DEPARTMENT OF MARINE SCIENCES

INCORPORATION OF CLIMATE EFFECTS IN MARINE SPATIAL PLANNING

Possible Climate Refugia on the Swedish West Coast Based on Two Climate Scenarios

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Popular science summary

Climate change is posing a risk to marine species and habitats worldwide. In general, sea salinity is expected to decrease and temperature to increase. Scientists are trying to explore new ways to protect them. One such strategy is the use of so-called climate refugia. Climate refugia are areas which offer better conditions for the species to live in the face of a changing climate. In this thesis, I focused on finding climate refugia for several species, including blue mussels, eelgrass, and sponges, on the Swedish West Coast. I used a technical programme called Geographical Information Systems, or GIS, which is used to analyse spatial data and map areas where these species' refugia can be found. Based on two climate scenarios, RCP 4.5 and RCP 8.5, the effects of changes in salinity and temperature were examined. The climate scenarios represent potential future concentrations of greenhouse gas emissions. Depending on the scenario, different levels of decreased salinity and increased temperature will be projected, where all three species have their own optimal lower limit of salinity and upper limit of temperature that they generally thrive in. The study found that these habitats will change to varying degrees, depending on which scenario was applied. In general, climate refugia for blue mussels and eelgrass will remain relatively similar to their current distribution on the West Coast. However, there are some local exceptions where current distributions are expected to disappear, where salinity change had the most impact. Furthermore, sponges are going to be more affected by climate variable changes, especially increasing temperature. Sponge refugia are expected in the northern part of where they currently exist, in areas not as much affected by the variable changes. Finally, the importance of studying climate refugia is crucial to protect our marine ecosystems. By finding areas that could potentially be climate refugia, we can ensure that these habitats will continue to exist at the end of the century, even if climate change takes its toll.

Abstract

Climate change poses a significant threat to the survival and distribution of marine species and habitats. Identification and conservation of climate refugia have emerged as a strategy to safeguard vulnerable habitats and promote species resilience. Refugia are areas with favourable conditions for species survival amidst changing climates, serving as vital havens for biodiversity and ecosystems. This study aimed to analyse the consequences of future climate scenarios on the distribution of blue mussel reefs, eelgrass beds, and sponge aggregations on the Swedish West Coast, and ultimately use this knowledge to identify potential climate refugia. Salinity and temperature were used as climate variables, where values were projected based on two climate scenarios, RCP 4.5 and RCP 8.5 and their respective model outcomes. The primary method used was analyses in GIS, based on geodata and previous research. The main findings revealed that these habitats will undergo alterations and retractions to different extents under different scenarios. The results showed that blue mussels and eelgrass refugia can be expected to be relatively similar to the current distribution, although with local exceptions where primarily salinity decreases had effects. Sponges were mainly impacted by temperature increases. However, decreasing salinity levels had a significant effect, as well. The distribution of sponges was altered to a larger extent compared to blue mussels and eelgrass, where refugia were primarily located in parts where salinity stayed high and temperatures low. The refugia using the species' optimal limits are to a large extent safeguarded from the impacts of changing variables. Despite uncertainties and limitations, studying potential climate refugia is vital for understanding species distribution, informing MSP, and preserving marine ecosystems effectively.

Keywords

Climate Refugia, Climate Change, Representative Concentration Patterns, Marine Spatial Planning, Geographical Information Systems, Temperature, Salinity, Marine Management, Swedish West Coast.

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List of abbreviations

˚C	Degree Celsius
CAB	County Administrative Board
CMIP5	Coupled Model Intercomparison Project 5
EEZ	Exclusive Economic Zone
EU	European Union
GIS	Geographical Information Systems
HELCOM	The Baltic Marine Environment Protection Commission
HRP	Historical Reference Period
IHO	International Hydrographic Organization
IPCC	Intergovernmental Panel on Climate Change
MPA	Marine Protected Area
MSP	Marine Spatial Planning
OSD	Optimal Species Distribution
OSPAR	The Convention for the Protection of the Marine Environment of the North-East Atlantic
PSU	Practical Salinity Unit
RCP	Representative Concentration Patterns
SLU	Swedish University of Agricultural Sciences
SMHI	Swedish Meteorological and Hydrological Institute
SSD	Symphony Species Distribution
SwAM	Swedish Agency for Marine and Water Management
UN	United Nations

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Preface

During the third semester of the master's program Sea and Society, I was given the opportunity to do a 20-week internship with the international WIO Symphony project, led by the Swedish Agency for Marine and Water Management (SwAM). With the knowledge and experience I had attained during the past years at the University of Gothenburg, the internship broadened my view of what I might use it for. My background, together with the internship experience, ended in taking on this study. The interdisciplinary project idea felt on the one hand reasonable with the background I had, but on the other hand as a completely new field of marine science and climate change. There were some struggles along the way, however, with much work and dedication, it turned out well in the end and I am proud of what I have achieved and accomplished during these past five months.

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Gothenburg, May 2023

1. Introduction

Marine ecosystems are critically important for a healthy state of our planet. They are maintained in an energy flow of primary producers, consumers and pathogens and circularly revived through decomposition. Marine communities are interlinked directly or indirectly through various interactions. Ocean and coastal ecosystems provide humanity with natural benefits that many societies are dependent on, such as fisheries. Anthropogenic climate change, however, jeopardises the continued existence of the oceans' species and habitats through its disturbance of this symbiotic way of life (Doney et al. 2012). There are, unfortunately, still many gaps on how climate change will impact these ecosystems, both today and in the future. Therefore, a better understanding of it is of high importance. Studies indicate the rapid rise of greenhouse gas emissions, where concentrations of it drive systems of the ocean into conditions not seen before in the history of mankind (Hoegh-Guldberg & Bruno 2010). These changes are at risk of causing a fundamental and irreversible transformation of our marine ecology, with impacts such as decreased productivity, changed food web systems, moved species distributions and extinction of them and their habitats. An additional change will continue to alter the state of our ecosystems, with aggregated effects causing escalation and cascading effects (Doney et al. 2012).

With certainties of climate change altering ocean ecosystems, there are, however, uncertainties when it comes to the spatial and temporal effects of climate change on species and habitats. To use our oceans sustainably, a broad perspective on the challenges we face is required. One way to do this is to investigate how climate change affects species and habitat distribution. The term refugia is used in biological sciences to describe places of limited spatial extent where components of biota have retracted due to some changes at their original spatial extent. These areas are buffered by contemporary climate change (Morelli et al. 2020). These areas may serve as important habitats for species that cannot tolerate changing conditions elsewhere in the ocean. It has become a term used when considering the dynamics of range in species together with climate change. Refugia also operates over a long period, often evolutionary timescales. It should be noted that this refugium is a space which they also could subsequently expand from. Even though the literature on refugia in the marine environment is scarce, it could, in principle, be applied to it beyond terrestrial borders (Keppel et al. 2012). Another definition made by Havenhand and Dahlgren (2017) describes climate refugia as areas where the effect of climate change is smaller compared to the surrounding environment.

Species within such an area of refugia could contribute to increased diversity and genetic variation in areas that are more affected by climate change variables, through the planktonic spread, for example. Thus, climate refugia contribute to preserving species and biodiversity, in turn increasing the resilience of its area and surrounding ones (Havenhand & Dahlgren 2017). Here, connectivity refers to the degree to which different populations of a species can exchange individuals through migration or dispersal. Climate refugia can serve as an important source of colonists for other areas in the ocean. If the refugia remain stable, the species can persist and act as a source population for colonization of nearby areas when conditions are favourable again. It will be crucial to consider refugia of species not only as conservation targets, due to their persistence from climate change, but also for their potential to aid movement and act as stepping-stones, to establish strong connectivity networks (Magris et al. 2014, Wilson et al. 2020).

The marine environment is made up of several ecosystem components, both living and non-living elements. These components are interconnected and play an important role individually to maintain the health and balance of the marine ecosystem. Components are structured into a few main categories; *abiotic factors* like temperature, salinity and nutrients that influence the distributions and abundance of marine organisms, *producers* like algae, phytoplankton and seagrass that are the primary producers of organic matter which is the basis of the food chain in the ocean, *consumers* that feed on producers and other consumers, like herbivores, carnivores and omnivores, *decomposers* like bacteria, fungi and microorganisms that break down organic matter into simpler compounds and recycles nutrients in the marine ecosystem, and lastly *physical structures*, habitats that provide shelter and food for, such as mussel reefs and rocky shorelines. Disturbances or changes, such as increased temperatures, to one of these components can have cascading effects on the entire ecosystem (Halpern et al. 2008, Worm et al. 2006).

Representative Concentration Patterns (RCP) are climate projections based on the United Nation’s (UN) Intergovernmental Panel on Climate Change (IPCC) assumptions of greenhouse gas levels. RCP 4.5 and RCP 8.5 represent intermediate and extreme scenarios, respectively (Stocker et al. 2013, Moss et al. 2010). According to these climate scenarios, environmental conditions such as temperature and salinity are going to change during the current century. Because these conditions affect the reproduction, growth and survival of marine species, major shifts in their abundance and distribution can be expected. To adapt to or mitigate such impacts, government agencies and regional authorities need to develop strategies and action plans. Adaptation strategies could be to develop marine protected areas

(MPA), restoration of degraded habitats or implement sustainable fisheries management practices. Social and economic implications from these strategies are of high importance to consider, as well as to involve stakeholders in the process of both plans and implementations (Miller et al. 2018).

Marine spatial planning (MSP) is an ecosystem-based management approach for marine environments and the sustainable use of its resources. There are often objectives to achieve within the three pillars of sustainability (ecologic, economic, and social), through a process of analyses and allocations of spatial and temporal distributions of human activities in the sea. It integrates various uses and stakeholders in a specific area, often regional or national. Stakeholder engagement is of high importance throughout the MSP process, together with the need for collaboration and communication between different sectors and government levels. Several coexisting challenges and opportunities are associated with MSP, for example, data sharing, capacity building and political will. Human activities are something we can plan and manage in marine areas, contrary to marine ecosystems or their components. However, by allocating these activities to a certain marine area by its objective, like fishing and wind farms, we can indirectly plan and manage the ecosystems, as well. Knowing where we should not disturb marine ecosystems is of high value in MSP (Ehler & Douvere 2009). Havenhand and Dahlgren (2017) report that the establishment of climate refugia is one appropriate measure to consider for climate change in MSP.

For example, the Swedish Agency for Marine and Water Management (SwAM) works on behalf of the Swedish government and plans to include considerations on the effects of climate change in MSP. Swedish MSP includes the designation of so-called small-n-areas, which call for consideration of existing high nature values. One of the criteria for identifying such areas is to which extent they may have a role as climate refugia. In the first Swedish MSP plan adopted in 2022, such climate refugia considerations were incorporated for the Baltic Sea and the Gulf of Bothnia (Hammar & Mattsson 2017). SwAM now seeks to assess refugia for the biota on the Swedish West Coast (Västerhavet) to revise the current small n-areas with the aim to reduce the effects of impacts from future climate change. Climate refugia are coveted to improve future Swedish MSP. The alignment of this study is the context of the development of marine spatial planning, based on previous Swedish experiences of climate change effects in MSP in other marine areas. To test this, producing climate refugia could be an alternative indicator to see climate change effects and how it could affect MSP from a Swedish perspective.

A vast amount of knowledge about our oceans’ status exists, but also data and models about how they will change in the future as a consequence of climate change. Reduced salinity and increased temperatures are variables that certainly will impact the West Coast in the coming decades, both directly and indirectly. Thus, this work is based on the hypothesis that species and habitat distributions will be altered and retracted following changes to climatic factors. Despite scale or geographical area, measured and predicted climate change will have cascading effects in the future, which are hard to anticipate in detail. Despite species and habitats shrinking in their distribution, or even disappearing, another consequence is that other species might take their place, probably causing additional effects that are even more difficult to predict (Hammar & Mattson 2017). Salinity and temperature changes are the chosen factors in this study that will be applied to some species and habitats that have been identified to represent the marine ecosystem of the study area as an important component that could be affected by the variables. Those selected species and habitats are blue mussels, eelgrass, and sponges. See chapter 2 for more information.

1.1 Aim

This study aims to analyse the consequences of future climate scenarios on the distribution of keystone species and habitats in the marine environment and ultimately to use this knowledge to identify potential climate refugia on the West Coast.

1.2 Research questions

1. Where are potential climate refugia on the West Coast for blue mussels, eelgrass, and sponges and where will today’s distributions potentially disappear?

2. How much difference will the impact be on each habitat when comparing different variables, their two RCP scenarios, and which variable impact respective species the most?

1.3 Delineations

The study was delineated with respect to species and habitats. First and foremost, the study had an initial idea of analysing climate refugia for more than just benthic species, such as important fish species and mammals. However, due to time constraints and difficulty to represent refugia reasonably with the data that was available, this was abandoned. Another major delineation is that the study's analysis was only made for the species' distributions within optimal ranges of the variables, and not all distributions within the study area. In other words, upper and lower optimal levels of salinity and temperature are considered, and not the species' minimum or maximum tolerance. The use of only bottom variables and not surface variables is motivated using only benthic living species, which in turn was constrained due to time and representation difficulties, as mentioned in the beginning. The variables are applied to the species separately and do not combine in a multi-criteria assessment due to data based on different periods. Cumulative effects from salinity and temperature change will be discussed rather than applied in the analysis and presented in the results. A major delimitation of the study was time and quality and quantity of data. Better and more data is often desired, but often not available or reasonable to create on your own. Much time was consumed trying different methods to give the best possible outcome of the results. However, many of these attempts were in the end discontinued due to the poor quality of the outcome and replaced by better, more representative methods. The time frame is set from two 30-year multiannual periods. 1976 – 2005 and 2070 – 2099. However, due to a lack of data on the historical reference period (HRP) of 1976 – 2005, data from 1993 – 2005 were used to represent that period. See more in chapter 3.3 explaining method decisions made during the conduction of the study.

1.3.1 Study area

The boundary of the study area is the Swedish exclusive economic zone (EEZ) on the West Coast (Västerhavet EEZ). This includes the International Hydrographical Organizations' (IHO) sea areas Skagerrak and Kattegat (which includes Öresund) and spans from Idefjorden in the north to the Falsterbo isthmus in the south. This extends from the Swedish inshore waters to the border of the exclusive economic zone (EEZ) for the West Coast (Flanders Marine Institute 2020). According to SwAM's report, the "Green Map" or "Gröna Kartan" in Swedish, shows that the study area has a generally high nature value and benthic species used in this study represent highly valued areas (Hammar et al. 2018).

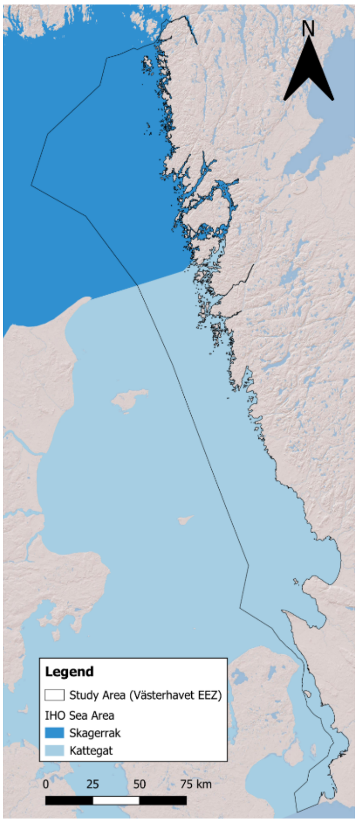

Figure 1. Map of the study area which encompasses the Swedish EEZ of the West Coast (Flanders Marine Institute 2018, 2020).

2. Background

This chapter describes the used variables salinity and temperature, the two RCP scenarios as well as species and habitats, to provide a more in-depth understanding of the result's outcome. It will also provide the connection of the variables to the species and habitats. The variables were chosen due to their high influence on current and future climate change. The species were chosen due to their high importance and representativeness of the marine ecosystem on the West Coast. They have an ecological value and a role in the ecosystem that could be affected and altered by the variables, which is why they were chosen for this climate refugia assessment.

2.1 Indicators of climate change

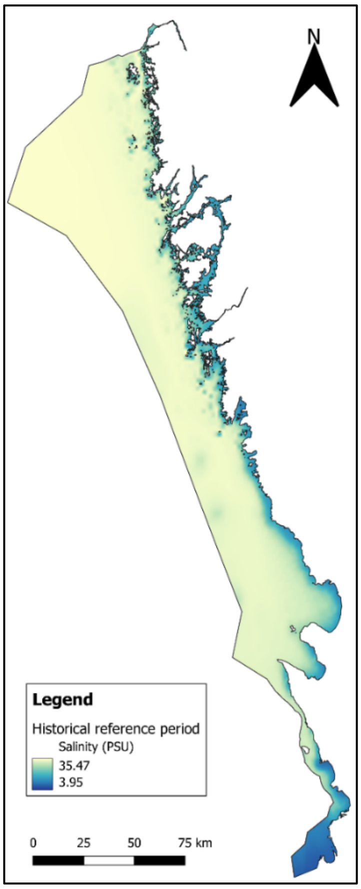

Figure 2. This figure on the left shows the mean salinity of the study area over the annual mean of the period 1993-2005, i.e., the historical reference period (Copernicus n.d.).

Salinity and temperature are important abiotic factors explaining distribution patterns since both variables can have strong physiological effects on the species within the study (Harley et al. 2006). Offshore, salinity remains more stable, while inshore, fluctuations can occur due to freshwater input. The variables that influence marine organisms' survival and behaviour, such as biological processes, reproductive capabilities, larval dispersal, distribution, et cetera (Smyth & Elliott 2016). Temperature can directly shift distribution and abundance since stable temperature ranges are crucial for organisms' performance and survival (Harley et al. 2006). Changes can impact the structure and distribution of marine organisms. Juveniles can especially be susceptible to salinity and temperature changes (Brierley & Kingsford 2009). Wåhlström et al. (2022) found in their study on projected climate change impacts that benthic habitats are one of the ones most likely to be sensitive to changes in the variables. The West Coast is highly sensitive to salinity reductions. The highly diverse ecosystem of the West Coast is not as tolerant to changes compared to the more brackish waters in the Baltic. They also found that the ecosystem in this area is most sensitive to bottom temperature increases. This is important for deep-water fauna, such as sponges, as they do not adapt well to fluctuations in surrounding temperatures (Wåhlström et al. 2022). See figure 2 and 3 for the mean salinity and temperature of the West Coast.

RCP scenarios are climate projections based on the IPCC assumptions of greenhouse gas concentration levels. RCP 4.5 and 8.5 are two different scenarios representing an intermediate and extreme scenario. The differences lie in the greenhouse gas emission trajectories that they represent. The intermediate RCP 4.5 assume a more moderate emissions pathway. It represents a future where emissions peak around the year 2040 and gradually decline thereafter. Humans take moderate efforts to mitigate climate change by reducing emissions, increasing energy efficiency, and adopting the use of better technology. RCP 8.5 represents the worst scenario with high emissions due to continued reliance on fossil fuels. It assumes a future with no real policies or effects to mitigate emissions. Instead of peaking, emissions will continue to rise throughout the century (Stocker et al. 2013, Moss et al. 2010). Table 1 below shows the overall ranges of salinity's practical salinity unit (PSU) and temperature (˚C) within the study area. See appendix figure 1 to 12 for different RCP projections of future salinity and temperature in the study area. Note that some areas in appendix figure 1 to 12 can have changes of several PSU or degrees, and not just the range shown in table 1.

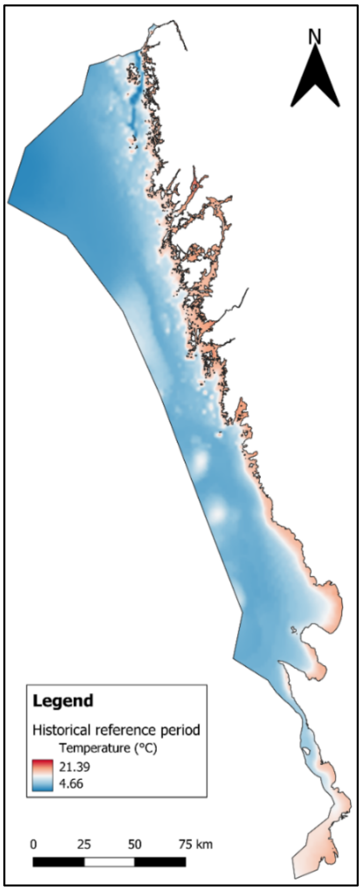

Figure 3. This figure on the right shows the mean temperature of the study area over the months May – September of the period 1993 – 2005, i.e., the historical reference period (Copernicus, n.d.).

Table 1. The table shows the span of the two variables (salinity (PSU) and temperature (˚C)) for each scenario and its respective model outcomes. These are visualised in appendix figure 1 - 12 in chapter 9. HRP stands for the historical reference period representing the mean of the years 1976 – 2005, based on data from 1993 – 2005.

Salinity (PSU)		**Temperature (˚C)**	
HRP	6.12 – 35.95	HRP	5.01 – 18.53
RCP 4.5 Max	5.85 – 35.69	RCP 4.5 Min	6.00 – 19.55
RCP 4.5 Med	5.41 – 35.16	RCP 4.5 Med	6.38 – 19.95
RCP 4.5 Min	4.82 – 34.85	RCP 4.5 Max	6.71 – 20.16
RCP 8.5 Max	5.47 – 35.29	RCP 8.5 Min	6.70 – 20.16
RCP 8.5 Med	4.91 – 34.93	RCP 8.5 Med	7.15 – 20.71
RCP 8.5 Min	3.95 – 34.56	RCP 8.5 Max	7.64 – 21.39

2.2 Ecosystem components

Blue mussels (*Mytilus edulis*) are mollusc species living in hard and soft bottoms, primarily from 0 - 50-meter depths. They attach themselves to rocks or form larger banks on the bottom which can consist of several thousand individuals per square meter. Blue mussels are efficient filterers, contributing to more transparent and cleaner water columns. These mussels are ecosystem engineers with ecologic and economic importance (Pleijel 2014, SLU Artdatabanken 2020).

Upon settlement, blue mussels can later release their mount and be transported to another site. Previous observations and reports point towards a decline in blue mussel distributions on the West Coast, however, the extent of it and specific reasons for it is missing. Even though blue mussels have a relatively high tolerance to changes in environmental factors such as temperature and salinity, numbers outside the tolerance can have severe effects on blue mussels, affecting size and distribution (Sundelöf et al. 2022). Repeated heat waves, which are expected to increase in frequency and intensity, can contribute to mass mortality (Seuront, et al., 2019). Studies estimate the upper water temperature tolerances of blue mussels to be between 28 and 29˚C (Zippay & Helmuth 2012). Hiebenthal et al. (2012) found that suboptimal salinity and temperature can contribute stress on blue mussel shell production to cellular processes and may have interactive effects. Other experiments and correlative studies indicated that tolerances to reduced salinity were lower when temperature increased (Westerbom et al. 2019, Knöbel et al. 2021). Regarding upper optimal temperature, temperatures above 20˚C have been reported to decrease the shell growth of blue mussels (Almada-Villela 1982). Salinity has a strong correlation to blue mussel distributions that are based on future climate projections. A PSU of 4 is seen as a lower limit of salinity tolerance, however, blue mussels are physiologically stressed already at 18 or less PSU, affecting their growth and sensitivity to disturbances. Studies show indicators of possible interactions between temperature and salinity tolerances, where there is a lower tolerance to reduced salinity when temperature increases (Hammar & Mattsson 2017). Another study of

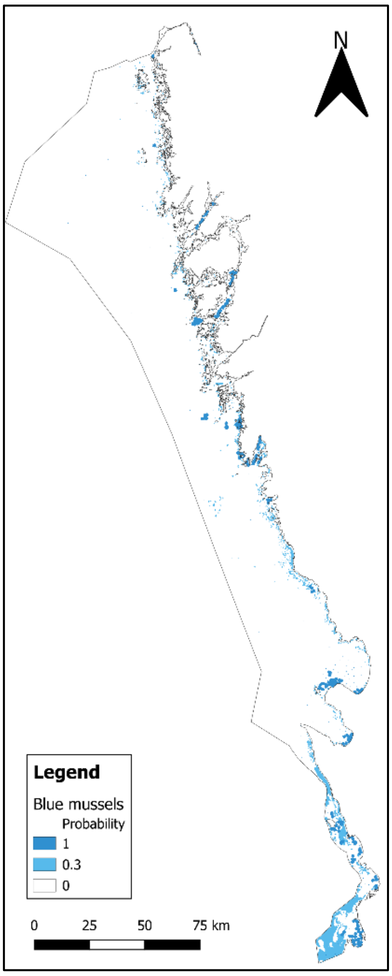

Figure 4. This figure shows the current probability of blue mussels in the study area.

blue mussels in the Kiel fjord suggested that growth decreased below 17 PSU (Kossak 2006), which was selected as the lower optimal limit for blue mussels in the analysis.

Blue mussels have an important role in constituting habitats and being a source of food, as well as their filtering abilities. Temperature and salinity are the variables that will be applied in the analysis of future blue mussel distributions and its climate refugia on the West Coast.

Eelgrass (*Zostera marina*) is an ecosystem serving angiosperm existing along the whole western coast of Sweden, especially sheltered bays in the county of Bohuslän and the Öresund area. Eelgrass grows on shallow, soft bottoms and composes important habitats in coastal areas, sheltering many other species and acting as a nursing ground for juvenile cod, eel, and crab. It has a high primary and secondary production, and it stabilises sediments with its underground rhizome, which, in turn, mitigates turbidity and erosion. Eelgrasses reduce wave energy impact and accumulate organic substances in the sediment. During the past decades, it is thought that around 60% of the species have disappeared in the Bohuslän area, and the maximum depth propagation has gone from 10 – 15 meters to 5 – 8 meters on the West Coast. Eelgrass is generally adapted to a colder climate, ranging from winter temperatures of -1˚C to summer temperatures of 25˚C (Moksnes et al. 2016). Eelgrass in coastal bays has been documented in the United States to have limited resilience to increases in water temperatures that are predicted from climate change. Increased mean water temperatures will likely result in more frequent and severe summer temperatures that can cause die-offs for eelgrass (Carr et al. 2012). Temperature is important for geographic patterns and is considered the overall parameter that controls the geographical distribution of all European seagrass species, including eelgrass. Temperature also affects seagrass metabolism, growth, and reproduction. Progressive temperature increases can be a major threat to local populations (Borum et al. 2004). The upper level for optimal temperature is 20˚C since temperatures above that cause stress (Nejrup & Pedersen 2008, Davison & Hughes 1998, Tyler-Walters 2008).

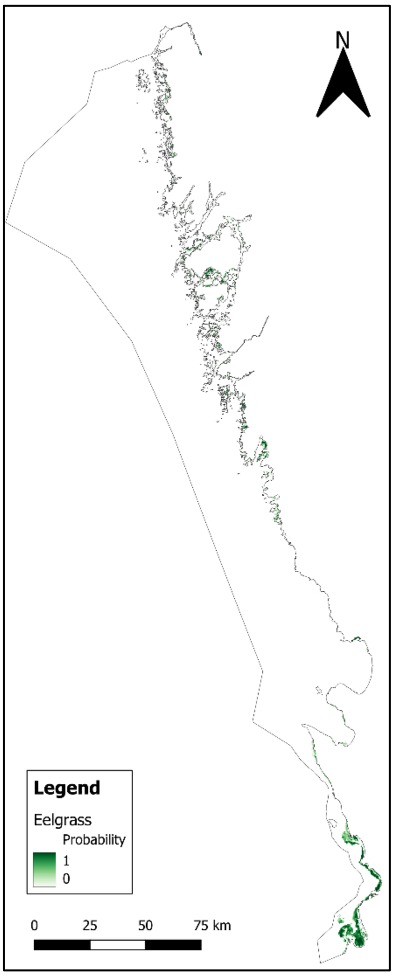

Figure 5. This figure shows the current probability of eelgrass in the study area.

The species' frequency seems to decrease along with reduced salinity. Less salinity contributes to a reduced ability to sexually reproduce, leading to increased clone reproduction and could make it more difficult to colonize new areas (Moksnes 2009). The salinity levels that eelgrass can handle stretch from 5 PSU to 35 PSU, although the lower salinity level for optimal growth and survival is 10 PSU (Nejrup & Pedersen 2008). However, studies show that the eelgrass on the West Coast is relatively tolerant to variations in salinity (Moksnes et al. 2016).

Eelgrass is a threatened species that is protected by nature reserves, Natura 2000 areas, European Union (EU) directives, OSPAR and HELCOM, together with other biotope protections. Eelgrass is used as an indicator species for classifications of the ecological status of the sea (Moksnes et al. 2017), making it a key species to include in this climate refugia analysis. Although climate change is not currently the primary threat to eelgrass, it could potentially increase its impact on eelgrass distributions in the future (Moksnes et al. 2016). Global warming, sea level rise and reduced salinity are potential climate change impacts on eelgrass, along with changed trophic patterns coming from a changing climate that contributes to reduced eelgrass distributions. Increased precipitation and runoff from land can dilute the salinity, and the salinity gradients shifted outwards towards the North Sea. This could have a great effect on eelgrass, especially in the less saline parts of southern Kattegat and Öresund. Although it is expected that climate-driven temperature rises would not affect eelgrass directly, increased temperatures can benefit algae growth that indirectly disadvantage eelgrass, especially if these high temperatures lead to lowered oxygen levels in the water (Moksnes et al. 2017).

Eelgrass' important part in the ecosystem of the West Coast is the main reason for it to be assessed in this climate refugia analysis. Due to its both physiological and ecological characteristics, changes in temperature and salinity will be applied to eelgrass to find climate refugia for it and to see where distributions disappear.

Sponges (*Porifera*) are in this study primarily deep-sea reefs made up of different types of aggregated sponges. Deep-sea sponge communities occur typically below a 250m depth, however, studies prove that sponge habitats occur at shallower depths around 30m. These sponges occur often together with cold-water corals, such as *Lophelia pertusa*, suggesting similar preferences of variables in their habitat (OSPAR 2010). Sponges enhance local nutrients and exchange energy, as well as biodiversity. They are important components of the benthic ecosystems, especially in aggregated sponge grounds (Knudby et al. 2013). According to a study in Skagerrak, deep-sea sponges seem to exist primarily in waters deeper than 40m, with temperatures rarely exceeding 12°C and salinity less than 30 PSU (Florén et al. 2017). The types of sponges located in the areas from the data used in this study seem to primarily be different types of *Halichondria*, *Axinella*, *Sycon*, *Phakellia*, *Mycale*, *Geodia*, *Myxilla*, and *Suberites*, in descending order (SLU Artdatabanken n.d.).

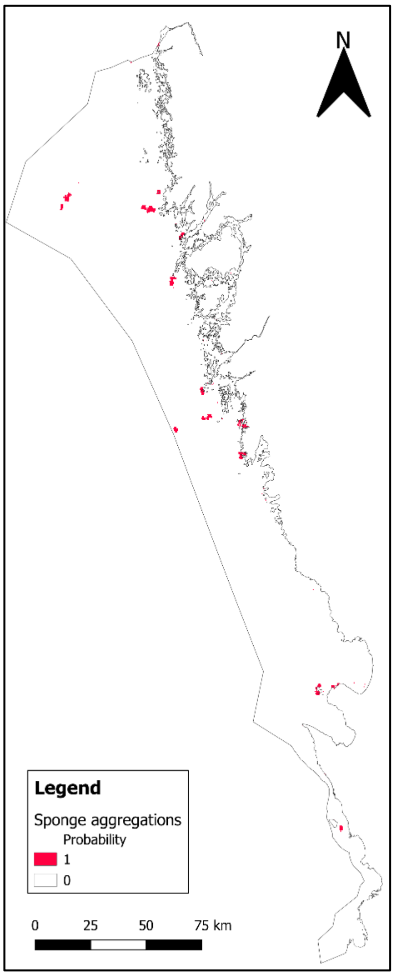

Figure 6. This figure shows the current probability of sponges in the study area.

According to the County Administrative Board (CAB) in Västra Götaland, sponge reefs are a prioritised marine habitat within the county and are a marine area of high value, or "värdetrakt" in Swedish (CAB 2019). Deep-sea sponge aggregations have been on the OSPAR List since 2003, where OSPAR work to ensure the protection of these habitats (OSPAR 2010). Most of the data of sponge distributions in this study lies within protected areas, such as national parks, nature reserves, Natura 2000 sites, or other types of protection of marine environments.

3. Materials and Methods

This section describes the materials and methods in this study and includes data and tools used during the process. The method was quantitative with data assessed through technical tools. Geographical Information Systems (GIS) was the primary tool for the methods trying to reach a result on identifying climate refugia on the West Coast. Both variables (salinity and temperature) were applied to all three species in the study.

3.1 Geographical data

Regarding tools used to conduct the analysis, two GIS programmes were used; QGIS primarily and ESRI ArcMap additionally, versions 3.30.1 Hertogenbosch and 10.8.1, respectively. The use of two programmes allowed using tools that perhaps did not exist in the other, so both were used back and forth to produce the best possible results. All the variable datasets used the unit degree Celsius (°C) for temperature and the PSU unit for salinity.

NetCDF files from Copernicus Marine Service were retrieved that included data on the bottom temperature and salinity of the study area. For temperature, the data was a mean for the period May 1st to September 30th over the years 1993 - 2005. 1993 was the furthest year back that Copernicus Marine Survey had data available. The same goes for salinity, but the data was annual (January 1 – December 31, 1993 - 2005) instead of May to September. This specific data was selected as the historical reference period to reflect the climate variable projections done by ClimeMarine (Copernicus Marine Service n.d.).

Raster data with multiannual (2070 – 2099) mean average projections of bottom temperature and salinity were used from the Swedish Meteorological and Hydrological Institute's (SMHI) ClimeMarine project. These projections are made to represent two climate scenarios from the UN's IPCC RCP climate scenarios 4.5 and 8.5 (Stocker et al. 2013). The climate scenarios are ensemble predictions based on five Coupled Model Intercomparison Project 5 (CMIP5) models, where minimum, median, and maximum model outcomes are reported. This is to account for the climate projection's uncertainties. All of these were used in this study to represent the typical and extreme model outcomes of the predictions. These datasets are based on source data models of assumptions on atmospheric climate gas concentrations, either for RCP 4.5 or 8.5. The projections change for the end of the century were calculated from an average of the historical reference period 1976 – 2005. However, temperature changes are within the period May 1st – September 30th for both multiannual periods (1976 – 2005/2070 – 2099) and changes in salinity are annual (January 1st to December 31st (Wåhlström et al. 2022, Törnqvist et al. 2022). Since temperature increases and salinity decreases, "maximum" refers to the highest temperature increase, while "minimum" refers to the highest salinity decrease.

Data on species and habitats were retrieved from SwAM's website to represent the current distributions of species used in the Symphony tool (Hammar et al. 2018). These data are referred to as the Symphony Species Distribution (SSD). Figure 4 – 6 in chapter 2.2 display the distribution data from Symphony. This study's blue mussels are based on the distribution of aggregated mussels or mussel reefs, primarily of blue mussels and based on two sources, a continuous prediction model of blue mussels and observations of other mussel species. The data was categorised as low probability (0), high probability (0.3), and observation (1) (see figure 4). Eelgrass came from angiosperm data of *Z. Marina* and *Characeae*. This data was satellite-based and displayed in a linear occurrence from unlikely (0) to full (1) coverage (see figure 5). Data of sponge distributions derive from Symphony data on deep reefs. The data is based on observations to display occurrences of reefs made up of sponges or *Lophelia pertusa*. The data was binary categoric and visualised as not surveyed/no occurrence (0) and observation/close observation (1) (see figure 6). Ideally, the distribution and extent of the SSD would coincide with the distribution predicted by the optimal conditions defined in the study, the Optimal Species Distribution (OSD). Because this did not hold for some of the species (the predicted area was usually smaller than the observed from the SSD), the area under different scenarios was primarily compared to the OSD, to quantify changes within identical areas. Additionally, data over background data such as boundaries etc. was also used to utilize and work properly with the variable data (see appendix table 1 in chapter 9 for information about data used in this study).

3.2 GIS analyses

With the help of GIS, this study's methods consist mainly of analyses in the programme, based on retrieved data and variable parameters set from previous studies seen in chapter 2.2. First, all data that was needed was either downloaded or requested from different sources seen in appendix table 1 in chapter 9. All data were reprojected to fit a similar grid that was used; ESPG:3006 – SWEREF99. Everything was organised in folders to be used efficiently.

Base layers of bottom salinity and bottom temperature were retrieved from the EU Copernicus Marine Survey as NetCDF files from the product

"BALTICSEA_MULTIYEAR_PHY_003_011". By default, the grid did not cover the fjords in the northern half of the study area and was therefore requested by Copernicus to access data over the area. The NetCDF files were converted to raster using the tool "*Make NetCDF Raster Layer*" in ArcMap. Another tool in ArcMap called "*Resample*" was used to convert the cell size of the layer from 1 nautical mile^2 to 250m^2. 250m^2 was chosen since additional data had the same size and it was a good mix between quality and efficiency. The resampled layers were then extrapolated to cover areas without cells containing data, using "*Fill nodata*" in QGIS. Finally, these layers were clipped to fit the extent of the study area, using "*Clip raster by mask layer*". See figures 2 and 3 in chapter 2.1.

Raster data with the multiannual (2070 – 2099) mean average projections of bottom temperature and salinity were retrieved from the Swedish National Data Service (SND) (Törnqvist et al. 2022). See table 1 in chapter 2.1 for the values range the different projections had within the study area. All layers were clipped to fit the study area, using "*Clip raster by mask layer*". The projection changes for bottom temperature and salinity were applied to the historical reference period, using the "*Raster calculator*" by simply adding them together. This gave an output of what temperature or salinity it might be in the period 2070 – 2099, May to September and annually, respectively. This was done for both RCP 4.5 and 8.5 for all three different model outcomes (minimum, median, and maximum). See appendix figures 1 - 12.

Regarding species distribution, raster data were retrieved from SwAM's Symphony tool (Hammar et al. 2018). These rasters were also clipped and fitted to the study area. For the climate refugia analysis, all species' distributions (figure 4 – 6) were extracted based on the set criteria seen in table 2 below. This was done so the represented current distribution of the habitats would match the refugia analysis. Using the "*Raster calculator*", all species distributions today were extracted where they exist within optimal limits of salinity and temperature. For example, eelgrass distribution was extracted < = 20˚C for temperature and > = 10 PSU for salinity. This gave outputs of representations of current distributions within optimal limits for each species.

Henceforth, using the current distributions within optimal limits of temperature and salinity today, these distribution layers could then be calculated with the projections from ClimeMarine with its changes that were earlier merged with the historical reference temperature and salinity layers. This was also done using the "*Raster calculator*". For temperature, the expression for salinity was for example: "*EelgrassCurrentOptimalSalinityDistribution* AND *SalinityRCP4.5Minimum* > = 10". For temperature, the expression was for example: "*EelgrassCurrentOptimalTemperatureDistribution* AND *TemperatureRCP8.5Maximum* < =

20”. Each species had twelve calculations of different refugia. All climate refugia analyses were then visualised in maps using QGIS Print Layout and fitted with a north arrow, scalebar, legend and zoomed-in example maps.

Finally, statistics were calculated using the “*Raster layer unique values report*” tool, to extract area values of the different distributions. These outputs from QGIS were given in m^2 and recalculated to km^2 in Excel, where these values were made into staple diagrams, showing changes and differences in species distributions depending on the RCP scenario and its respective model outcomes. See figures … in results chapter 4.2 for more.

Table 2. Climate variable and the species optimal conditions (environmental tolerances) of variables in the analysis to calculate climate refugia for habitats.

Climate variable	**Optimal conditions**		
	Blue mussels	**Eelgrass**	**Sponges**
Salinity (PSU)	> = 17	> = 10	> = 30
Temperature (˚C)	< = 20	< = 20	< = 12

3.3 Method discussion

Since the study was based on time spanning over a longer period with annual salinity and May – September temperatures for 30-year multiannual periods, the resulting output of the analysis gave minor changes. In combination with long periods, that do not include extreme values such as heatwaves during summer or heavy precipitation periods that could change salinity, optimal limits of variables for the species were used. The species’ maximum or minimum tolerance of temperatures and salinity would therefore not be possible in this analysis, with the projections done by ClimeMarine having those periods mentioned above for salinity and temperature. The data from Copernicus that represent ClimeMarine’s historical reference period, were therefore adapted to the respective time frame.

When comparing the maps in chapter 2.2 of today’s distributions of the species and the climate refugia maps in the results, habitats do exist outside the optimal limits that were extracted and used for the analysis. However, some distribution areas disappeared when extracting habitats from their optimal ranges today (1993-2005) and were therefore not included in the analysis. See table 3 - 5 in the results (chapter 4.2) for the area differences.

Another consideration worthy of discussion is the quality of the variable layers. Since the historical reference data for salinity and temperature are based on Copernicus data with a resolution of 1 nautical $mile^2$ and not covering all areas, like certain fjords for example, this data is certainly not precisely accurate. This data is derived from downscaled models and different projections that are reprojected. In more open waters, the values tend to represent reality better than within the areas not initially covered by the 1 nautical mile^2 pixels. The extrapolation to cover these areas giving output values is highly uncertain. Especially uncertain areas are narrow fjords like the Gullmarn and Idefjorden. The large pixels do in some areas cover the whole width of these fjords with one value. This is therefore of high uncertainty since these fjords can go over 100m deep. The pixels from Copernicus had no fitting towards the seabed. Instead, the bottom temperature and salinity values represent the full lowest grid cell. The variable value of each cell corresponds to the value of the variable at the bathymetric depth at that location. In other words, the value of these large pixels represents the value of the shallowest part of that pixel, and therefore, these deep fjords are not very representative of the variables at deeper depths. However, the only species that would be affected by this in the climate refugia analysis are sponges since they tend to live at deeper depths than blue mussels and eelgrass. Sponges in these areas were although not included in the analysis since those areas ended up outside the optimal limits. For blue mussel and eelgrass habitats, located at shallower depths, the bottom variables should be more accurate for them in these areas. With this, higher uncertainty is expected in inshore areas, compared to lower uncertainty in offshore areas.

In contrast to the method used as explained in the paragraph above, another method was initially tested to represent the historical reference period. Point data from measurements from the period 1976 – 2005 were retrieved from SMHI and ICES, to represent the actual historical reference period used by ClimeMarines' projections. This data was combined in Excel and calculated a value from similar coordinates, but at different dates, to represent values spanning over the whole 30-year multiannual period. The point data was then made into a raster by using the ArcMap interpolation tool "*Spline with barriers*". One point could be one measurement from one particular date, giving a wrong representation for the whole period. This method was therefore discarded due to less overall representativeness compared to the method based on data from Copernicus. Another method that was regarded was to only use the minimum and maximum (salinity and temperature, respectively) projections added to periods of lowest salinities and highest temperatures of the year. This could have made it possible to assess refugia for absolute tolerances for the species. However, this was discarded, as well, due to the projections having minimum and maximum values spanning over several months or annually.

Discussing the used species in this study will conclude the method discussion. First, within the sponge aggregation raster used, the cold-water coral *Lophelia pertusa* is included together with sponge aggregations. This was left out of the analysis due to its very low distribution compared to sponge aggregations and the fact that the corals are within the same areas as in the data. That the study undertook only optimal variable ranges, as explained at the beginning of this section, leads thoughts to the fact that species can tolerate large fluctuations in salinity and temperature over different periods. Blue mussels' have for example good tolerance and adaptation to changes in salinity and temperature. However, as mentioned, the study is delineated there due to a lack of data. The results therefore only show areas where the species will probably still be but within their optimum ranges of living.

4. Results

The results section is structured in the same way and order as the research questions are stated. In chapter 4.1, results are presented for each species examined, based on the outcome of the GIS climate refugia analysis. The sum of all coloured areas represents the future distribution under each scenario, where red indicates the least favourable model outcome for the species (out of the CMIP5-models), orange is the median outcome, yellow is the most favourable outcome, and black areas represent the current distribution within optimal limits. Black areas are situated at the bottom, then in order yellow, orange, and red on top. In other words, under all red areas are orange, yellow, and black areas. Furthermore, chapter 4.2 presents results for each species examined, based on the variables' outcome differences of the two RCP scenarios and their respective model outcomes.

4.1 Climate refugia

The results of the climate refugia analysis of the three habitats gave different distributions depending on variables and respective model outcomes (minimum, median, or maximum). Each model outcome has a gradually diminishing impact. In general, areas of climate refugia for the respective species are located quite like their current optimal range distributions (black), with some retractions in some areas. Yellow, orange, and red areas constitute climate refugia for the 30-year multiannual period at the end of the century (2070 – 2099). The impact from changes in salinity and temperature had some effects locally, depending on the scenario and respective model outcome. With such minor changes and overall large areas of refugia, the zoomed-in locations show where the habitats retracted.

4.1.1 Blue mussels

Regarding blue mussels, their climate refugia have similar distribution as their current optimal range distributions (black). The refugia of blue mussel habitats have different distributions depending on the scenario and model outcome. Impacts of salinity changes in both RCP scenarios point towards changes in areas A (east of Tjörn), B (around the Onsala peninsula), C (southern Laholm Bay), and D (Öresund) in figure 7 and 8, with RCP 8.5 having a larger overall impact. Area A, which is located east of the island of Tjörn, tend to be the area that will be altered the most for both RCP scenarios. These distributions tend to retract gradually southward for both scenarios. See appendix figures 13 and 14 for zoomed-in areas of A, B, C, and D.

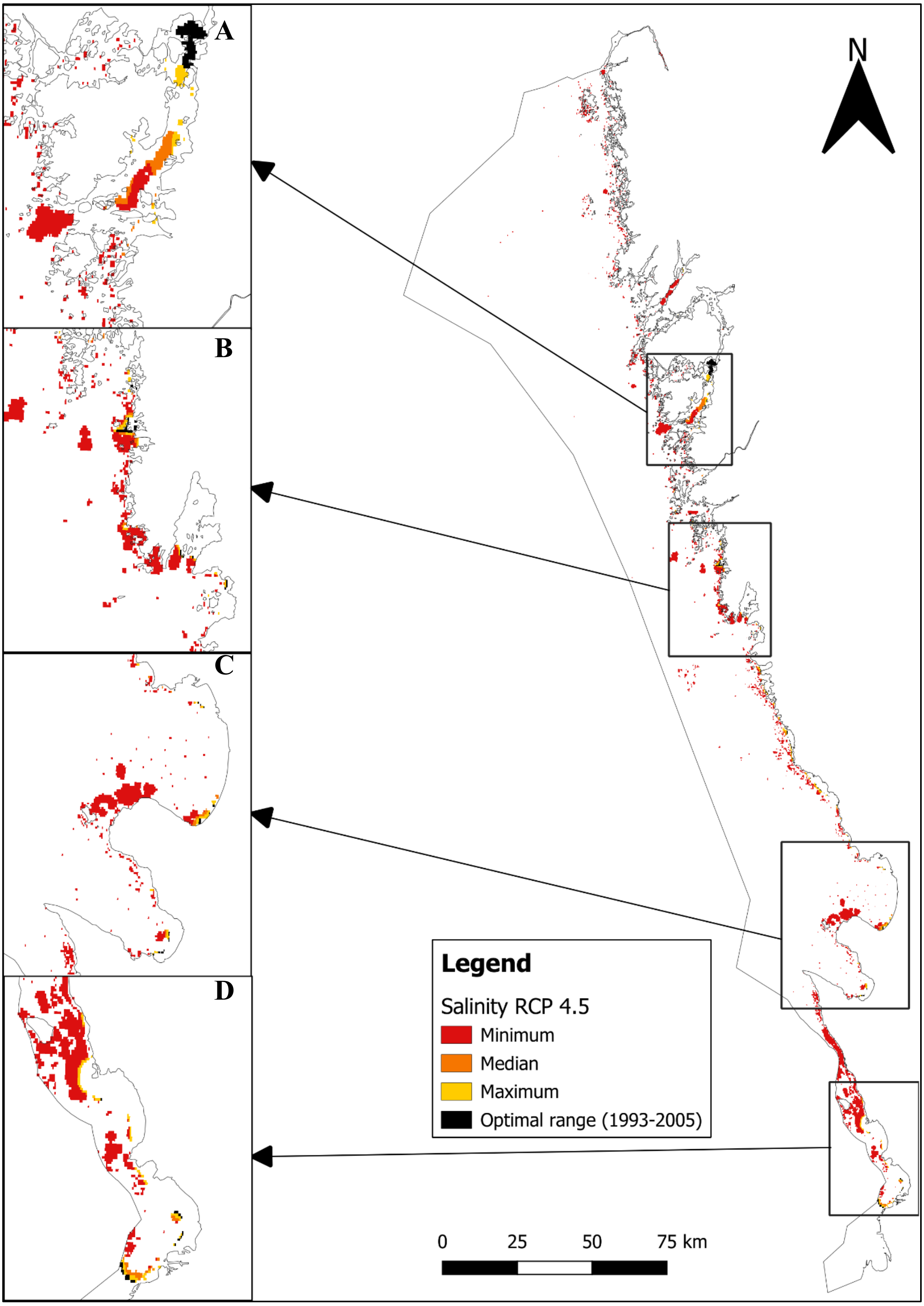

Figure 7. The figure shows blue mussel habitats within optimal distribution ranges when it comes to projected salinity decreases in RCP 4.5, and its respective outcomes are indicated by overlayed colours (yellow, orange, red).

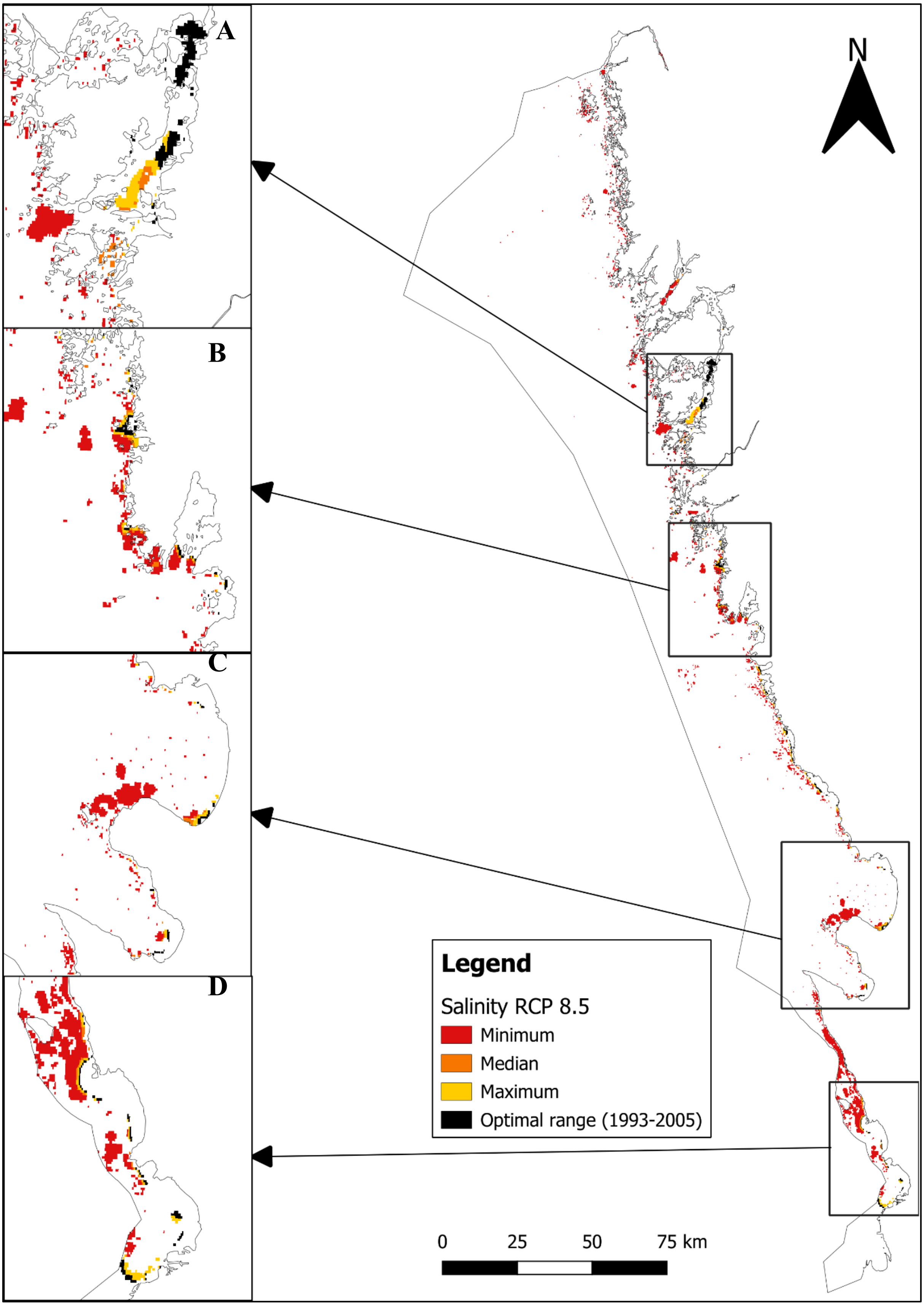

Figure 8. The figure shows blue mussel habitats within optimal distribution ranges when it comes to projected salinity decreases in RCP 8.5 and its respective model outcomes.

The impact of temperature had different implications on blue mussel distributions. Refugia from temperature increases can be expected in most areas of the current distributions within the optimal temperature limit. RCP 4.5 (figure 9) had almost no effect on the distribution of blue mussel habitats, while RCP 8.5 had severe local impacts for areas E (Idefjorden), F (Gullmarn), G (Kungsbacka fjord), and H (northern Laholm Bay) in figure 10. The minimum model outcome from RCP 8.5 showed little change in blue mussel habitat distribution, where more changes appeared with the median and finally worst with the maximum. Temperature impacts from RCP 8.5 here tend towards having a larger impact locally in bays like the shallow ones seen in areas G and H (see appendix figure 25 for the study area's bathymetry), but also deeper ones like E and F. See appendix figure 15 and 16 for zoomed in areas of examples E – H.

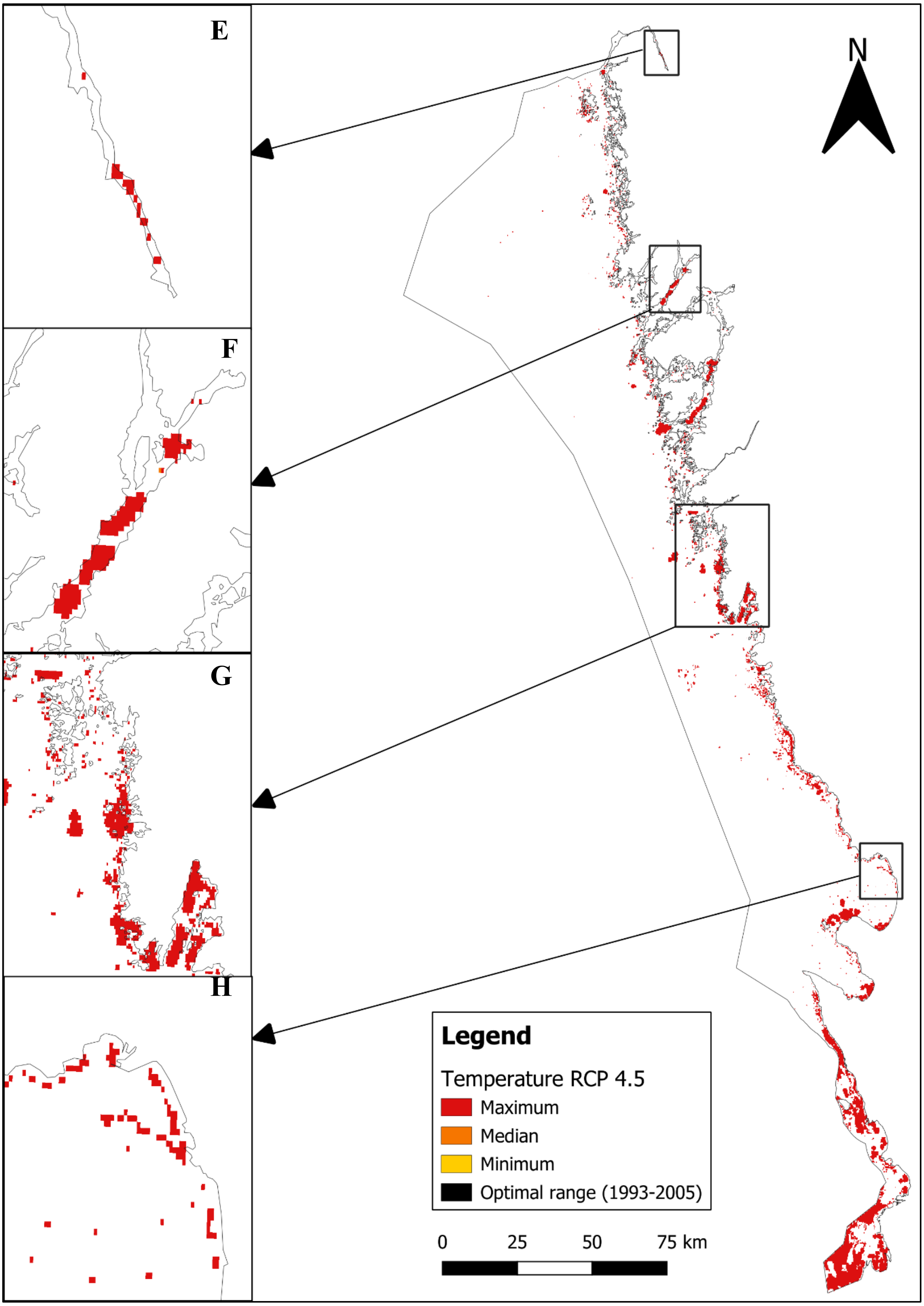

Figure 9. The figure shows blue mussel habitats within optimal distribution ranges when it comes to projected temperature increases in RCP 4.5 and its respective outcomes.

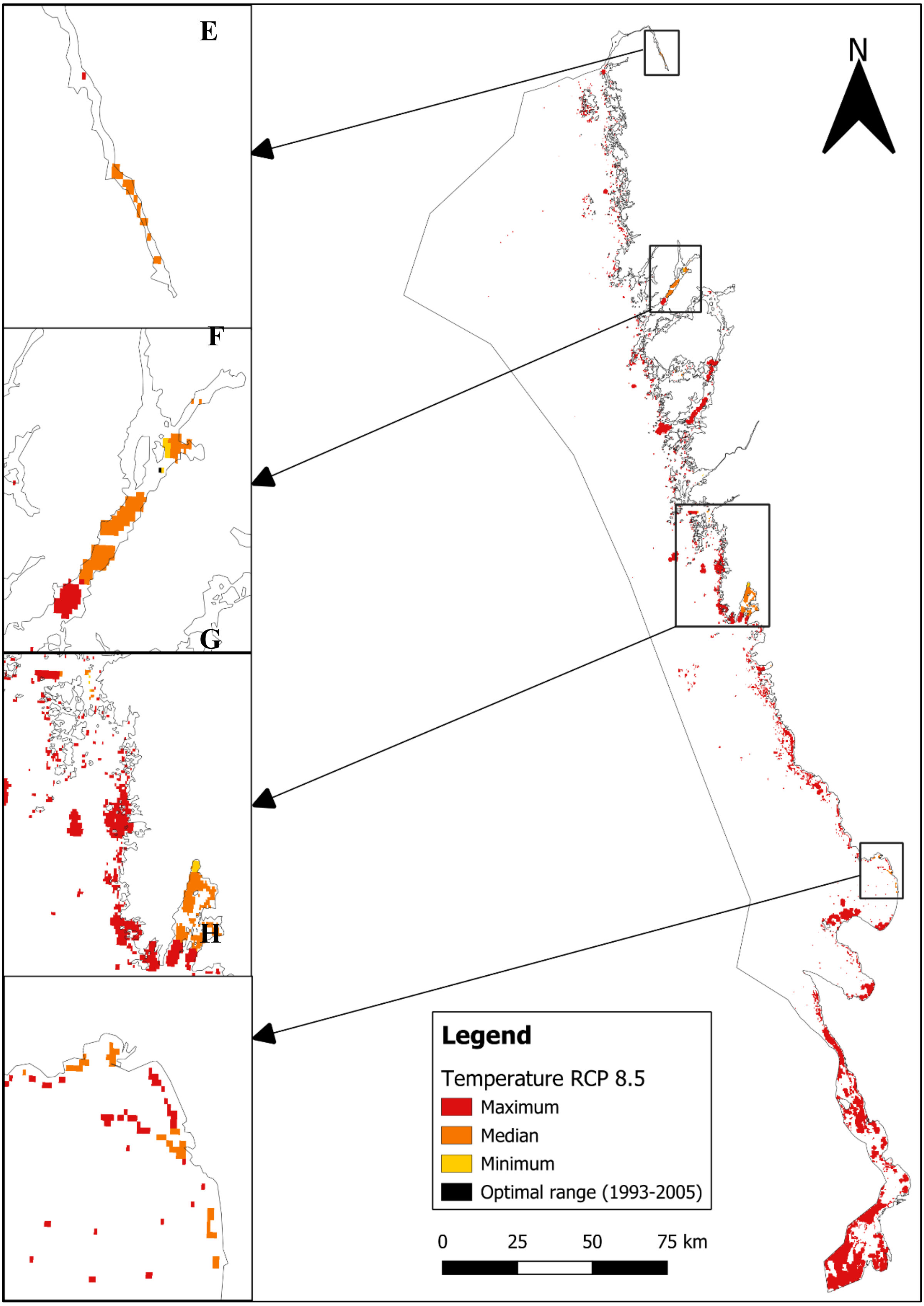

Figure 10. The figure shows blue mussel habitats within optimal distribution ranges for projected temperature increases in RCP 8.5 and its respective model outcomes.

4.1.2 Eelgrass

The results of the climate refugia analysis of eelgrass habitats have in general a quite similar distribution as eelgrass within current optimal limits of salinity and temperature. Regarding salinity's impact on eelgrass, RCP 4.5 (figure 11) had little impact in area I (south of the Gothenburg harbour inlet) with its median and minimum model outcome values. RCP 4.5 in area J (Öresund) had more effects, gradually shrinking eelgrass habitats with each model outcome. RCP 8.5 in figure 12 had more effect than RCP 4.5 on the same areas (I and J), where eelgrass distributions retract gradually even further. The results indicate that changes in salinity will have more effect on eelgrass in the southern part of the study area and that eelgrass within the current optimal limits of salinity will be relatively safeguarded against future changes in the variable. See appendix figures 17 and 18 for a closer look at the areas I and J.

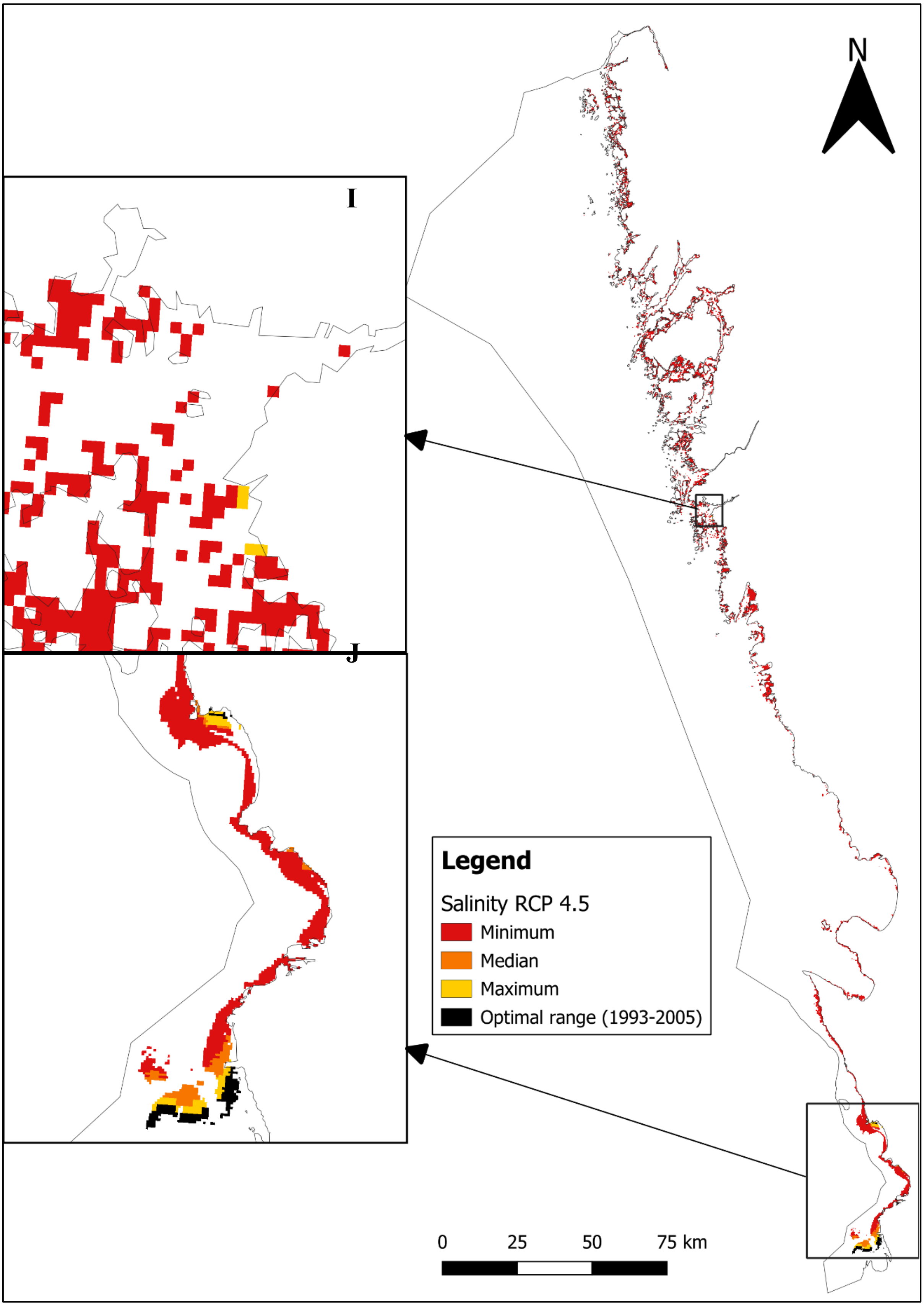

Figure 11. This figure shows eelgrass distribution impacted by salinity. The black areas show the current eelgrass habitats within the optimal salinity limit.

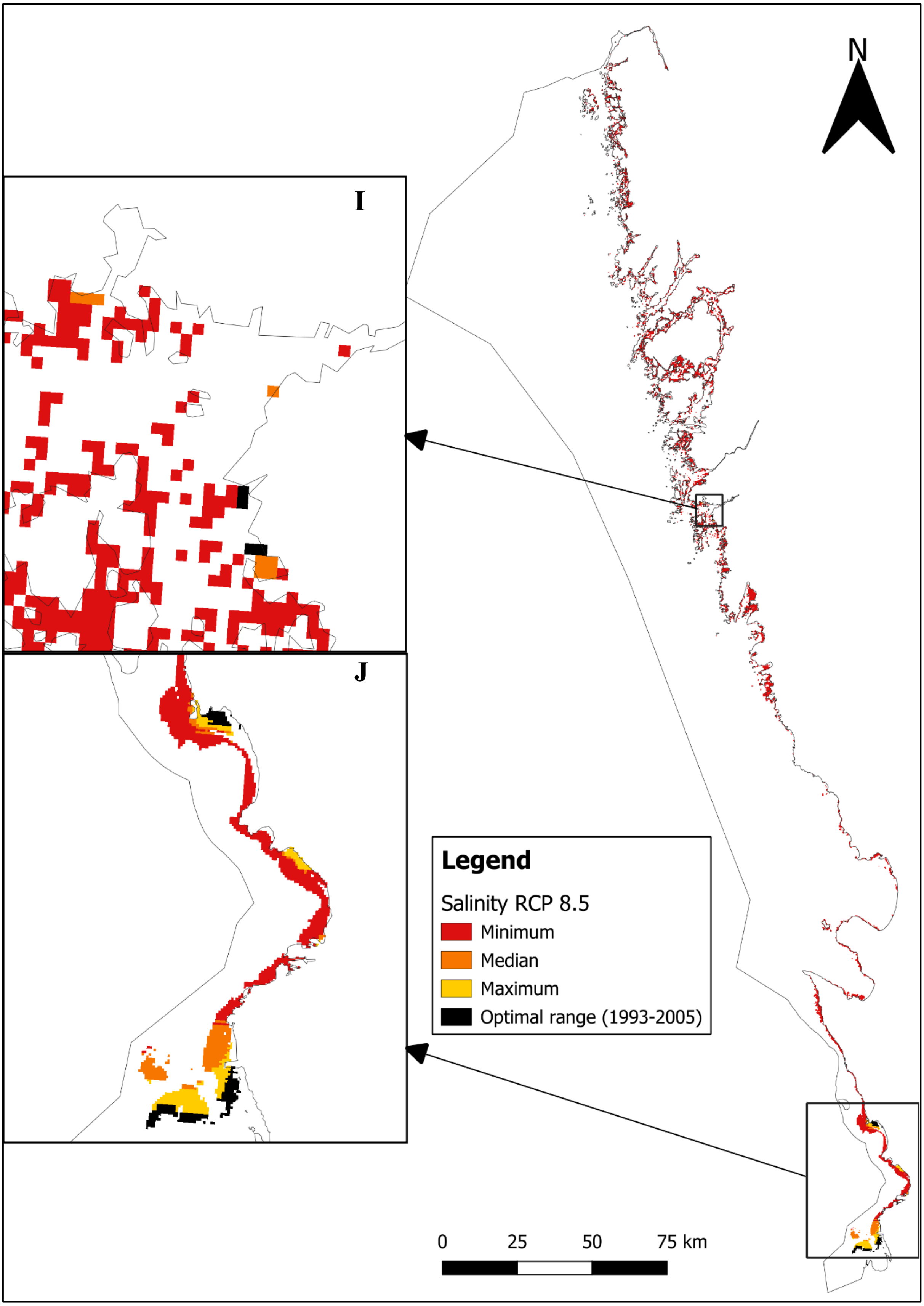

Figure 12. This figure shows eelgrass distribution impacted by salinity. The black areas show the current eelgrass habitats within the optimal salinity limit.

The results of temperature impacts on eelgrass habitats indicate that, in general, habitats within the current optimal temperature limit will have almost similar distribution at the end of the century, with some local changes. For RCP 4.5, the maximum model outcome was the only causing effects on eelgrass habitats seen in area K (northern Gullmarn) in figure 13. RCP 8.5, however, gave way more impacts locally in areas K, L (around Hisingen island), M (Kungsbacka fjord and Kloster fjord), and N (northern Laholm bay) seen in figure 14. The minimum model outcome gave little effect on eelgrass, just slightly in a few areas in area K. The median temperature model outcome from RCP 8.5 had more effect in areas K and L, while the maximum temperature model outcome from RCP 8.5 had more local impacts in all example areas in figure 14. See appendix figures 19 and 20 for a closer look at areas K – N.

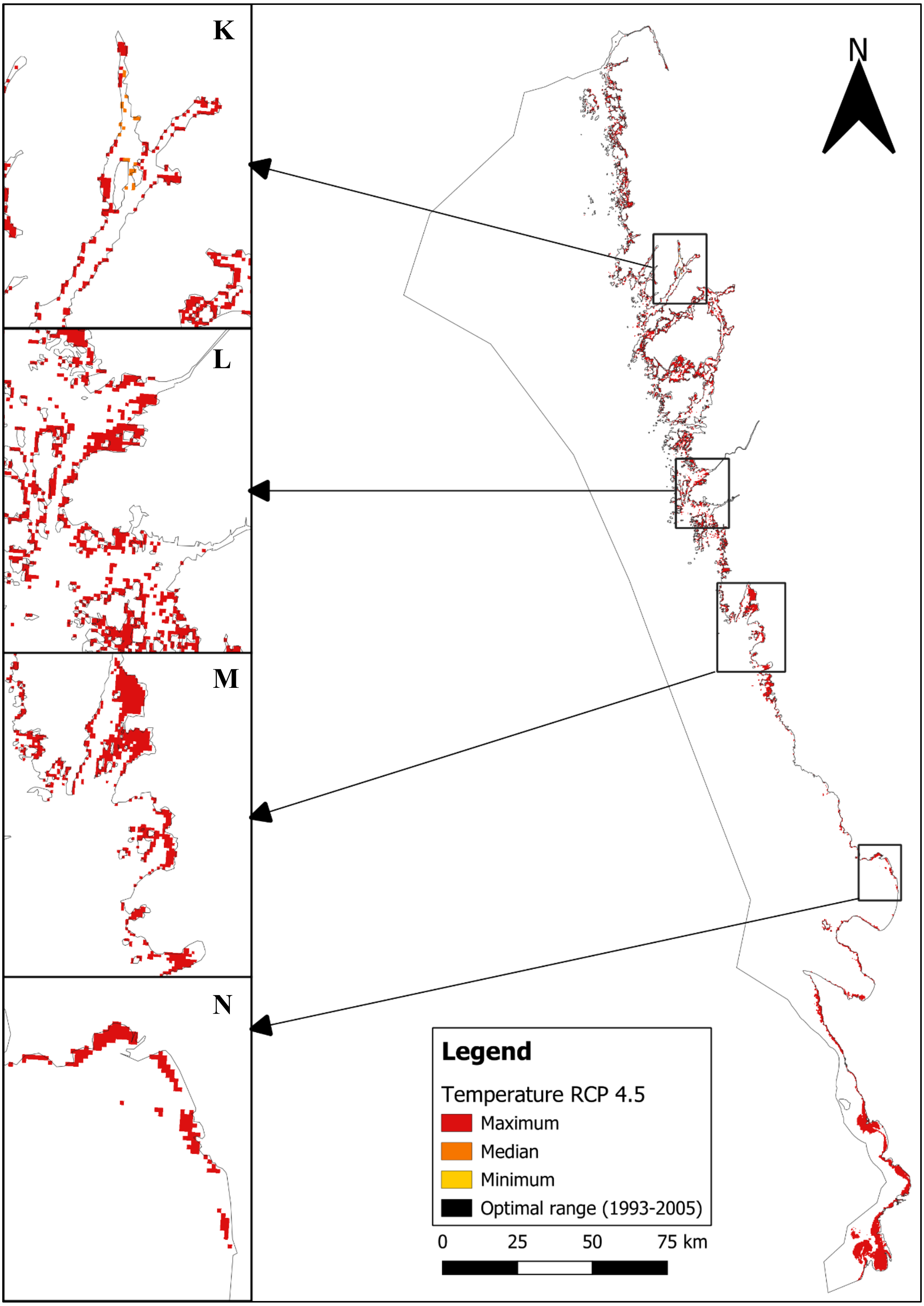

Figure 13. This map shows eelgrass distribution within the current optimal temperature limit and applied RCP scenario 4.5, with its respective model outcome.

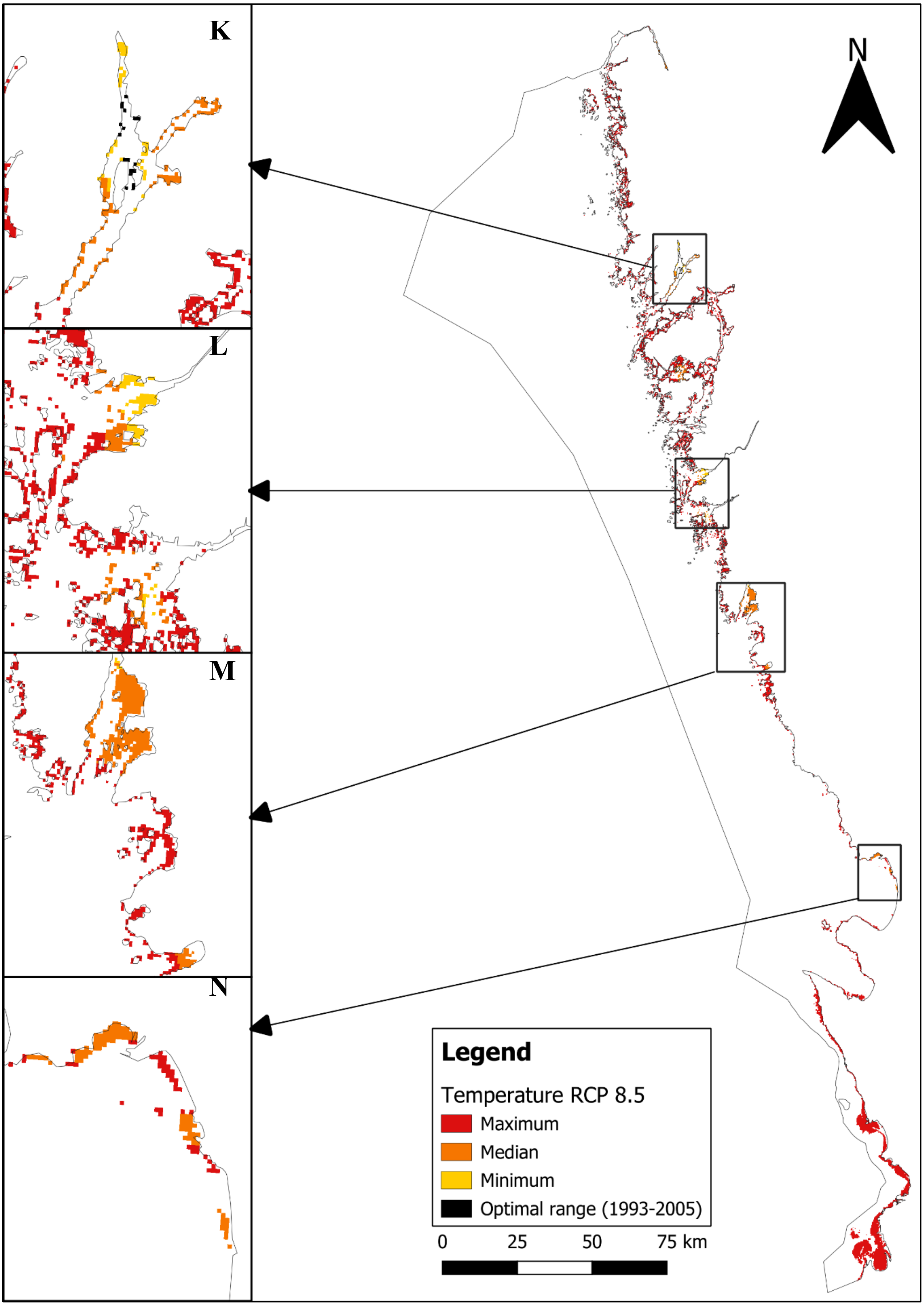

Figure 14 This map shows eelgrass distribution within the current optimal temperature limit and applied RCP scenario 8.5, with its respective model outcome.

4.1.3 Sponges

Sponge aggregations were impacted a lot by the two variables. With a generally scarce distribution compared to blue mussel and eelgrass habitats, both variables retracted the habitat to a certain extent, depending on the RCP scenario and its respective model outcomes. The overall result point towards sponge aggregations having climate refugia at deeper depths, when comparing the distributions to the study area's bathymetry seen in appendix figure 25. Salinity in scenario 4.5 seen in figure 15 impacted all example locations (O, P, Q, R), but the most in the southern part of the study area around Hallands Väderö and Staffan's bank (R). RCP 8.5 impacted areas O, P, and Q and more at area R, where sponge aggregation habitats completely disappeared with the maximum model outcome, almost completely with median and over half with the lowest model outcome values, as seen in figure 16. See appendix figures 21 and 22 for zoomed-in locations of areas O – R.

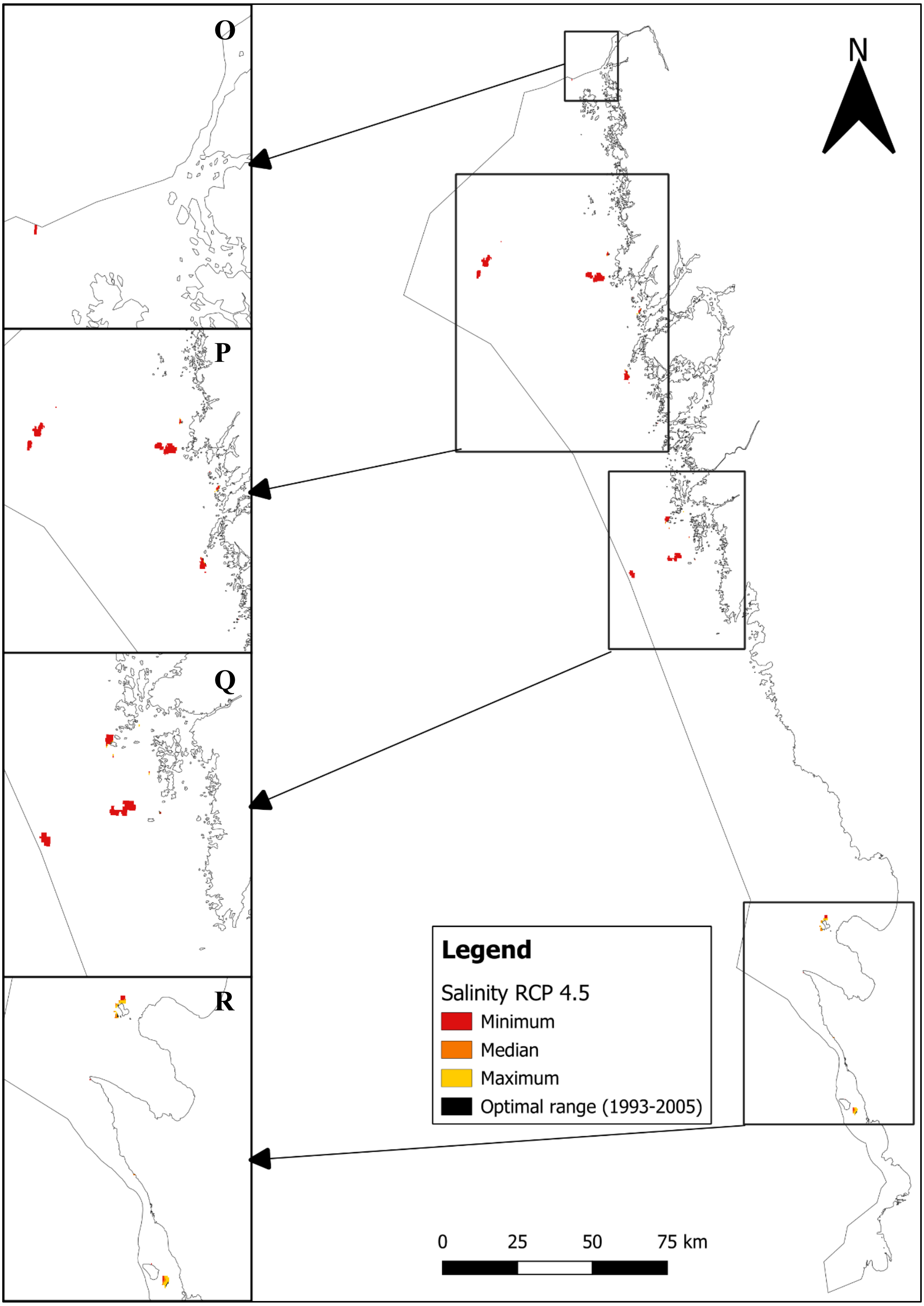

Figure 15. The figure displays the distribution of sponge aggregations within the study area. Black areas indicate the current distribution within the optimal salinity limit.

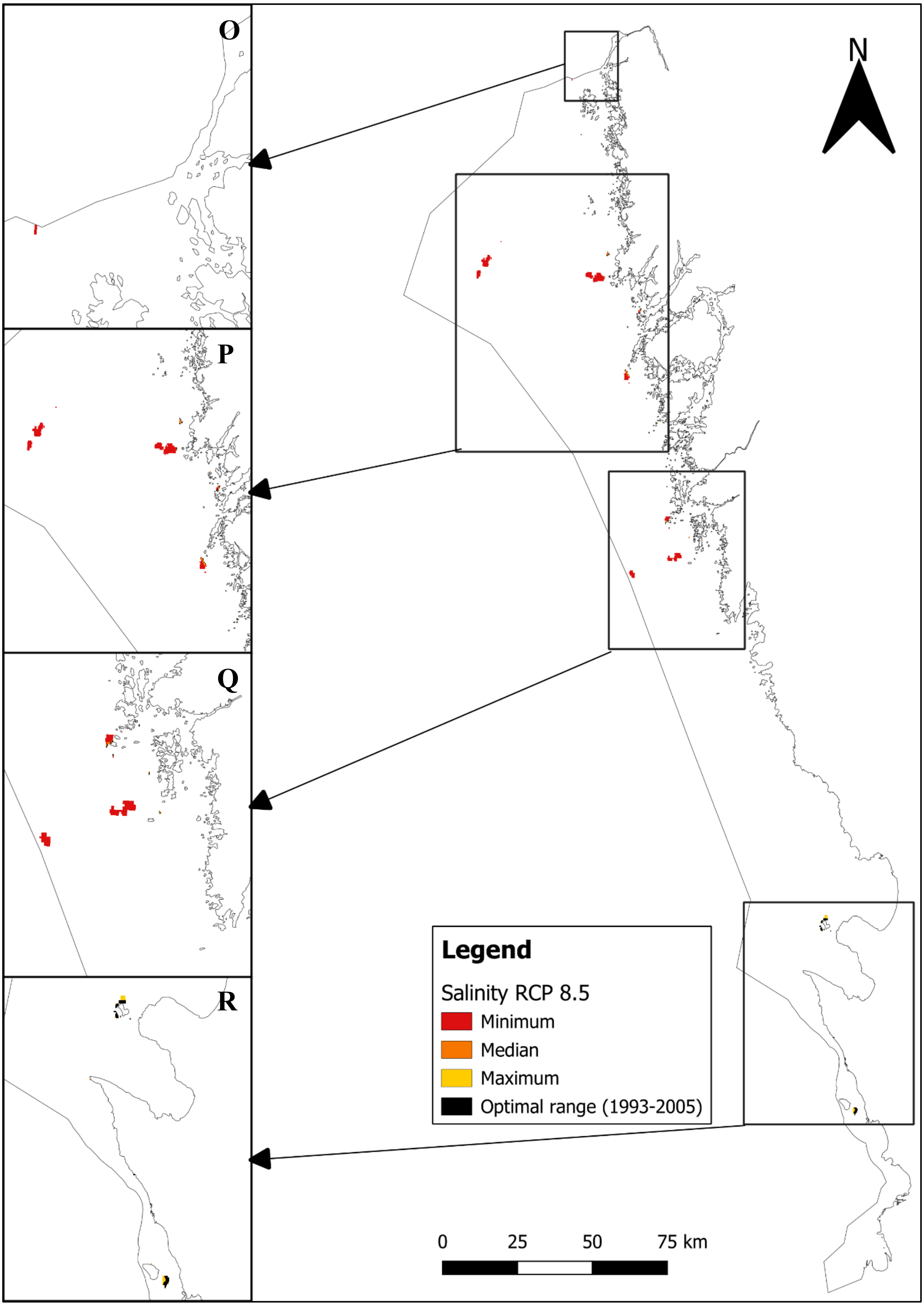

Figure 16. This figure shows sponge aggregations within the optimal salinity limit, with RCP 8.5 applied.

When it comes to impacts on sponge aggregations from temperature changes, it seems to impact most of the distributions on the West Coast. RCP 4.5 have a decent amount of impact seen in figure 17, with sponge aggregations completely disappearing at some locations in area T, U, and V. Area S only makes it in RCP 4.5 with the minimum model outcome. RCP 8.5 has an even more severe impact on sponge aggregations as seen in figure 18, with almost all distributions gone in area V for all three model outcomes. The only area completely making it from all model outcomes' changes in each scenario is the Bratten area in the western part of area T. See appendix figures 23 and 24 for zoomed-in locations of areas S – V.

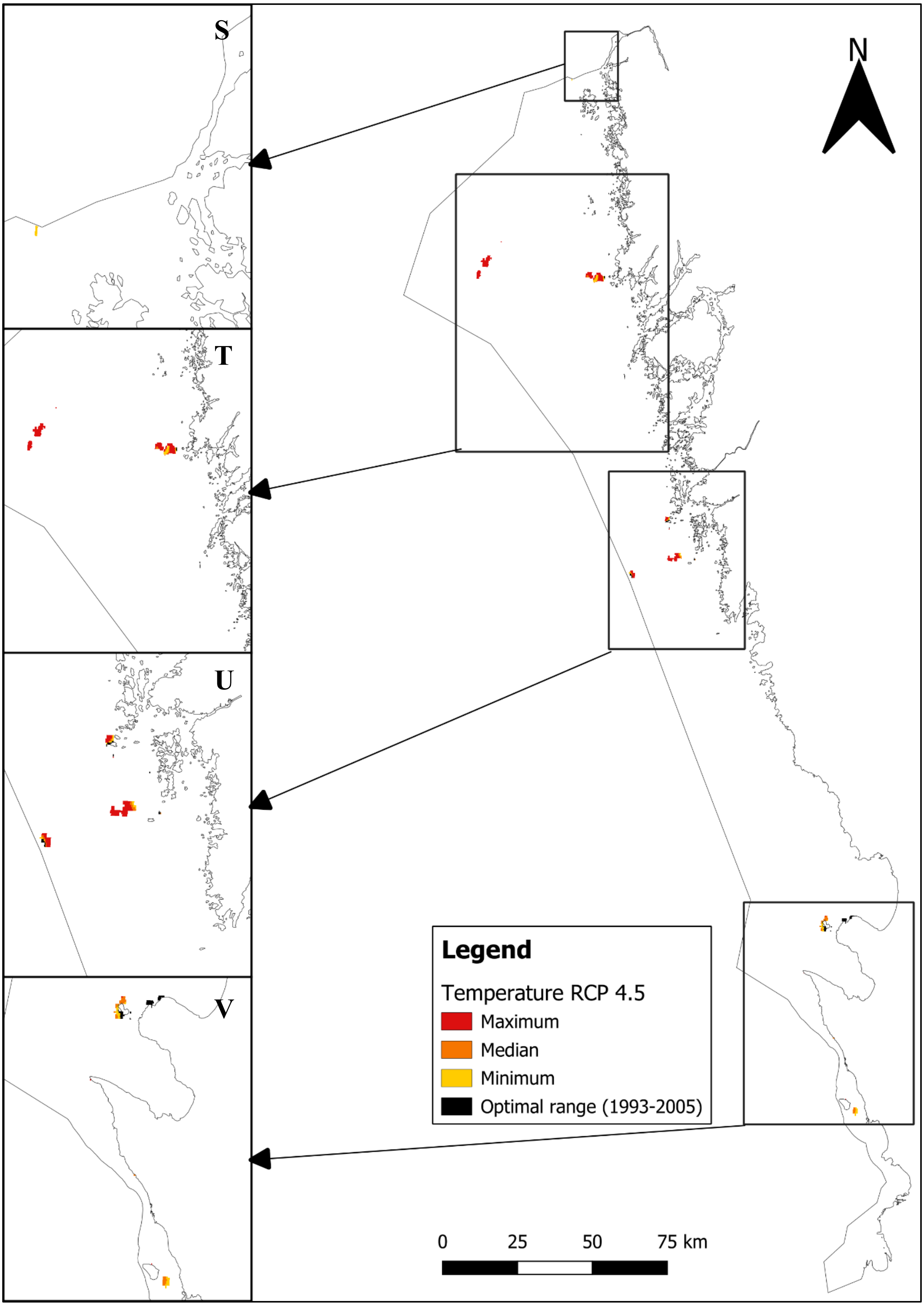

Figure 17. The end-of-the-century distribution of sponge aggregations concerning temperature increases from RCP scenario 4.5.

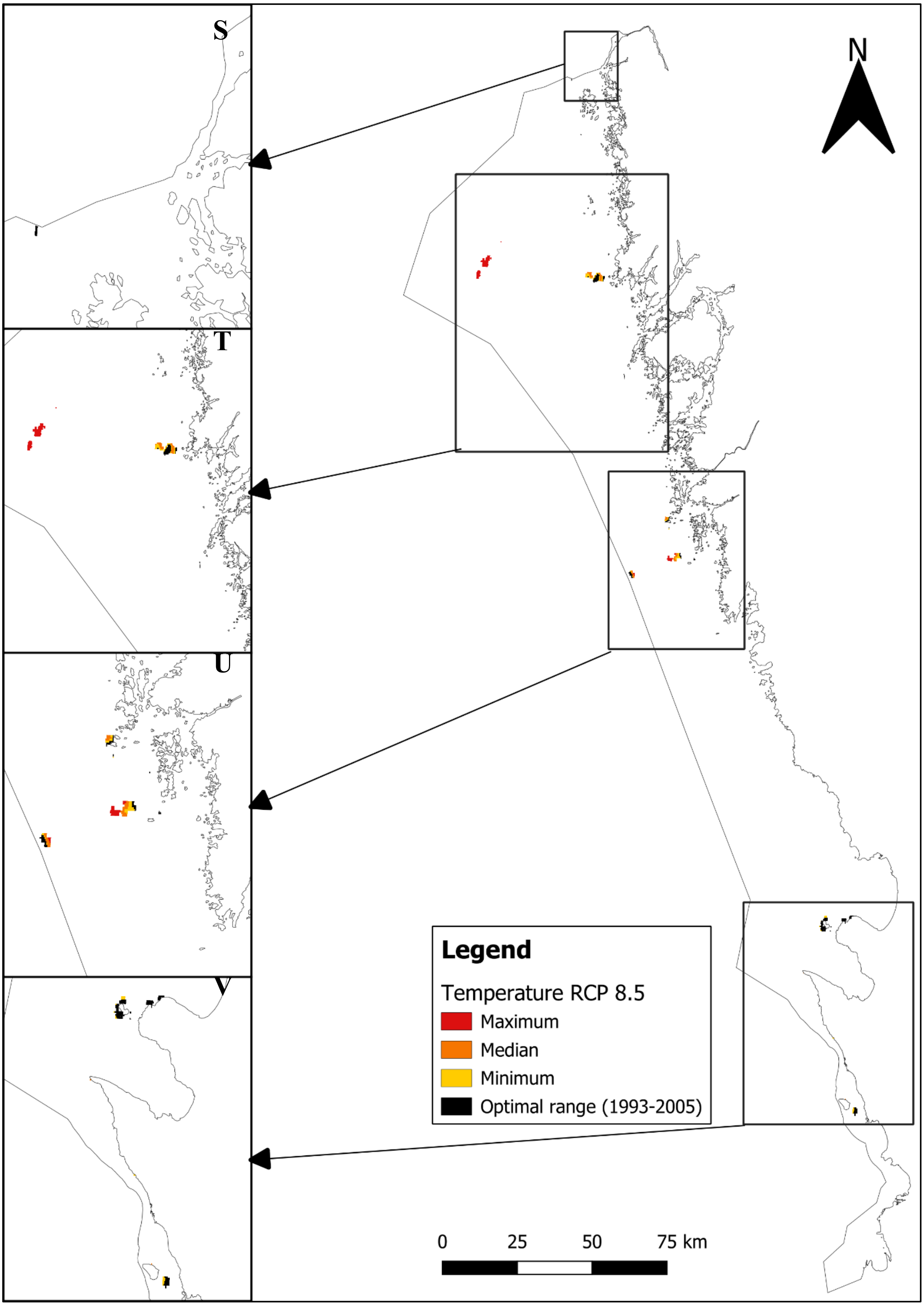

Figure 18. The end-of-the-century distribution of sponge aggregations concerning temperature increases from RCP scenario 8.5.

4.2 Spatial losses

Distribution areas were calculated and compared to confirm the impacts of the variable scenarios on every three species. These results show the impact and differences between the two variables, their scenarios, and their respective model outcomes.

4.2.1 Blue mussels

The results of the impact from the variables on blue mussels indicate that the climate refugia within the study area will be retracted compared to their current distribution within optimal salinity and temperature limits, as seen in table 3. Regarding the salinity impact, between 439 km^2 and 389 km^2 will be left as refugia in RCP scenario 4.5. This equals a percentage change of 3.9% and 14.9%, based on the current distribution area of 457 km^2. In RCP 8.5, between 414 km^2 and 357 km^2 are left. However, 412 km^2 or 380 km^2, depending on the scenario, could be considered the most realistic area of climate refugia for blue mussels, with habitat changes of 9.8% or 16.9% gone at the end of the century, depending on the RCP scenario. When looking at the absolute refugia, in other words, the climate refugia within the optimal salinity limit based on the Symphony Species Distribution (SSD), the numbers are different. This leaves only around half of the current blue mussel distribution left at the end of the century in both scenarios.

Table 3 also shows the climate refugia area and percentage left within the optimal temperature limit at the end of the century for impacts from the temperature on blue mussels. There were in general slight decreases in distribution, with even the least favourable model outcome in RCP 8.5 leaving 95% of the current habitat as climate refugia at the end of the century. However, when calculating the refugia based on the SSD, the result showed a few percentages less than based on the Optimal Species Distribution (OSD).

Table 3. OSD areal extent of blue mussels in km^2 with the climate variables salinity and temperature. The area and percentage of SSD are given in brackets.

Salinity

RCP	**OSD**	**Max**	**% change**	**Median**	**% change**	**Min**	**% change**
4.5	457 (776)	439	3.9 (43.5)	412	9.8 (46.9)	389	14.9 (49.9)
8.5	457 (776)	414	9.4 (46.7)	380	16.9 (51)	357	21.9 (54)

Temperature

RCP	**OSD**	**Min**	**% change**	**Median**	**% change**	**Max**	**% change**

4.5	746 (776)	746	0 (3.9)	746	0 (3.9)	746	0 (3.9)
8.5	746 (776)	746	0 (3.9)	744	0.3 (4.1)	709	5 (8.6)

4.2.2 Eelgrass

For salinity, the refugia for eelgrass had between 597 km^2 and 572 km^2 in RCP 4.5, compared to RCP 8.5's refugia of 595 km^2 and 554 km^2. This equates to relatively high percentages of eelgrass distribution left within the study area in general. The results when calculating area and percentages left based on the SSD, however, the climate refugia for eelgrass within the optimal salinity limit by the end of the century were all less than 90%.

Regarding temperature, the OSD and SSD were the same, meaning that the climate refugia had the same area for both standard distributions they were calculated from. The changes for both RCP scenarios were generally small, with only the maximum model outcome in RCP 8.5 having a major impact with only 604 km^2 (9% change) left as eelgrass climate refugia.

When comparing the impact of the two variables, salinity decreases tend to have a larger impact on eelgrass distributions compared to temperature increases. Salinity-impacted eelgrass was more evenly distributed for both scenarios and their respective three different model outcomes were based on. As mentioned in the paragraph above, the temperature only significantly impacted eelgrass in RCP 8.5's maximum model outcome.

Table 4. OSD areal extent of eelgrass in km^2 with the climate variables salinity and temperature. Area and percentage of SSD are given in brackets.

Salinity

RCP	**OSD**	**Max**	**% change**	**Median**	**% change**	**Min**	**% change**
4.5	611 (664)	597	2.3 (10.1)	587	3.9 (11.6)	572	6.4 (13.9)
8.5	611 (664)	595	2.6 (10.4)	574	6.1 (13.6)	554	9.3 (16.6)

Temperature

RCP	**OSD**	**Min**	**% change**	**Median**	**% change**	**Max**	**% change**
4.5	664 (664)	664	0 (0)	664	0 (0)	662	0.3 (0.3)
8.5	664 (664)	663	0.2 (0.2)	655	1.4 (1.4)	604	9 (9)

4.2.3 Sponges

The sponge aggregations were impacted the most out of the three analysed habitats. In table 5, climate refugia of sponges were altered negatively by both variables to quite different extents.

Based on the OSD, salinity decreases in RCP 4.5 shrunk the distribution by a few percent in the maximum model outcome to over 16% in the minimum. RCP 8.5's salinity decreases gave a sponge climate refugia area between 42 km^2 and 38 km^2, a respective 14.3% to 22.5% change, depending on the scenario's model outcomes. Concerning area and percentage based on the SSD, salinity decreases by the end of the century shrinking the sponge habitats to areas and percentages around half of the current habitats.

Regarding temperature increases based on the OSD, sponges have a climate refugia in RCP 4.5 of 42 km^2 in the minimum model outcome, 35 km^2 in the median model outcome, and 28 km^2 in the maximum model outcome. This respectively equals 87.5%, 72.9%, and 58.3% of sponge distribution left as climate refugia in RCP 4.5 when assessing the distribution within the optimal limit of temperature. For RCP 8.5, however, the temperature had even more severe effects, leaving just 60.4% (minimum), 44% (median), or 27.1% (maximum) left as climate refugia for sponges. Concerning SSD, temperature increases alter the sponge areas by over half for almost all model outcomes in both scenarios, with just the minimum values in RCP 4.5 above 50%. The percentage of sponges left in the minimum model outcome values in RCP 8.5 was 34.5%, the median 25%, and 15.5% habitat left in the maximum values.

When comparing which variable impacted the most, temperature increases had, in general, way more severe effects than salinity decreases. This result indicates that future temperature increases will impact sponge aggregations way more than salinity decreases, even if the salinity variable impacts sponges a lot, as well.

Table 5. OSD areal extent of sponge aggregations in km^2 with the climate variables salinity and temperature. Area and percentage of SSD are given in brackets.

Salinity

RCP	**OSD**	**Max**	**% change**	**Median**	**% change**	**Min**	**% change**
4.5	49 (84)	48	2 (42.9)	43	12.2 (48.8)	41	16.3 (51.2)
8.5	49 (84)	42	14.3 (50)	40	18.4 (52.4)	38	22.5 (54.8)

Temperature

RCP	**OSD**	**Min**	**% change**	**Median**	**% change**	**Max**	**% change**
4.5	48 (84)	42	12.5 (50)	35	27.1 (58.3)	28	41.7 (66.7)
8.5	48 (84)	29	39.6 (65.5)	21	56 (75)	13	72.9 (84.5)

5. Discussion

The results gave clear indications of the retraction of the habitats within the study area of the Swedish West Coast. Generally, distributions within or close to areas of freshwater influx (from the Baltic and rivers) and shallower areas (that have a larger general bottom temperature increase) are the ones tending to disappear. Except for temperatures' impact on eelgrass, the changes were much different when comparing the OSD and SSD. With regards to the SSD areas, there are habitats left outside the climate refugia that might persist in the future and would not necessarily be annihilated. The results of the OSD show the areas that will be buffered from the changes in the variables, hence the use of the species' optimal preferences. Blue mussels, for example, are relatively adaptable to changes in climate variables, but might not necessarily thrive in conditions outside the limits set in this study.

Blue mussels and eelgrass seem to be relatively stable from changing climate variables over longer periods, while sponge aggregations tend to be more sensitive. Blue mussels were impacted by the variables differently. Comparably, temperature increases had way less impact on blue mussels than salinity decreases, both for the OSD and SSD. Salinity decreases impacted for the most part in area A in both scenarios. Temperature increases had barely any effect on RCP 4.5. RCP 8.5, however, had more impact. It was also more evenly distributed over the affected areas (E – H), compared to the areas affected by salinity (A – D). Just like for blue mussels, decreases in salinity will have a larger impact than the temperature on eelgrass. Eelgrass had, in general, quite a large climate refugia based on both the OSD and SSD, when referring to the areas in table 4. Local impacts from salinity decrease in area J were significant for both scenarios. Temperature increases did barely have any effect in RCP 4.5 and RCP 8.5 had more impacts locally in areas K – N. Even though salinity had more impact on eelgrass than temperature, the effects from the temperature in RCP 8.5 are interesting. The third habitat of sponge aggregations was more affected by temperature, contrary to blue mussels and eelgrass. However, it was also majorly impacted by salinity decreases, almost similar in the area as blue mussels were in both scenarios. These results point towards nominating refugia for areas P and Q since they tended to be buffered the most from future climate change.

The results show that there are typically more differences between the three model outcomes in the two scenarios, than between the same model outcomes of the two scenarios. This highlights the importance of using all model outcomes instead of just the median for each scenario. Which of all these areas constituting refugia should be worthy of protection is difficult to decide. Surely, all areas should to some extent be protected from disturbances that could alter the climate variables' impacts. Many of the refugia from the results are probably already under some sort of protection. The results can therefore be used both to ensure why already protected areas are worthy of protection and perhaps to adjust protected areas today to cover the refugia of future distributions.

With, for the most part, large areas of blue mussel, eelgrass, and sponge aggregation left as refugia after the analysis, whether these results can be considered climate refugia can be discussed. Are the coloured areas climate refugia? It could be argued that these areas should be called something similar to "remaining suitable habitats" instead of climate refugia. Climate refugia could therefore be spared for selected areas where the habitat would remain in areas otherwise strongly affected by expected losses. Nevertheless, with the study's approach to habitats' optimal variable ranges, the results can be considered as climate refugia. With the climate refugia definitions by Morelli, et al., 2020, Keppel, et al., 2012 and Havenhand and Dahlgren, 2017, the use of the optimal limits (OSD) of salinity and temperature tolerance might even be a better way to conduct refugia analyses, instead of using the absolute climate variable tolerance. The use of the OSD will buffer the habitats from their absolute tolerances of salinity and temperature, and therefore safeguard against coming changes, regardless of RCP scenario. The results are simulations of a future reality of what could be an approximate climate refugia with regards to respective variables. To make sure of the climate refugia, the use of the extreme red areas could be used on its own to absolutely ensured refugia in a larger period. As Magris et al. (2014) and Wilson et al. (2020) described, the refugia of these results might work as stepping-stones for connectivity and used for colonization of other areas that might have been lost due to climate change, if these changed variables were to retract again. The optimal limits of salinity and temperature were set to the minimum and maximum (see table 2), since salinity decreases and temperature increases. Areas that today lack blue mussel reefs, eelgrass beds, or sponge aggregations due to unfavourable conditions in the opposite way (too high salinity or too low temperatures), might gain favourable conditions due to decreased salinities and increased temperatures and be up for colonisation from the refugia.

It should be remembered that these, in general, small changes (at least for blue mussels and eelgrass) are long-term climate change with data based on larger timescales, with annual salinity and May – September temperature. An extension of the study might be to investigate the value ranges and how they correlate with shorter periods of higher temperatures and lower salinities. Questions arise on what the projection changes from ClimeMarine represent in shorter, more sensitive periods. What does a 2˚C increase over this May – September period represent in only August, for example? Regarding the paragraph above, these projection changes might not be the ones causing habitats to disappear. Instead, impacts from extreme events such as heat waves or rapid salinity decreases from increased precipitation might alter the already affected areas that are in the results. With variable data spanned over such long periods, the projected end-of-the-century salinity and temperature have relatively a low-value range. Thus, no radical distribution changes in the habitats. This might have been expected if data over periods with extreme events or the method of absolute tolerances were used, like the study done by Hammar and Mattsson (2017). Future research on the impact of extreme events for shorter, more sensitive periods on these habitats is recommended. Contrary to this study showing buffered refugia, such investigations could portray die-offs of the habitats. The inclusion of additional variables would also be potential inclusion in further studies, such as depth and freshwater inputs from estuaries.

What also can be said about the results of this study is that these changes indicate where the habitats will be retracted. The different model outcomes (minimum, median, maximum) might also work as indicators of where the species will retract from first since they do so gradually with the different model outcomes. Leaving some of the habitat areas left at the end of the century, based on their preferred limits of the variables, gives indications of what might be refugia for them. Regarding the RCP scenarios, it is hard to anticipate which scenario will be the way we take until the end of this century. The results make it clear of more impacts from RCP 8.5 compared to 4.5, which could be expected. Within each scenario, values differ depending on their ensemble minimum, median, and maximum. The median ensembles are probably the projections we can expect. However, the minimum and maximum values give room for interpreting what could happen within the respective scenario, as stated by Wåhlström et al. (2022). Which way of these unprecedented future changes for these habitats will go, is highly unpredictable and yet to be known.

The study's methods are to some extent already discussed in chapter 3.3. However, with the results, the data needs to be discussed. Methods of prediction models, observations, and satellite imagery used to model the distribution of blue mussels, eelgrass, and sponges are questionable. The distribution of species (figure 4 – 6 in chapter 2.2) based on Symphony data (Hammar et al. 2018) might have areas that were left out due to a lack of observations of sponge aggregations or left in due difficulty to see eelgrass beds from satellite imagery. For example, it is known that sponges aggregate in the Koster fjord (Florén et al. 2017), which is not included in the Symphony data. As previously discussed in chapter 3.3, the certainty of impacts on primary sponges and to some extent blue mussels, which tend to live deeper, can be disputed. Due to low-resolution variable data from Copernicus, which was generalised to the shallowest depth within the cell, eelgrass refugia from the result might be the most accurate ones, followed by blue mussels and sponge aggregations, since they tend to exist in more shallow waters. Overall, species distribution data, therefore, needs improvements. The analysis used set terms of the habitat's optimal variable limits, which there were very little research and data over. More research had been done on the absolute tolerances as described in chapter 2.2. If they would have been used, another method and data on the variables and their projection changes would be necessary. Research on these habitats is conducted on the interacting effects of different climactic factors, such as Halpern et al. (2008) and Worm et al. (2006) described the affecting factors on the marine environment. In areas where the three species are not expected to disappear due to salinity or temperature changes, these areas could potentially disappear anyway with these effects combined or other variables, hence cumulative effects. Even if these areas of climate refugia from this study are relatively buffered, cumulative effects might therefore threaten the existence anyway. With studies such as Hiebenthal et al. (2012), interactive and cumulative effects of salinity and temperature, and perhaps other factors, would be an interesting further study to conduct where climate refugia are incorporated. Unfortunately, this was not possible based on the available data that was used. Better data would probably have given different, and perhaps more accurate, results. Together with the need for more climate refugia research, it is also an absolute need for more data quantities and better qualities to conduct further, more accurate predictions of climate refugia. This of course does not only apply to the West Coast, but to all species and habitats around the world.

Ultimately, despite uncertainties, lack of data and interactive effects, studies such as these are important to give indications of where potential future climate refugia and, in general, future species distributions will be. Havenhand and Dahlgren (2017) highlighted the importance of incorporating climate refugia in MSP. With a climate refugia assessment done for the Baltic already by Hammar and Mattsson (2017), these results can, in theory, be used for MSP on the West Coast, and perhaps for environmental protection. Since their study had a different approach and the fact that the variables in the Baltic are in general going to be higher than the West Coast, their study resulted in more pinpointed areas of climate refugia.

6. Conclusions

As this study focused on the optimal species distributions (OSD), the outcome of this analysis gave changes in the habitat distributions, as the underlying hypothesis predicted. To different extents, blue mussel, eelgrass, and sponge aggregation habitats will be altered and retracted following changes in climatic factors. Quite obviously, RCP 8.5 will strike the habitats harder than RCP 4.5 will. The impacts of climate variables differ for the three species. Blue mussel refugia, compared to the current distribution, is to a large extent found along the whole West Coast, with some local exceptions in areas A – D and E – H. Blue mussels will be impacted primarily by salinity decreases. Temperature increases impact too, however less and very little in RCP 4.5. Eelgrass will also primarily be impacted by salinity decreases. Its refugia can to a large extent be found along the whole West Coast, as well. Compared to the current distribution, it will have some local exceptions in area I – J, where salinity decrease the impact. In the areas K – N, temperature increase in RCP 8.5 will have notable effects, unlike RCP 4.5 which barely has any. For sponges impacted by salinity decreases, refugia are located in more saline parts of the study area for both scenarios (area O – Q), whereas the southern habitats (area R) will be impacted a lot by increased salinity. Temperature increases impact more evenly distributed over current distributions, however, to a larger extent. Sponges will, contrary to blue mussels and eelgrass, be more impacted by temperature increases, even though the salinity impacts are very high, as well.

These areas of climate refugia should be considered for protection and conservation, despite them being relatively safeguarded from climate variable impacts, due to the use of the species' lower optimal salinity limit and upper optimal temperature limit. The use of all the RCP scenarios model outcomes was also important since each scenario can have significant differences. Furthermore, it is recommended to investigate the impact of extreme events on these habitats over shorter, more sensitive periods. More research, better data, and improved quality of it are needed to conduct accurate predictions of climate refugia and future species distributions overall. Despite uncertainties and data limitations, studies on potential climate refugia are crucial for understanding future species distributions, can inform marine spatial planning and environmental protection, and thereby safeguard as many of these unique and important marine ecosystems as possible.

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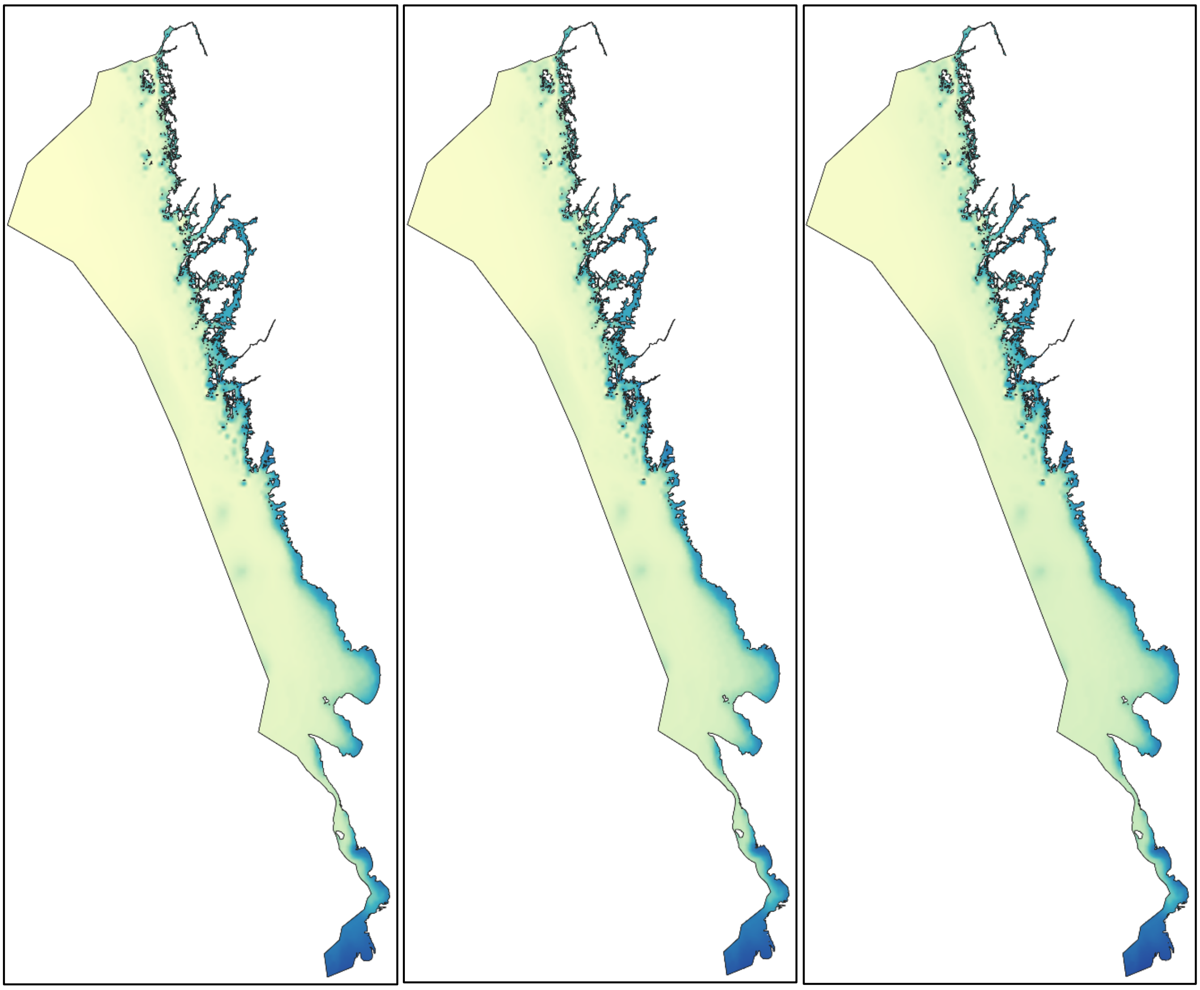
9. Appendices

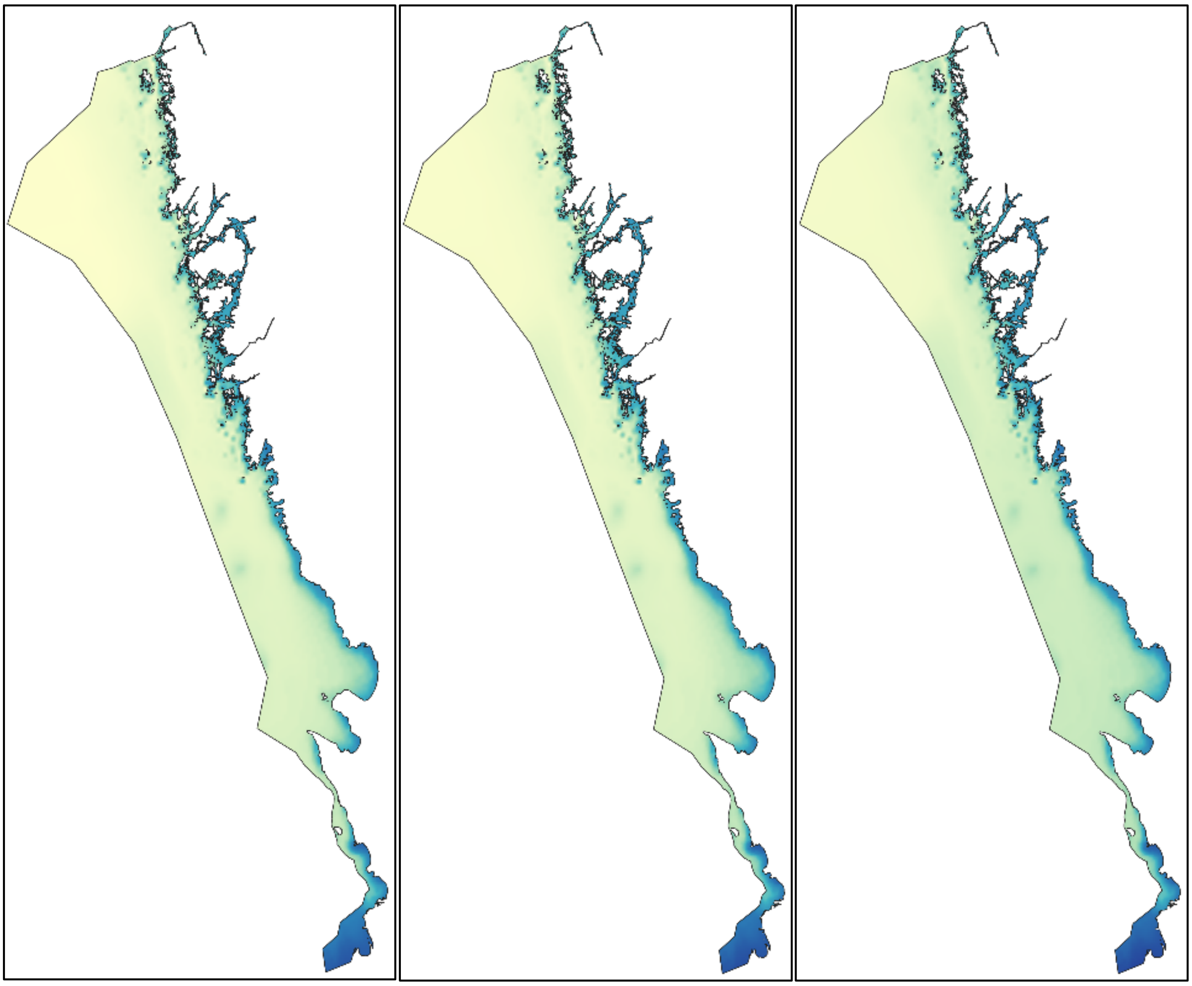
Appendix table 1. Source information about the raw geodata used in the study.

Data	**Data type**	**Provider**	**Data created**	**Data representing period**	**Link to the data**
Bottom salinity	NetCDF	Copernicus Marine Service	n.d.	January 1st – December 31st, 1993 - 2005	https://data.marine.copernicus.eu/product/BALTICSEA_MULTIYEAR_PHY_003_011/description
Bottom temperature	NetCDF	Copernicus Marine Service	n.d.	May 1st – September 30th, 1993 - 2005	https://data.marine.copernicus.eu/product/BALTICSEA_MULTIYEAR_PHY_003_011/description
Bottom salinity RCP 4.5 Median	Raster	SMHI Clime Marine	2022	January 1st – December 31st, 2070 - 2099	https://snd.gu.se/en/catalogue/study/2021-302/1/1#dataset
Bottom salinity RCP 8.5 Median	Raster	SMHI Clime Marine	2022	January 1st – December 31st, 2070 - 2099	https://snd.gu.se/en/catalogue/study/2021-302/1/1#dataset
Bottom salinity RCP 4.5 Minimum	Raster	SMHI Clime Marine	2022	January 1st – December 31st, 2070 - 2099	https://snd.gu.se/en/catalogue/study/2021-302/1/1#dataset
Bottom salinity RCP 8.5 Minimum	Raster	SMHI Clime Marine	2022	January 1st – December 31st, 2070 - 2099	https://snd.gu.se/en/catalogue/study/2021-302/1/1#dataset
Bottom temperature RCP 4.5 Median	Raster	SMHI Clime Marine	2022	May 1st – September 30th, 2070 - 2099	https://snd.gu.se/en/catalogue/study/2021-302/1/1#dataset
Bottom temperature RCP 8.5 Median	Raster	SMHI Clime Marine	2022	May 1st – September 30th, 2070 - 2099	https://snd.gu.se/en/catalogue/study/2021-302/1/1#dataset
Bottom temperature RCP 4.5 Maximum	Raster	SMHI Clime Marine	2022	May 1st – September 30th, 2070 - 2099	https://snd.gu.se/en/catalogue/study/2021-302/1/1#dataset

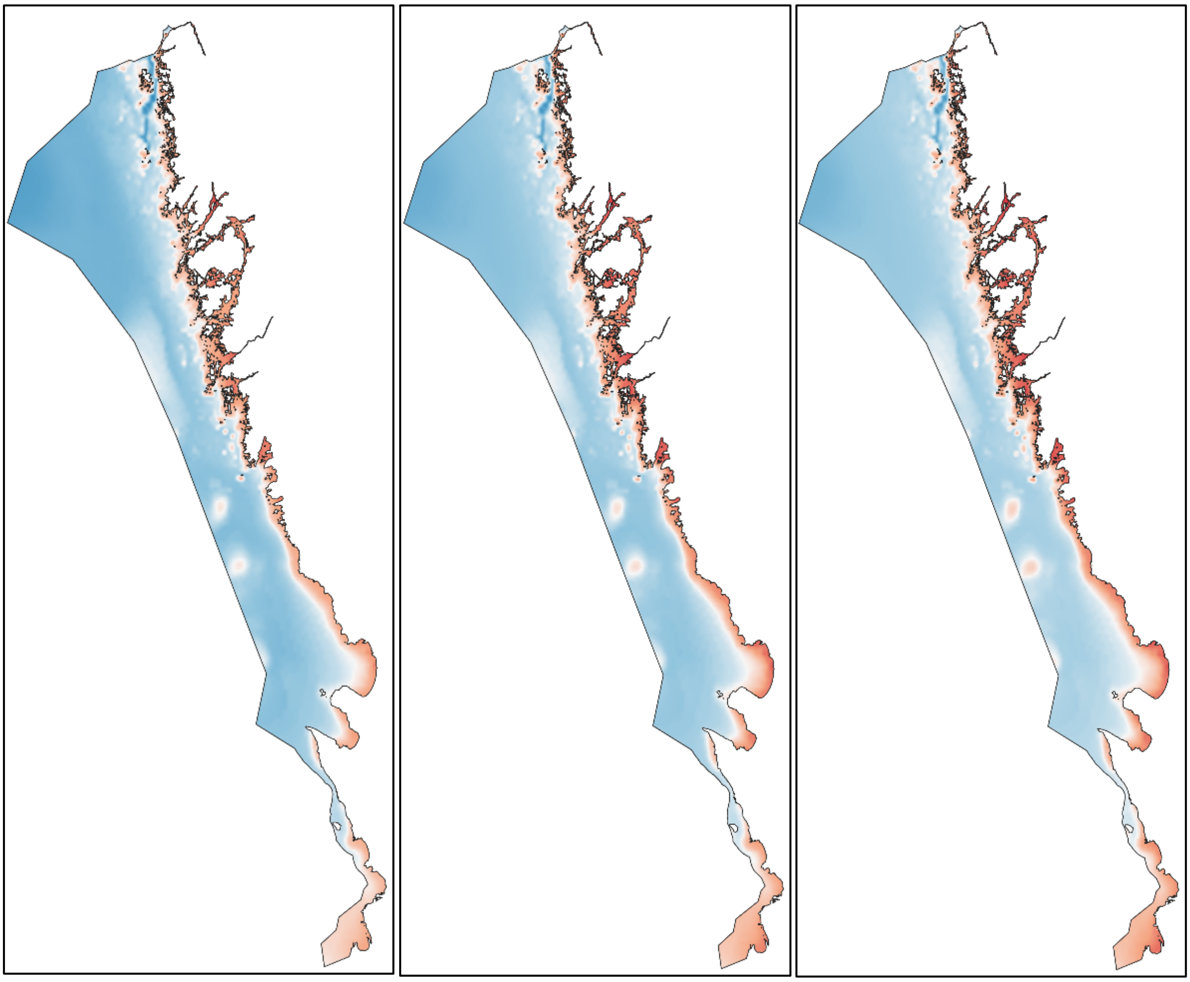
Bottom temperature RCP 8.5 Maximum	Raster	SMHI Clime Marine	2022	May 1st – September 30th, 2070 - 2099	https://snd.gu.se/en/catalogue/study/2021-302/1/1#dataset
ESRI Shaded Relief	Raster	ESRI Quick Map Service	2019	2019	Embedded in GIS. https://www.arcgis.com/home/item.html?id=9c5370d0b54f4de1b48a3792d7377ff2
Bathymetry	Raster	EMODnet	2022	2022	https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/1bcc2cea-9b4b-4515-9d9e-fd8833947ed2
Swedish EEZ - Skagerrak	Vector	Marine Regions	2020	2023	https://marineregions.org/gazetteer.php?p=details&id=25228
Swedish EEZ - Kattegat	Vector	Marine Regions	2020	2023	https://marineregions.org/gazetteer.php?p=details&id=25225
IHO Sea Area - Skagerrak	Vector	Marine Regions	1953	2023	https://marineregions.org/gazetteer.php?p=details&id=2379
IHO Sea Area - Kattegat	Vector	Marine Regions	1953	2023	https://marineregions.org/gazetteer.php?p=details&id=2374
Blue mussels' distribution (Mussel reef)	Raster	SwAM	2018	2006 – 2016	https://www.havochvatten.se/data-kartor-och-rapporter/rapporter-och-andra-publikationer/publikationer/2018-04-10-symphony---integrerat-planeringsstod-for-statlig-havsplanering-utifran-en-ekosystemansats.html
Eelgrass distribution (Angiosperms)	Raster	SwAM	2018	2008 - 2016	Same source as blue mussels.
Sponge aggregations distribution (Deep reef)	Raster	SwAM	2018	2006 - 2016	Same source as blue mussels.



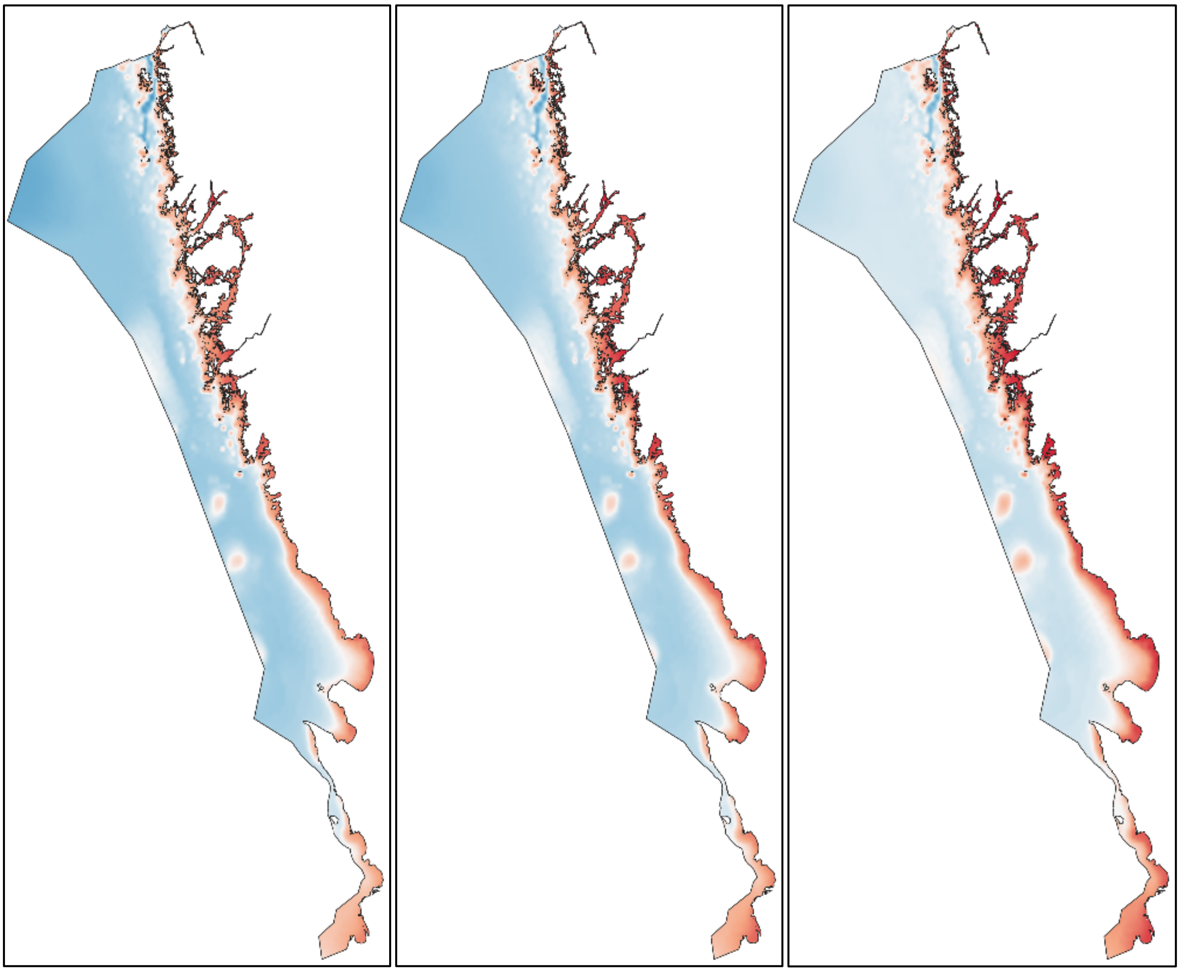
Appendix figure 1 (left), **2** (middle), and **3** (right) shows the RCP 4.5 projected salinity levels of the study area at the end of the century period (2070 – 2099). Figure 1 shows the maximum model outcome, figure 2 the median, and figure 3 the minimum. All maps use the same value range as the legend in figure 2 in chapter 2.1 to visualise differences between them. For specific value range of each figure, see table 1 in chapter 2.1.



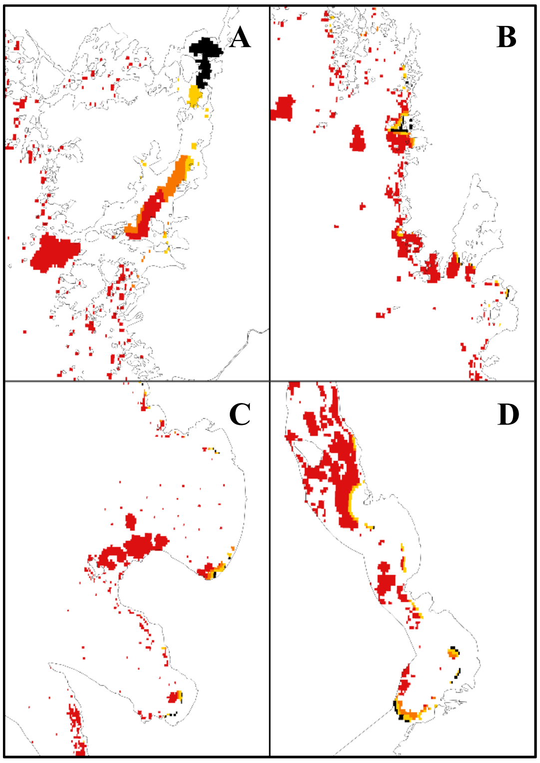
Appendix figure 4 (left), **5** (middle), and **6** (right) shows the RCP 8.5 projected salinity levels of the study area at the end of the century period (2070 – 2099). Figure 4 shows the maximum model outcome, figure 5 the median, and figure 6 the minimum. All maps use the same value range as the legend in figure 2 in chapter 2.1 to visualise differences between them. For specific value range of each figure, see table 1 in chapter 2.1.

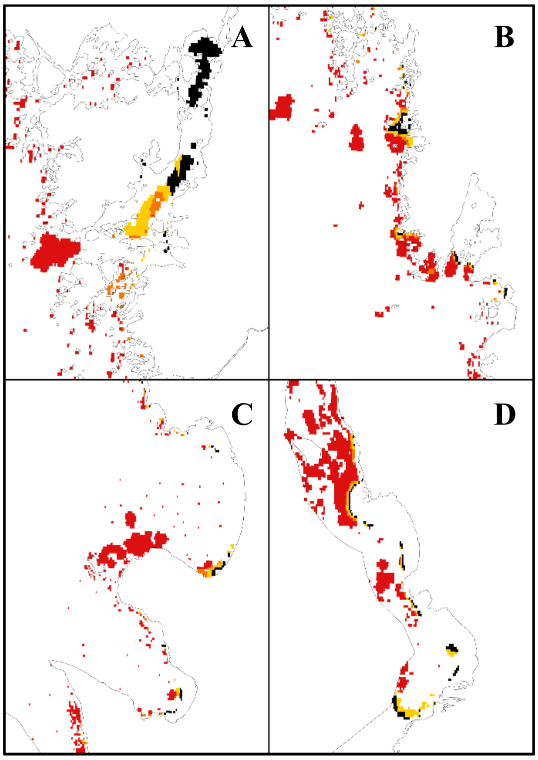


Appendix figure 7 (left), **8** (middle), and **9** (right) shows the RCP 4.5 projected temperature levels of the study area at the end of the century period (2070 – 2099). Figure 7 shows the minimum model outcome, figure 8 the median, and figure 9 the maximum. All maps use the same value range as the legend in figure 3 in chapter 2.1 to visualise differences between them. For specific value range of each figure, see table 1 in chapter 2.1.

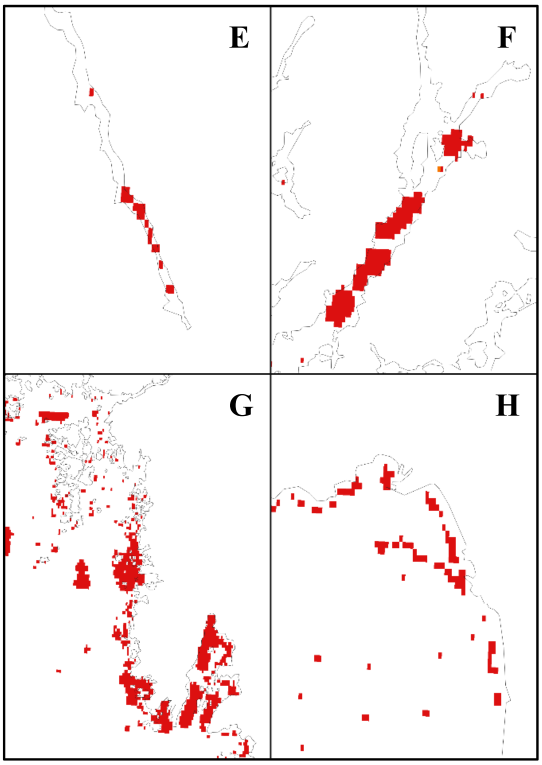


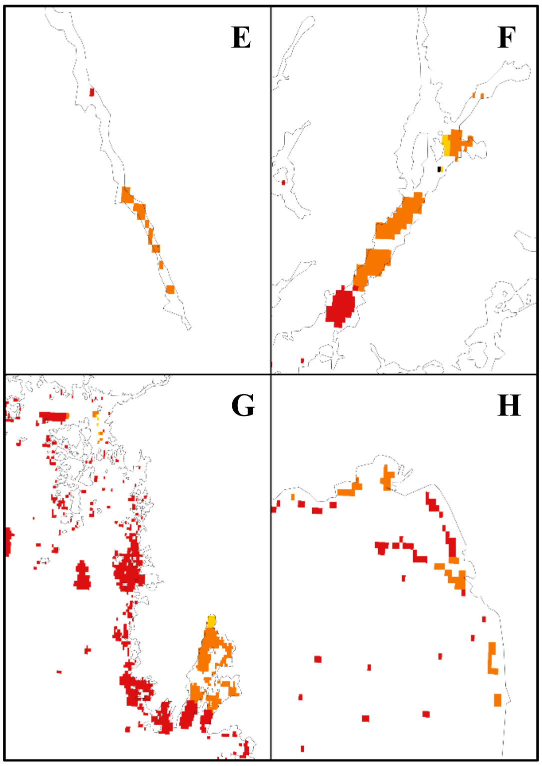
Appendix figure 10 (left), **11** (middle), and **12** (right) shows the RCP 8.5 projected temperature levels of the study area at the end of the century period (2070 – 2099). Figure 10 shows the minimum model outcome, figure 11 the median, and figure 12 the maximum. All maps use the same value range as the legend in figure 3 in chapter 2.1 to visualise differences between them. For specific value range of each figure, see table 1 in chapter 2.1.



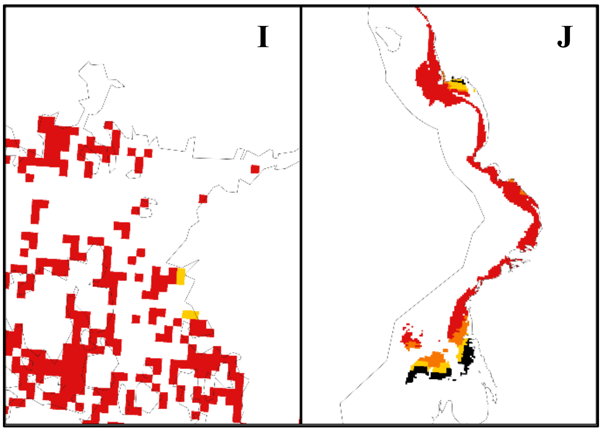


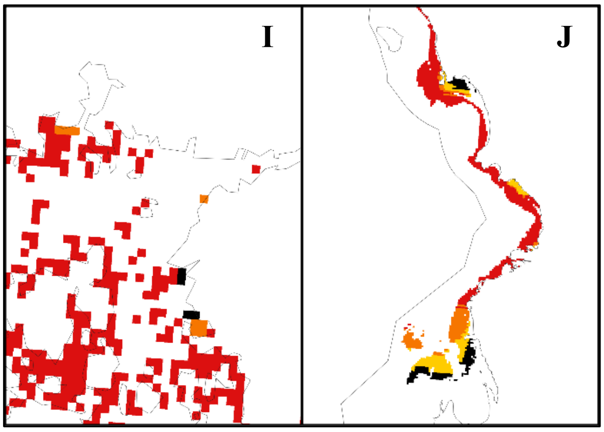
Appendix figure 13 (left). Zoomed-in locations from figure 7 in the results. The figure show areas of where blue mussels retract based on salinity decrease in RCP 4.5. **Appendix figure 14** (right). Zoomed-in locations from figure 8 in the results. The figure show areas of where blue mussels retract based on salinity decrease in RCP 8.5.



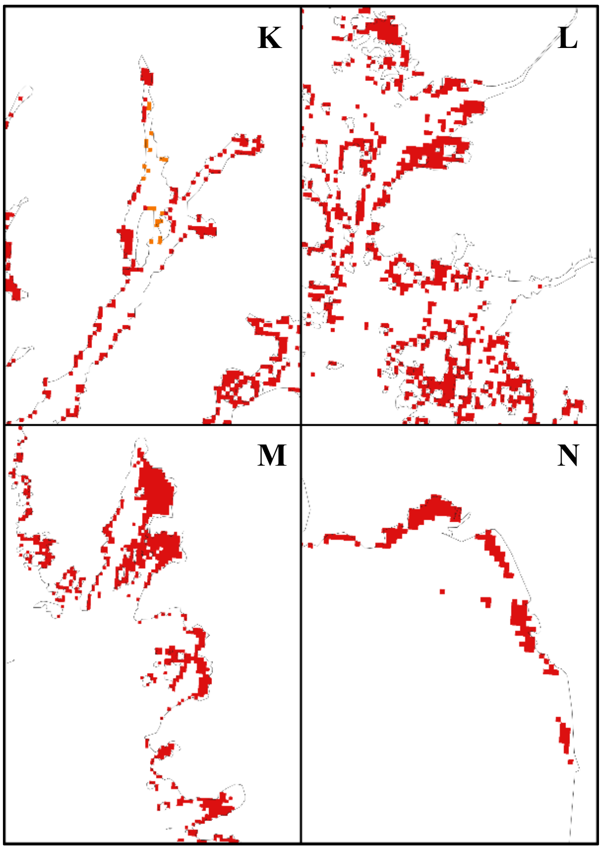


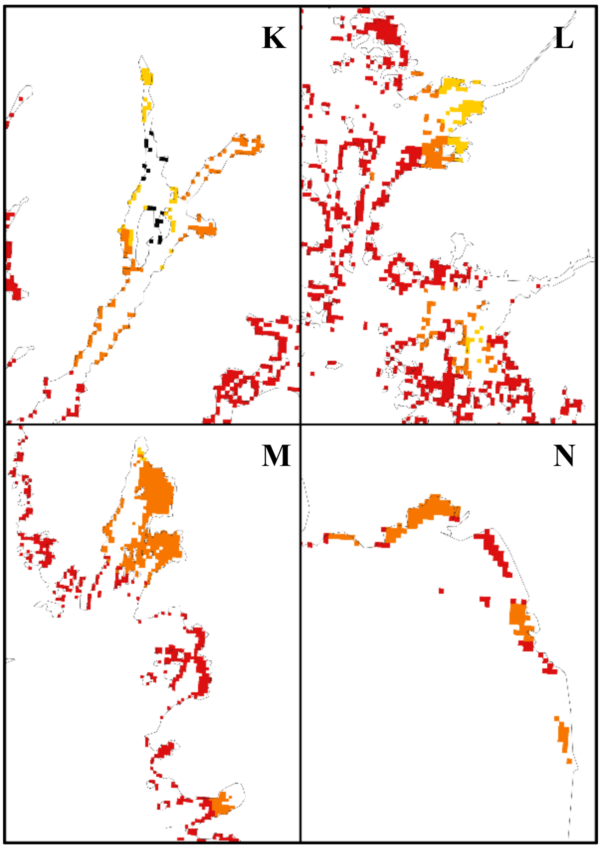
Appendix figure 15 (left). Zoomed locations of figure 9 in the results. The figure show areas of where blue mussels retract based on temperature increase in RCP 4.5. **Appendix figure 16** (right). Zoomed locations of figure 10 in the results. The figure show areas of where blue mussels retract based on temperature increase in RCP 8.5.



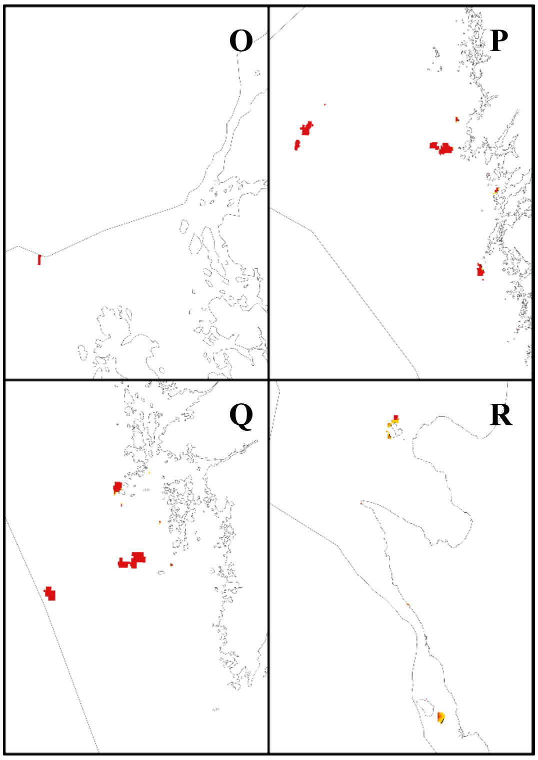


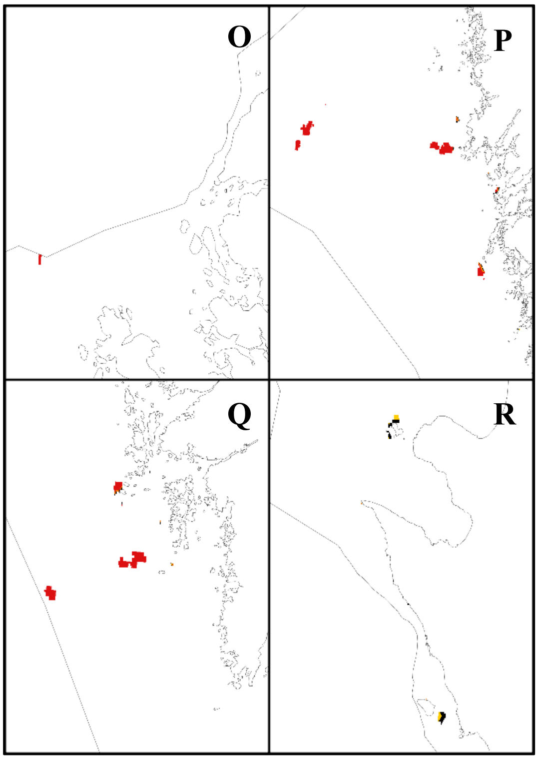
Appendix figure 17 (left). Zoomed-in locations from figure 11 in the results. The figure show areas of where eelgrass retract based on salinity decrease in RCP 4.5. **Appendix figure 18** (right). Zoomed-in locations from figure 12 in the results. The figure show areas of where eelgrass retract based on salinity decrease in RCP 8.5.



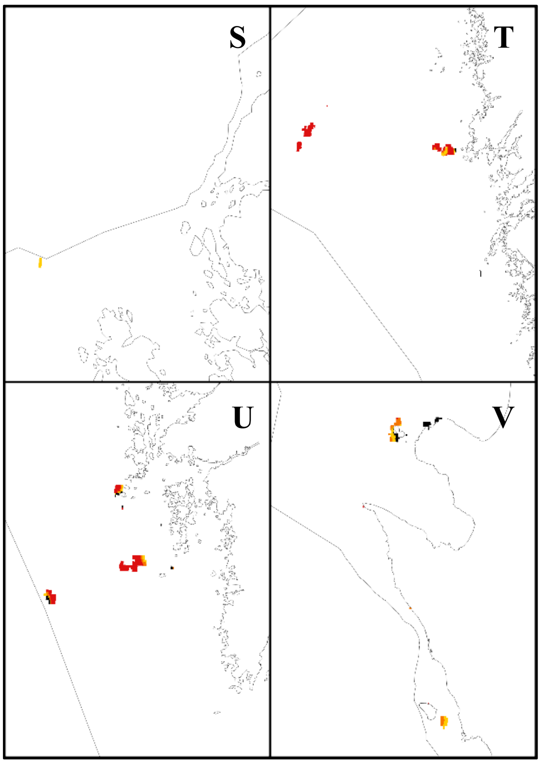


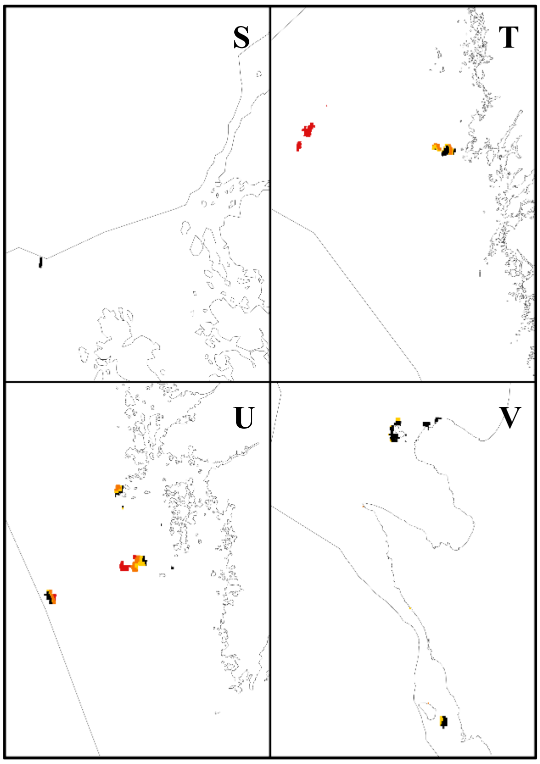
Appendix figure 19 (left). Zoomed-in locations from figure 13 in the results. The figure show areas of where eelgrass retract based on temperature increase in RCP 4.5. **Appendix figure 20** (right). Zoomed-in locations from figure 14 in the results. The figure show areas of where eelgrass retract based on temperature increase in RCP 8.5.



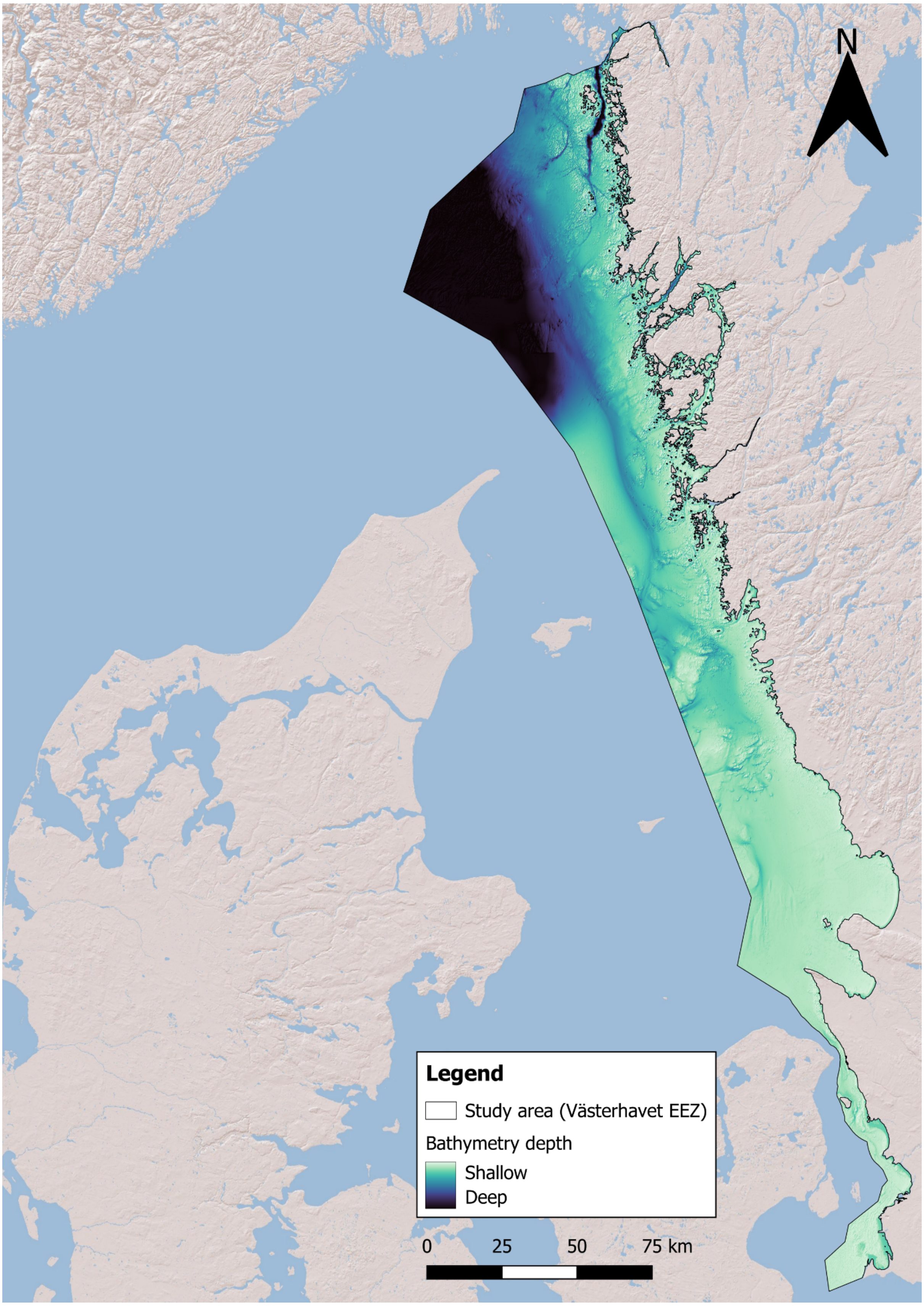


Appendix figure 21 (left). Zoomed-in locations from figure 15 in the results. The figure show areas of where sponges retract based on salinity decrease in RCP 4.5. **Appendix figure 22** (right). Zoomed-in locations from figure 16 in the results. The figure show areas of where sponges retract based on salinity decrease in RCP 8.5.





Appendix figure 23 (left). Zoomed-in locations from figure 17 in the results. The figure show areas of where sponges retract based on temperature increase in RCP 4.5. **Appendix figure 24** (right). Zoomed-in locations from figure 18 in the results. The figure show areas of where sponges retract based on temperature increase in RCP 8.5.



Appendix figure 25. Bathymetry of the West Coast (Västerhavet EEZ) study area.