasets of Paper IV could be further evaluated to provide insights on the other species groups or biotopes that have been heavily affected by the decreasing light availability at the seafloor.

Data in Paper III shows signs of recent positive development at certain sites. However, major improvements in the state of marine environments still require the underlying reasons for the reduction in light availability on the seafloor to be addressed. In order to reduce eutrophication development and sediment discharges, actions for marine protection should include active collaboration with land owners and regional authorities. Negative impacts on marine environments are often not visible for people practicing agriculture or forestry in the watersheds. Therefore, increasing public awareness could provide a good starting point towards a healthier Baltic Sea.

4.6 Species distribution modeling supports human impact assessments but requires control of various uncertainties

Species distribution modeling can provide valuable insights about where sensitive environments are likely to occur. SDM methods can also be used to estimate impacts caused by large-scale environmental change (Paper III). Models are especially beneficial when mapping vast regions where all areas cannot be sufficiently covered by traditional underwater inventory methods. However, modeling introduces uncertainties that should be controlled before using modeled data. In this thesis following factors have been noted to require special attention when planning species distribution modeling:

1) <u>The quality of the environmental variable data used</u> is one of the key components determining the outcomes of species distribution modeling (e.g. Mod et al. 2016). However analyzing the quality of the variables and choosing relevant environmental data for modeling has not been intensively researched. This thesis displays how differing methods of describing a certain variable, such as Secchi depth derived from satellite interpretation vs. Secchi depths measured in the field, provide a dissimilar image of the local environmental characteristics (Paper III). Furthermore, a lack of details in substrate or bathymetric data (see Papers I & III) affect the precision of modeling results.

Modeling processes might also cause uncertainties as the methods usually can only use one raster at a time to describe one environmental gradient. Often benthic species growth is strongly seasonal (e.g. Berglund et al. 2003; Piepho 2017). Using multiple measurements to describe the mean, maximum or minimum values for the environmental variables might not represent the most relevant time period for the modeled species. Comprehensive evaluation of how different species groups occurrence and coverage change depending on the time of year on the Finnish coasts would provide valuable insights when choosing the most representative environmental data for future modeling studies.

2) <u>Spatial and temporal bias in species observation data or environmental variables</u> can also create uncertainties in modeling processes (e.g. Boakes et al. 2010; Moua et al. 2020). Bias in the data will affect the modeling outcomes by indicating false correlation with species observations and environmental variables (e.g. Paper III, Figure 5). When using species presence data, the inventory effort will affect the count of species observations. As an example, most inventory boats cannot access or travel fast in shallow locations (<1 meter depth), this can lead to more observations at deeper locations even if the species in question would prefer the shallow sites. A limited sample area or absent sample data in parts of the environmental variables' gradient can also create bias as models can usually predict only suitability for similar areas where the species in question has been observed. The absence data (where the species in question has not been observed) can be used to tackle the bias (e.g. Moua et al. 2020). Paper III addresses the issue by presenting a means of calculating a corrected observation gradient (COG). COG can be used to remove bias in observation counts on an environmental variables gradient (see Paper III). Paper III is the original publication on calculating COG.

   Modeling with abundance data, such as observed coverages of the species on the seafloor, is usually less affected by the inventory effort as it focuses on where the most abundant sites for the species have been found. Nevertheless, abundance models can contain bias related e.g. to the growth season. Underwater field inventories are relatively expensive, and usually one site on Finnish coasts is only mapped once in the national underwater inventory program (VELMU). If one location is visited at the beginning of the growth season and the second one in the latter half of the summer, the coverages are likely to differ, even if the sites would be equally suitable for the modeled species. This is especially apparent with annual species that might not be visible at the beginning of the growth season. The growth season starts at different times in different regions (North-South gradient) and different species reach their full extent at different stages of the season; subsequently a suitable time window for optimal inventories can be difficult to determine. For further research, the change of species coverages during the growth season should be examined regionally to select representative inventory samples for modeling.

For environmental variables, the locations of sampling stations can create bias in the data. As an example, if nutrient concentrations were evaluated only using data from the frequently monitored coastal areas near the mainland, the dataset would not be representative of open sea conditions. Higher spatial coverage could be achieved by including stations with only a few samples, but as the nutrient concentrations have a strong temporal variation, this would most likely also cause misinterpretation of the overall situation.

3) Evaluating the performance of models with biased data is problematic. One of the most common method for evaluating the success of a model is calculating the correlation between the modeled species distribution with the observations or abundance recorded in the field. This can be problematic if the original data contains a bias created by sample placement (see Paper III, Figure 5). Usually the test data contains the same bias as the modeling data, as separate field campaigns for collecting test data are not usually organized (e.g. Newbold et al. 2010). Even if the datasets would have been separate during the modeling process and randomization would have been applied, bias from the original data can prevail. Moreover, the traditional way of visually inspecting the model results using biased observation data can lead to the wrong conclusions. If moderate areas for species occurrence have been visited frequently and the most suitable locations only rarely, it is likely that most of the observations have been recorded in the moderate areas. The moderate sites can have some patches of high coverages, also resulting in a bias in the abundance models.

4) Species observation data is often affected by human pressures. Past deterioration of seafloor communities along the Finnish coastline has affected their current distribution (e.g. Kontula & Raunio 2019; Paper III). Therefore, observation data might not reflect the most suitable locations for benthic communities in natural conditions. However, human pressure data is not commonly used in the species distribution modeling due to gaps in the data and comprehensive knowledge concerning the environmental impacts of different human activities. Modeling on the basis of already deteriorated species occurrence might provide a limited view on the species potential

distribution. Because of the limited knowledge on the issue, further studies for including human pressure data in SDM processes are highly recommended.

5 Conclusions and Recommendations

This study provides new insights into location based human pressure and impact evaluations on marine environments. The work also provides tools and methodological solutions for environmentally conscious coastal planning and contributes to increasing knowledge concerning benthic communities in the northern Baltic Sea. The methods presented in this thesis can be applied for evaluating historical, current and future pressures and impacts on shallow seafloor environments.

The conclusions of this work are following:

Open source data combined with proper methodologies can promote sustainable planning decisions in coastal environments. The work on Papers I-III demonstrate that commonly available environmental information of the underwater nature can be used to indicate where suitable sites for sensitive species groups are located. Targeting detailed planning with available general level data can save resources and help to minimize conflicts with different interest groups. Currently data is available but scattered over various actors and databases. Therefore further efforts to collate available data or data sources should be highly encouraged.

LiDAR -based underwater mapping data can be utilized to guide coastal activities to suitable locations. Paper I presents how LiDAR waveform data can be used to provide a comprehensive spatial overview of certain species groups and seafloor characteristics in the process of coastal wind turbine site selection. High-resolution LiDAR data is especially beneficial in priority areas of planned activities or constructions near sensitive environments. Currently LiDAR data is available only on selected locations and with relatively low spatial coverage. Hence for future studies, large-scale LiDAR mapping campaigns should be highly encouraged to provide broad and accurate information on valuable environments at shallow coastal sites.

Cumulative human pressure and impact modeling provides an indirect overview of the state of benthic communities on a local scale. The work on Paper II suggests that cumulative human pressure and impact modeling can be applied to general planning and can provide valuable information on potentially disturbed locations. However, the impacts of multiple simultaneous and alternating human pressures on the underwater nature are still widely unknown and site-specific uncertainties are common in the assessments. For evaluating causalities and targeting measures to remove harmful activities it is recommended that different pressure groups would be evaluated separately. The quality and methods for evaluating individual pressures and their spatial extent still require further development. Focused underwater inventory campaigns near identified pressure sources are to be encouraged for providing more information on how human activities affect the species distribution in the sea. Additionally, developing a set of field measurement indicators for evaluating the overall human pressure status is to be highly promoted.

Biotope classifications are beneficial, but usually they cannot represent all the important species groups. The findings of Paper IV indicate that for the Baltic Sea region, it would be beneficial to improve the HELCOM HUB biotope classification by combining species groups with red algae. Currently individual red algae groups are often lost in the classification process as they are evaluated separately. However, the HUB biotope classification succeeds in creating a comprehensive overview of benthic communities on a national and regional scale. Therefore biotope classifications can be seen as an especially valuable on coastal planning processes that often have limited possibilities on detailed species –level examinations.

Species distribution modeling and recorded change of environmental conditions can reveal past occurrences of important benthic species groups. The created modeling workflow in Paper III presents a way of using current species inventory data and past records on environmental parameters to spatially evaluate changes in species distribution. The methodology was used in this work to display a large scale degradation of *Fucus* spp. biotope. Similar approach can be applied to different underwater species groups, environmental parameters and it could also be used to evaluate changes of species distribution on land. Further studies utilizing this methodology are to be highly encouraged as long time series of benthic species monitoring data are rare and often spatially limited.

Handling data bias should be carefully planned in species distribution modeling. Paper III shows that species distribution modeling can provide good overview of suitable areas for benthic species, but data bias can distort the results. Evaluating data bias is recommended to be included comprehensively in SDM processes, especially when modeling with presence/absence data. Despite the uncertainties, utilization of SDMs should be promoted as they can help to transform local inventory data into a suitable form for spatially comprehensive geographical examination.

The findings of this thesis promote environmentally conscious and information-based coastal development. The research suggests improvements to the processes involved in geographical human pressure and impact evaluation and also contributes to methodological developments in the field. I hope the findings of this thesis will promote sustainable planning choices and improve the quality of further research on human pressure and impact evaluations.

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