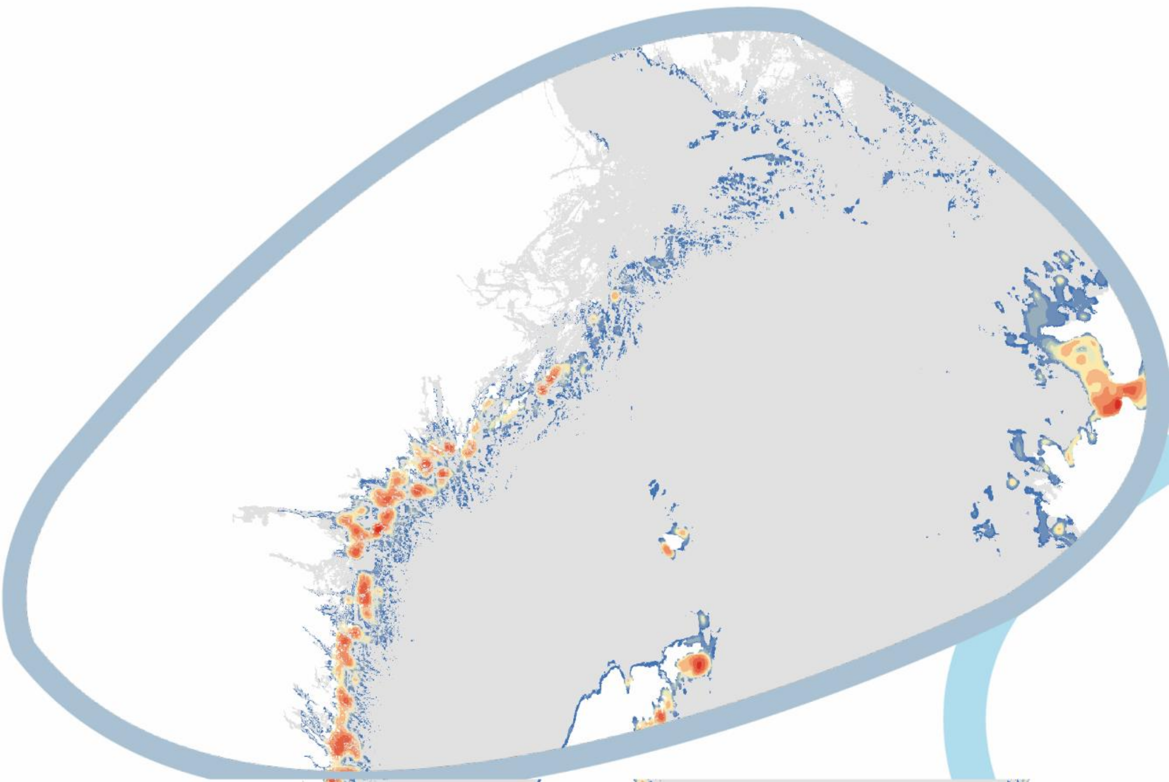
Co-funded by the
European Maritime and
Fisheries Fund of the
European Union

Climate refugia in the Baltic sea

Modelling future important habitats by using climate projections



Authors:

Oscar Törnqvist, Geological Survey of Sweden, oscar.tornqvist@sgu.se

Per Jonsson, Department of Marine Sciences, University of Gothenburg, per.jonsson@gu.se

Duncan Hume, Geological Survey of Sweden, duncan.hume@sgu.se

Suggested Citation:

Törnqvist, O., Jonsson, P.R. & Hume, D. 2019. *Climate refugia in the Baltic sea. Modelling future important habitats by using climate projections*. Pan Baltic Scope report, Uppsala & Gothenburg.

Acknowledgements:

Data used in this project have been kindly provided by the Swedish hydrological and metrological institute (SMHI) and the Geological survey of Sweden (SGU), and is part of the ClimeMarine project.

Disclaimer

The contents and conclusions in this report, including the maps and figures, were developed by the participating project partners and related experts with the best available knowledge at the time. They do not necessarily reflect the respective national governments' positions and are therefore not binding. The European Commission or Executive Agency for Small and Medium-sized Enterprises is not responsible for any use that may be made of the information this report contains.

ISBN 978-91-88727-64-0

Executive Summary

The Baltic Sea is undergoing drastic environmental changes that are partly due to climate change. The ecology of this sea is particularly susceptible to climate change as its waters vary from cold and fresh in the north to brackish in the central area and saline and warmer in the west.

Many of the major habitat-forming species of the Baltic are key species in the provision of ecosystem services, green infrastructure and a blue economy. The future distributions of these species are, or should be, of fundamental concern to marine spatial planning, environmental protection and the development of coastal economies.

Using the latest climate models, SMHI has predicted future changes to several major ecologically structuring factors, such as salinity, temperature and nutrients. By modelling the presence and absence of key species today using historical reference data, it is possible to predict future species distributions, given the projected changes in structuring factors. For this purpose and in this project, habitat changes for two climate change scenarios have been modelled, one resting on assumptions of ambitious mitigation efforts (RCP 4.5, c. 2°C global warming) and the other representing a *laissez faire*-scenario (RCP 8.5, c. 4.5°C global warming).

It is shown here that under all climate scenarios most of the modelled species will have a radically different distribution in the year 2100. While the distribution of freshwater species will remain similar or with slight changes for different reasons (lower salinity, higher temperature, changes in water clarity and nutrients), species limited by salinity will be radically reduced in the northern and central Baltic Sea, as well as the Bothnian Sea, in both scenarios. Especially hard bottoms will lose much of their ecosystem functions with the loss canopy-forming macro-algae including two of the three *Fucus* species, and the loss off the eelgrass *Zostera marina* will result in severe degradation of the values of sandy bottoms.

By studying the connectivity of habitats, with respect to their value as sources for the habitat network and their strength based on how the network contributes to the habitat patches, it can be shown that certain areas stand out as especially important in the models as core areas or as refugia or "last stands" at the fringe of the distributional limit. Such especially valuable areas should be considered in marine spatial planning, in environmental conservation and in environmental impact studies.

Using a predicted future distribution of key species, it is possible to assess the change and distribution of future ecosystem services, with implications for a blue economy. From what the models tell us, the future state of these key species implies such radical changes to the ecosystem and to the basis of the marine economy that immediate and drastic actions to mitigate climate change and to restore damaged habitats to salvage ecosystem functions seem warranted.

Based on these results, recommendations are proposed for future-proofing marine spatial planning, environmental protection and the development of the blue economy; to predict future green infrastructure and the ecological base for future ecosystem services and a more vital marine economy. Recommendations include modelling the predicted future distribution of all major ecologically important species and compile maps of future important ecological hotspots for biodiversity and for specific ecosystem services that have been identified and discussed in various reports. Such ecosystem services are vital for regional economy e.g. through fish reproduction, but also on a local level by maintaining clean bathing waters, an attractive environment, rich wild life and recreational fishing.

Table of Contents

Abbreviations

Abbreviations	Specification	Comment
RCP	Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC for its fifth Assessment Report (AR5) in 2014	See: https://en.wikipedia.org/wiki/ Representative_Concentration_Pathway
MSP	Marine Spatial Planning	
SPT	Spatial planning tools, e.g. Symphony. There are others for analysing impact from environmental stressors (like HELCOM HOLAS or Ecopath/Ecosim/Ecospace) or for planning use of space with respect to conservation (like Marxan).	See: https://www.havochvatten.se/en/swam/eu--international/marine-spatial-planning/symphony---a-tool-for-ecosystem-based-marine-spatial-planning.html
RCO-SCOBI	RCO (Rossby Centre Ocean model) is an oceanographic circulation model. SCOBI is a model for nutrients and algae. By coupling the models one can, e.g., study transports of nutrients and changes in the sea environment on long time scales.	See: https://www.smhi.se/en/research/ research-departments/ oceanography/rco-english-1.8323
SDM	Species distribution model, in practice an ecological niche model with probability of occurrence or sometimes abundance or other measure of richness or strength.	In this context realized with the BIOMOD2 package using the R language

1. Introduction

1.1. The need to valuate habitat forming species

Essential for a future prosperous blue economy in the Baltic Sea area is the mapping and valuation of ecosystem services. These services rely on the existence of certain species and habitats providing those ecosystem services. A lot of effort has been put into identifying key habitats and their links to specific ecosystem services (e.g. Ivarsson et al. 2017, Bryhn et al. 2015). Habitat forming species central to the ecosystem and its services are often called keystone or foundation species (e.g. HaV 2013:7).

There have been many attempts to map and model such key species and habitats. Perhaps the most ambitious efforts in the Baltic have aimed at ranking the value of areas according to their potential value for the ecosystem and its services through the MOSAIC valuation framework (Hogfors et al. *in prep*). This framework, however, tries to establish ecological value in the context of green infrastructure rather than estimating value for specific ecosystem services, which may also include economic and cultural services.

Thus, species central both to the provisioning of ecosystem services and for green infrastructure are extremely important. Reduction or alteration of the distribution and abundance of these species is important to monitor, understand and, if possible, mitigate. For a future prosperous blue economy, it would even be profitable to develop these services further, for example, via environmental protection or habitat restoration.

1.2. The challenge of climate change

Being a brackish inland sea, the Baltic Sea (including the Gulf of Bothnia) is characterized by very pronounced gradients in biologically structuring factors such as salinity, temperature and nutrients. These are all heavily affected by any climate changes and small fluctuations may result in drastic ecosystem shifts over large areas. As many species live on the fringe of their possible distribution or are uniquely adapted to the brackish water, climate effects can have profound impacts on the biodiversity of the Baltic Sea.

In Swedish waters some effort has been made to add climate effects to the analysis of anthropogenic cumulative impact on key species and habitats, e.g. through the spatial planning tool (SPT) called Symphony (Hammar et al. 2018, 2019). However, this approach is complicated because habitats are not only are progressively and proportionally affected by climate changes, but rather certain climatological thresholds dictate suitable areas for certain habitats or species to exist. In addition, in environments which are altered by multiple pressures radical shifts in ecological regimes are known to occur (Conversi et al. 2015). SPTs used to assess pressures on habitats/species often do not consider synergistic effects between multiple pressures or the possibility of ecological regime shifts.

There is thus a need for a complementary route to the analysis of cumulative impact in e.g. MSP or environmental protection, by which future suitable habitats for key species are assessed. Environmental protection, extraction of resources, spatial planning etc. then become more future proof, both with respect to the handling of resources and values but also in preparation for and adaptation to changes in future ecosystems and ecosystem services. The challenge and opportunity then become to plan for and protect future resilient habitats, and to understand what major shifts that the ecosystem can undergo, and the effects these shifts may have for e.g. fishing and tourism as well as for the composition of the ecosystems.

1.3. The concept of climate refugia

The term *climate refugium* for a habitat or species in this context means an area where climate change has not or will not severely affect the habitat or species, in a larger area where climate change as a contrast has affected or is affecting (by reduction, displacement, impoverishment) the habitat or species. Given the nature of climate change in the Baltic Sea, especially with regards to altered salinity and temperature gradients, marine refugia in the area will often be present at the fringe of the distribution of the species or habitat, the “last stand” next to unsuitable locations. But refugia can also be present at locations where local conditions create resilience and preserves a viable, healthy and strong, presence of the habitat or species as a contrast to other nearby areas, e.g. through nutrient-rich upwelling, pristine seafloor or clear waters. Thus, climate refugia here denote the last remaining viable habitat patches often, but not always, on the fringe of the region populated by the specific habitat or species.

1.4. Preceding work and recent developments

Underpinning this initiative was the ambitious effort to develop an analytical framework, tools and datasets for MSP called Symphony (Hammar et al. 2018, 2019). During the development of this framework it soon became apparent that the inclusion of climate change effects is necessary for a SPT to be more “future-proof”. To develop Symphony and to produce relevant model data over environmental parameters, the Swedish Water Administration and Management (SWaM), the Swedish Metrological and Hydrological Institute (SMHI), University of Gothenburg and the Geological Survey of Sweden (SGU) collectively initiated the ClimeMarine project. The aim of ClimeMarine was to produce high resolution model data for inclusion in Symphony and to investigate methods for assessing the cumulative impact of climate change and anthropogenic pressures to a selection of marine habitats and species.

Previously, climate change in the Baltic Sea has been addressed by HELCOM (e.g. HELCOM 2013b). However, the assessments and the recommendations put forward by HELCOM have centered on environmental risk, stress and mitigation efforts, not on assessing the direct geographical effects on biodiversity. This is due to the fact that the Baltic Sea Action Plan that HELCOM advocates centers primarily on broad-scale environmental assessment, monitoring and actions, not on the detailed investigation and mapping of habitats and environmental change, which is the level at which MSP, local environmental protection and restoration efforts and a local economy need to focus to be effective. There is thus a need to address climate change from the perspective of local environmental impact, and to design tools for working with this issue. A previous effort was made at SWaM to model future distribution of some key species (Hammar & Mattson 2017). This effort must be evaluated given the new climate scenarios and explored by new modelling methods.

Consequently, ClimeMarine, aided by results from the current project, tries to complement the impact analysis of Symphony by directly predicting future ecological distribution and climate refugia, given scenarios of climate change rather than centering on expert judgement of ecological stress, cumulative impact and impact severity. Within Pan Baltic Scope, the methods and geodata produced within the ClimeMarine project have been used with kind permission from SMHI.

1.5. Purpose

The purpose of the project behind this report is twofold: evaluation of previous attempts at identifying future climate refugia, and to then make new efforts at identifying such areas for additional species. This will be achieved using both updated climate projections and more advanced, modelling tools.

1.6. Limitations

The models presented in this report are produced either using simple GIS analysis or from ensemble modelling based on machine learning. Simple GIS analyses yield climate envelopes or areas within which the species could occur when all other aspects are neglected. In contrast, modelling based on machine learning produces a continuous assessment of probability of presence, based on many (thousands) of documented occurrence records and local environmental factors.

For both types of modelling, only physical characteristics (salinity, temperature, depth, nutrients, transparency etc.) are considered. All physical data are each subject to varying degrees of spatial uncertainty related to both the source data quality (more & better field data = lower uncertainty) but also related to the heterogeneity and dynamism of the environment (e.g. inshore areas are generally more complex /dynamic which increases uncertainty). SMHIs projections of future climatic conditions in addition are subject to significant increases in uncertainty over time - more so in some variables (e.g. salinity) than others (e.g. temperature). In addition to uncertainty in the physical data used, complex ecological dependencies such as those between macroalgae and fish, competition for space, or predator-prey relationships are not considered and neither is future environmental degradation as a result of human activity (e.g. coastal development).

The results from this initial study are therefore predictions which are well suited to screening possible future ecological changes and identifying target areas for management actions and policy however in many situations additional research into the data limitations and knowledge gaps will be required depending on the decision risk. In general, however, we consider that the results could be taken as indicators of habitat changes relevant for marine spatial planning, estimation of ecosystem services or planning of protected areas, with some certainty relevant on a national scale and with an increased uncertainty on a regional or local scale.

Data underpinning modelling are of varying resolution, from detailed topographic data on the scale of meters to climate and oceanographic models with resolutions varying from 1 to 5 nautical miles. The resulting model resolution is therefore high with respect to Baltic-wide climate and environmental models but relatively coarse (based on a 250 meter grid) for assessing local habitats and conditions (e.g. for environmental protection or estimation of green infrastructure).

2. Projecting habitat changes

A complementary method to the cumulative impact methods used in some SPTs to assess pressures and risks for ecosystem changes is to model future scenarios for habitats or species. Given the data already produced in ClimeMarine for Symphony, it is possible to re-use the these climate variables and data for modelling future scenarios.

By modelling ecosystem changes, it is possible to delineate areas where climate effects are projected to have direct impact, both positive and negative, to the ecosystem components in the SPT. As such, the results from this model, comprising ecosystem component maps under future climate conditions without considering future direct human pressures, can be used for several purposes, namely:

- Delineations or bracketing of future climatic limits to valuable areas for ecosystem components and services, i.e. climate envelopes and ecosystem limits at a habitat level.
- Modelling of valuable areas in respect to current as well as future ecosystem components and services, e.g. as a basis for a more future-proof "green map", aggregated by ecosystem service or ecosystem value e. g. using the MOSAIC framework (Hogfors *et al.*, 2017).
- Delineation of areas with habitat patches resilient to climate change, an aspect that should be considered in spatial planning for the future.
- Identification of especially valuable resilient habitat patches that may form climate refugia in the future; either locations on the climatic fringe of habitats, patches central in the future green infrastructure (through connectivity, germination, movement etc., see below on connectivity) or habitat patches valuable through their future size and biomass/abundance.

Habitat models can also be used to create location-specific pressure data for use in SPT. As modelled habitat changes take many factors into account (climate data together with other habitat predictors such as depth, seabed substrates, photosynthetic radiation, currents etc.), the local pressure on habitats due to climate can be estimated by measuring modelled presence or abundance of habitats, given climatic variables, at each location. As such, this method is complementary to the more general pressure levels assigned to species and habitats in the MSP process. A future area of development is thus how the habitat change model can be incorporated into the pressure calculations of the SPT.

2.1. Identifying key species

The selection of key species rests on their importance for the ecosystem services and on our ability to assess climate effects, i.e. the sensitivity of the species to changes in salinity, temperature etc., and our ability to model distributional changes across space and time.

Following the list of key species by Vuorinen et al. (2015) and the compilation of ecosystem services by Garpe (2008) and Ahtiainen & Öhman (2014), some species stand out based on their roles in primarily supporting services S1-S6, (biochemical cycling, primary production, food web dynamics, biodiversity, habitat and resilience, see Garpe 2008:31–66), namely:

- *Zostera marina* (eelgrass), a flowering plant with its distributional margin in the central Baltic.
- *Fucus vesiculosus* (bladder-wrack), *Fucus radicans* and *Fucus serratus* (toothed wrack), macroalgae that together cover much of the hard bottoms of the West coast, Baltic sea and Bothnian sea but individually occupying different salinity regimes.
- *Stuckenia pectinate* (pondweed), a flowering plant suited for more brackish water and a possible successor to *Zostera marina* where salinity is reduced to due climate change.

These species are therefore subject to modelling. For its role in regulating services (climate, atmosphere, sediment, eutrophication) and as a key species for food production and biodiversity, *Mytilus edulis/trossulus* (blue mussel) is also included.

2.2. Selecting timeslot, scenario and data for future habitat distribution modelling

Available data for relevant parameters covers the historical reference climatic period (1961-1990), the midpoint of future projections (2050) and the end point (2100). For each parameter, available data gives estimates for monthly averages, as well as minimums and maximums, for the different scenarios (RCP 4.5, RCP 8.5), for each model (according to Saraiva et al. 2019b) as well as means, minimums and maximums for the model ensemble. Even at an aggregation level based on monthly averages, there is a broad range of optional values to construct models from;

1. Monthly and seasonal averages for models or the ensemble, e.g. average summer temperature.
2. Extreme cases: e.g. warmest/coolest month, per year, season or month with least oxygen (even though these extreme values are based on average values of extreme months, not worst-case days).
3. Average highs and lows: ensemble average of highest/lowest monthly, seasonal or yearly averages.
4. Number of months above or below a certain threshold for e.g. temperature, salinity or oxygen.

For the purpose of testing this methodology, ensemble averages (case 1 above) have been chosen for the RCP 4.5 and RCP 8.5 scenarios and for the end point (i.e. year 2100). For some parameters such as bottom oxygen, a moderate estimate of plausible peaks and lows in data has been chosen in the form of ensemble minimums and maximums within each season (case 3 above, e.g. month with lowest oxygen, ensemble average).

Habitat modelling is performed for three scenarios; (i) the reference period, using reference data, forming a baseline or predicted distribution today, (ii) RCP 4.5 at year 2100 with ensemble mean vales, and (iii) RCP 8.5 at year 2100 with ensemble mean vales. Ensembled minimum and maximum values will be tested later on once the predictions of future habitats based on mean values have been produced. Specifically, minimum and maximum values will be tested with respect to factors that likely have strong adverse effects on benthic communities, such as low oxygen and low salinity during a single season to investigate possible magnitudes and extents caused by extremes over century-long return times.

2.3. Climate data for modelling habitat changes

Owing to the mesosaline character of the Baltic sea, salinity gradients have a strong effect on zonation of benthic communities. Likewise, the mix of cool freshwater runoff in springtime, ice formation in the winter, cold and saline bottom waters, and warm coastal waters in the summertime make temperature gradients a major additional structuring factor. Oxygen depletion primarily in the deeper portions of the Baltic and dissolved nutrients in the photic nearshore zone together with water transparency and the composition and density of phytoplankton also limit the spread and abundance of most sessile organisms, while some species benefit from nutrient availability. Sea level rise affects light penetration and the extent of the shallow coastal zone.

These parameters, all volatile and strongly influenced by climate change, interact with the more stable marine seascape consisting of the seabed substrate, average wave climate and bottom currents to shape the benthic communities. The parameters are all tested and selected using the modelling techniques, described below, based on their relevant explanatory power.

2.4. Data preparation and validation needed for working with habitat changes

Both physical and chemical data need to be harmonized before applying them in habitat modelling. A challenge is to make the coarse models (from a habitat perspective) from e.g. RCO-SCOBI useful on a level relevant to MSP. Model data have a resolution of about 2 nautical miles, while much reference data available through the Copernicus marine data hub (http://marine.copernicus.eu/) has a resolution of about 1 nautical mile.

The harmonization has two aspects; geographical (areal) adjustments/interpolations and temporal generalization. A positive aspect is that, as water is in constant flux due to waves and currents, a more coarse-grained model for water characteristics can be taken as a useful approximation for water characteristics over time. Likewise, benthic biota seldomly react to momentary changes in the physical or chemical properties of the surrounding water. This means that with a wise choice of temporal and spatial generalizations, various climatic indicators, useful on a MSP level, can be assembled from the more coarse-grained model-data available. The following datasets are for this purpose created:

- Total means, maximums and minimums of ensemble means (not ensemble extremes or model extremes) for yearly and seasonal data (cold period, warm period).
- Data for bottom layer, surface layer and mean of water column and the above values and seasons.
- These datasets adjusted to the resolution (interpolated, bilinear) and extent of analysis grid.

As model data is missing in many complex near-shore environments (fjords, archipelagoes) data needs to be projected into these areas from adjacent pixels. The method proposed here is to extrapolate the most probable adjacent value into the empty pixels. Probable values vary with data type, but the following method can be used as a starting point:

- Winter temperature, oxygen, Secchi depth and salinity are formed from the minimum of adjacent pixels, as the coastal zone is chilled by cool runoff, the oxygen situation is lower in the nutrient-rich inner archipelagos and Secchi depth is adversely affected by high turbidity and nutrients in the inner coastal zone.
- Summer temperature and nutrients are calculated from the maximum of adjacent pixels, as shallow coastal areas are quickly heated by sunshine and the shallow nearshore, protected archipelagoes and sounds trap nutrients from runoff.

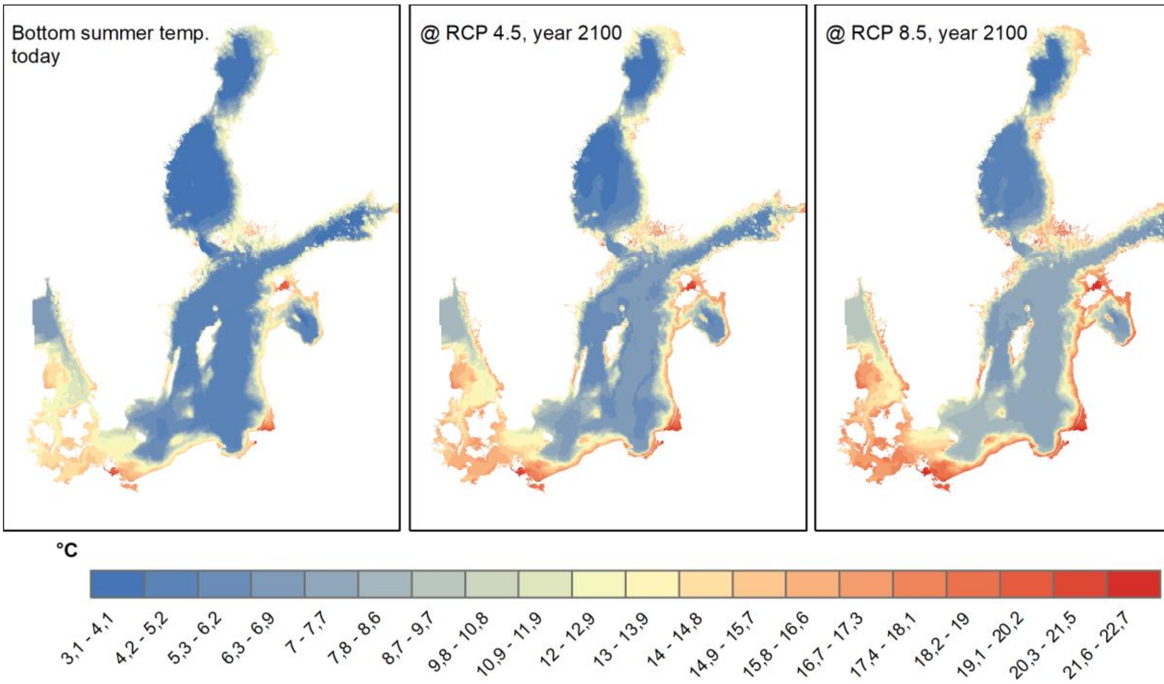


Figure 1. An example of a parameter from the climate modelling: Average summer water temperature at the seafloor.

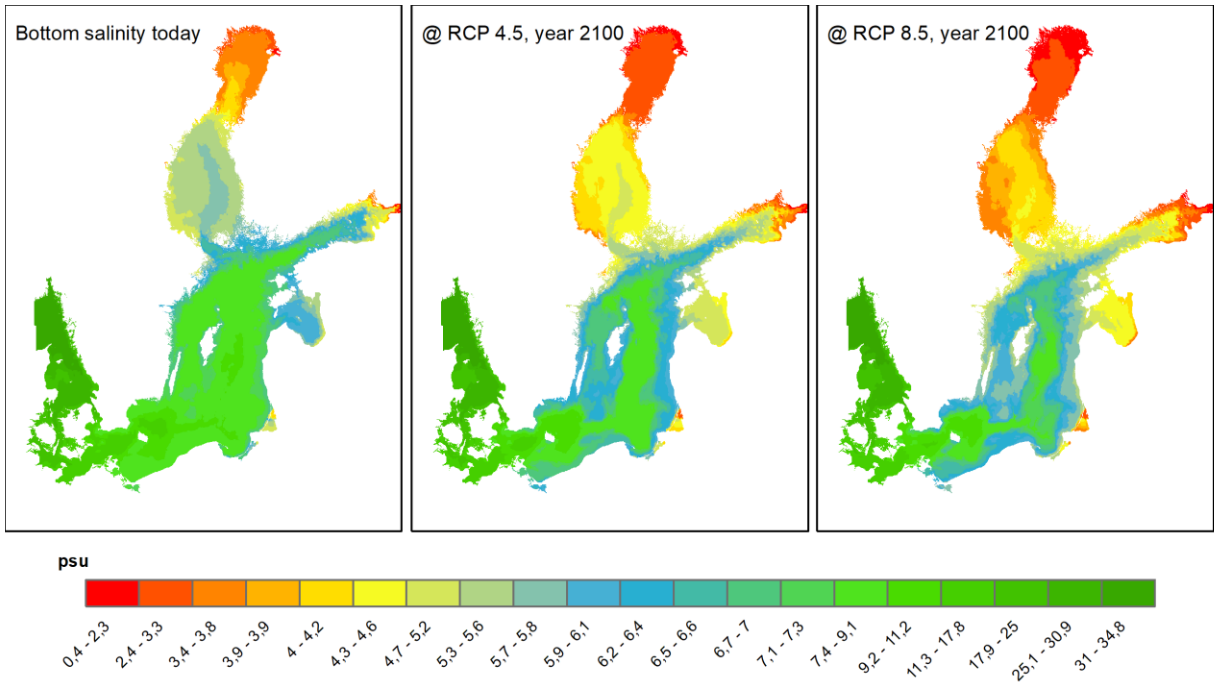


Figure 2. A second example of a parameter from the climate modelling: Yearly average salinity at the seafloor.

2.5. Preparing and adapting supporting physical data

In addition to data already available in the SPT and climatic data prepared from climate models, the following datasets need to be assembled and adjusted to the analysis grid for habitat modelling:

- Water velocity at the seabed, both from currents and wave force. Data source is the Copernicus marine data hub (http://marine.copernicus.eu/).
- Benthic topographic indexes, outlining crests and depressions etc., calculated from the bathymetry.
- Slope and rugosity, also calculated from bathymetric data, assembled from EMODnet, the Swedish maritime administration and the Geological survey of Sweden.
- Isostatic uplift, affecting future bathymetry, calculated with data from the Swedish National land survey (https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/gps-geodesi-och-swepos/Referenssystem/Landhojning/).
- Photosynthetically active radiation (PAR) at the seabed, calculated from Secchi depth, water characteristics and bathymetry (Cameron & Askew, 2011).
- Seabed substrate modelled and harmonized based on data from EMODnet geology (https://www.emodnet-geology.eu/)
- Wave exposure at the surface, calculated from existing methods and data (Wijkmark & Isæus, 2010).

The following data, affecting habitat structuring, need to be adapted to a change of climate by using datasets mentioned above to model the environment for year 2100:

- Bathymetry needs to be adjusted to a change in sea level (model data) but also to isostatic uplift.
- Photosynthetic radiation on the seabed needs to be adjusted by a change of depth (bathymetry) as well as Secchi depth.

Data on future currents and waves are as of this writing missing and therefore omitted but does most probably affect shallow benthic communities either in the most sheltered or the most exposed locations. This will be investigated further in the future in the light of available data.

2.6. Methods for modelling habitats using climate data

The mechanistic relationship between benthic communities and physical/chemical parameters are poorly understood and are very complicated. However, pragmatic approaches to model the distribution of species and the influence upon them exist. For an overview, see e.g. Kuhn & Johnson (2013) and Franklin & Miller (2009). Instead of empirical/experimental studies, it is by these methods possible to model the probable extent of habitats (climate envelopes, niche models, habitat suitability) by establishing statistical relationships between physical/chemical variables and species occurrence/abundance using correlative modelling techniques and machine learning (Guisan et al. 2017).

Once such relationships are established, future extents of habitats can be modelled by applying future physical/chemical variables to the modelled relationships (e.g. Roberts & Hamann 2012, Pearson & Dawson 2003, Esfahani 2008, Elith et al. 2011). There are numerous techniques for this based on presence-only data, on presence-absence records and on measures of abundance, which in turn gives different results of continuous probability of occurrence, binary predicted occurrence (absence/presence) or predicted abundance (percent cover, weight etc.) with associated measures of statistical significance (e.g. Reiss et al. 2011, Tarkesh & Jetschke 2012, Saupe et al. 2011, Shabani et al. 2016).

This project tests various methods and selects the most robust one, yielding high measures of confidence (e.g. TSS or ROC). The analytical framework is the R programming language and methods tested include GLM (Generalized Linear Models), GBM (Generalized Boosted Models/Boosted Regression Trees), GAM (Generalized Additive Models), ANN (Artificial Neural Networks), MARS (Multiple Adaptive Regression Splines), Maxent (Maximum entropy models) and RF (Random forest). Modelling is performed with the Biomod2 package in the R environment (Guisan et al. 2017).

Results comprise predicted habitats of selected benthic species as well as a quantification and localization of changes (loss and gain of habitat) accompanied with measures of model performance. From these habitat models, maps of high ecological values with respect to potential for key species are created, as well as maps of predicted habitat change and habitat refugia showing future modelled presence weighted by resilience (habitat patch size, abundance) according to the selected method (Appendices B-D).

2.7. Preparing species presence/absence data

The modelling method relies on species presence and absence data to establish a probability model for habitat distribution. Presence records are compiled from the following data sources:

- SHARKweb, SMHI, Sweden, https://sharkweb.smhi.se/
- ArtDatabanken, analysportalen, https://www.analysisportal.se/
- GBIF, https://www.gbif.org/
- ICES ecosystem data, http://ecosystemdata.ices.dk/inventory/index.aspx
- OBIS / EurOBIS, https://obis.org/ / http://www.eurobis.org/
- EMODNet Biology, http://www.emodnet-biology.eu/toolbox/en/download/occurrence/explore
- Unpublished datasets from various agents and agencies, primarily local administrative boards

The datasets are overlapping and contain data with different resolution and detail. For that reason, data was collated and generalized so that presence points were generalized at a 250 m grid. Data was then subsampled, and 4000 records were kept for each species.

In reality, true absence data is seldom recorded, as surveys most exclusively record presence data. There is a standard method to create pseudo absence data by randomly distributing points over the whole study domain and assigning absence to those points. This method, however, has several drawbacks. First, it is not obvious that species are absent from those points. Secondly, randomly distributed absence points are not guaranteed to capture the distribution of the most significant environments, at or near the limits of the distribution of the species. When trying to model species present in shallow near-shore environments, randomly selecting absence points across the Baltic will not yield a robust measure of the distribution of the complex near-shore habitats.

As a remedy to the above-mentioned drawbacks to random sampling, absence points are created by assuming that presence of one benthic habitat-forming species implicitly conveys the absence of another. Otherwise, that other species would also be recorded. For example, if *Zostera marina* is recorded at a location where no *Fucus vesiculosus* is recorded, then we can be quite confident that there is no *F. vesiculosus* at this location, otherwise that species would also have been recorded. Implicit absence records at a distance greater than 250 m from an explicit presence was kept. This implicit sampling is complemented by random sampling of absence points over the study area as well as in areas with directly unsuitable habitats with respect to substrate and, for species relying on photosynthesis, lack of light at the seabed. From these absence records, 4000 records were randomly selected for each species.

3. Using the results from the habitat models

There are three ways of using the results from the habitat modelling undertaken here:

1) Quantifying probable habitat change will directly show areas resilient to projected climate change, and thus point to areas of concern to MSP and high conservation values.
2) The extent of habitat change (presence or cover/abundance) is also a robust indicator of the sensitivity to climate changes, which means that by quantifying predicted habitat change, data for further refining the sensitivity matrix per species and per climate-dependent parameter can be collected to be implemented in MSP tools like Symphony. This is possible as the habitat modelling methods convey the explanatory strength of each variable, i.e. to what degree the distribution of a species depends on salinity, temperature etc.
3) A map of changes (loss-gain of habitat) can be used to form a situational map of local, climate-induced, stress. A loss of probable occurrence would then correspond to an increased pressure while a predicted loss of habitat would lead to a pressure of maximum value at a particular location.

All these three ways of using habitat change could lead to further refinements of the MSP methodology with respect to the sensitivity matrix, cumulative impact, ecosystem values and marine spatial planning.

Maps of projected habitats today and in the future are presented in appendix B.

3.1. Modelling habitat distributions and change

Biomod2 creates results from individual models and ensemble averages of various types. The method chosen is "EMwmean", the weighted mean of probabilities, with TSS cutoff at 0.7 for individual models. This method gives ensemble average probabilities of presence in the scale of 0-1000 ‰, representing 0-100 %. Due to inherent uncertainties in data and the coarse scale of analysis, where each pixel represents 6,25 ha, it is meaningless to try to establish a cutoff threshold for a binary presence/absence prediction. For instance, bathymetry near the coast varies enormously within a search radius of 250 meter. This means that probability of presence, or ecological suitability – likeness of the pixel to a pixel with known presence – must be viewed and evaluated on an *ad hoc* basis. However, experiments within the current project show that from a pragmatic point of view a relatively low cutoff of around 200‰ can be used to assess predicted absence in a cell with reasonable confidence. For further details see section 5.3 below.

Change, then, from baseline to future projections can only be vaguely sketched, both due to model uncertainty and geographical coarseness.

Maps of projected habitat change is presented in appendix C.

3.2. Connectivity effects

Connectivity is in this context for each species measured in terms of *sources* and *sinks*, on a geographically explicit basis.

- **Source** denotes the proportion of the seeds, larvae, spores etc. which are produced by the species at a given location that by hydrodynamic transport are carried to suitable locations where colonization can occur. This factor thus shows how strong the location is as a *source of growth* for the habitat network.
- **Sink** denotes the amount of seeds, larvae, spores etc. from the species that are carried from the habitat network to a given location for settling and germination. This factor is thus a measure of the *strength or resilience* the location receives from the network.

Maps of habitat strength weighted with source and sink values are presented in appendix D.

3.2.1. Constructing the connectivity matrix

Dispersal of the microscopic spores, seeds and free-swimming larvae are strongly influenced by ocean currents although larvae may exert some active control by changes in drift depth and the length in time of the pelagic larval duration (PLD). Dispersal trajectories in the seascape were simulated with a Lagrangian particle-tracking model (TRACMASS, De Vries & Döös 2001) driven off-line with flow fields from an ocean circulation model. The stored ocean transport data were produced with the NEMO-Nordic model (Hordoir et al. 2019) covering the Baltic Sea and the eastern North Sea. The model has a horizontal spatial resolution of 2 NM (3.7 km), and 84 vertical levels (3-23 m thick depending on the depth). The model has a free surface, and the atmospheric forcing is based on the re-analysis data set ERA40 (Uppala et al. 2005). Climatological data from a number of different databases for the Baltic Sea and the North Sea provided freshwater runoff. Validation of the NEMO-Nordic model has showed that the model is able to correctly represent the SSH, both tidally induced and wind driven (Hordoir et al. 2019).

Particles simulating drifting spores or larvae were released from all model grid cells overlapping with the habitat for each species, although at a coarser resolution. From each grid cell 49 particles were released (a 7x7 array) each spawning month. This was repeated for 8 years (1995-2002), which cover a wide range of the North Atlantic Oscillation index (Hurrell & Deser 2009), which is known to correlate well with the variability in circulation pattern in this geographic area. To simulate organisms with different traits relevant for dispersal (i.e. spawning season, duration of the pelagic dispersal stage, and dispersal depth), virtual particles were released at different times of the year, were allowed to drift for a predetermined period, and their vertical position was locked at predetermined depths. If the actual depth of the ocean basin was less than the determined depth the trajectories resided as deep as possible.

In the present study, simulations of dispersal were carried out for three contrasting combinations of dispersal traits and habitat restrictions representing *Fucus vesiculous*, *Zostera marina* and *Mytilus edulis/trossulus*. The selected combinations of traits were based on extensive empirical data collected on plankton surveys in the HELCOM area for *M. edulis/trossulus* (Corell et al. 2012) and published data for *F. vesiculous* (see references in Jonsson et al. 2018) and for *Z. marina* (Jahnke et al. 2018). The dispersal for the shallow-water *F. vesiculous* with propagules drifting for a 5-day period may represent an upper limit although this is still not well-known considering the potential for rafting thalli.

Potential connectivity (Watson et al. 2010) between model grid cells, satisfying the habitat restriction was calculated as the proportion of trajectories starting in grid cell *i* and ending in grid cell *j* and then summarized in a connectivity matrix. For more details see Jonsson et al. (2016). The normalized connectivity matrix was then used to calculate the source and sink strengths for each grid cell.

The results from the analysis consist of (a) the fraction of the released particles from a location that end up in the network (source), and (b) the number of particles ending up in each cell (sink).

3.2.2. Adding connectivity effects

To weigh in source and sink effects to the results on predicted habitats, the values of the SDM is treated as a proxy for abundance and cell-based strength. A cell with high probability is thus seen as a location with high suitability and thus with basic prerequisites for resilience. This basic relative potential resilience is then adjusted by source and sink effects by multiplying the source and sink strength with the habitat probability. The process is, in short, the following:

1. Model habitat suitability, creating an SDM. Summarize cell probabilities (250 x 250 m) within each NEMO-Nordic cell (c. 3.5 x 3.5 km).
2. For these selected NEMO-Nordic cells as sources, calculate source and sink strength for each selected NEMO-Nordic cell from the connectivity matrix.
3. Multiply the habitat suitability with source /sink in each analysis grid cell.

4. For each location having at least 20% probability of presence, sum the values from the previous step within a search radius of 15 x 15 pixels, to account for local hydrodynamic effects, uncertainties and difference in resolution between the higher resolution SDM and lower resolution sink/source model.

These process steps result in two raster datasets per species with a relative measure of suitability and source / sink strength which, given high values, can be assumed to convey (a) areas that feed the network for internal or external colonization, and (b) areas that have high resilience through high suitability and the reception of seeds, larvae etc.

One can make a couple of general observations here. First, the calculations are based on multiplying two sums of completely different dimensions; suitability and sink/source strength. It is therefore not obvious how to normalize the two data sets, which in turn affects the distribution of hotspots. Secondly, it can be noted that connectivity effects tend to promote secluded, sheltered areas where seeds, gametes etc. stay and resettle. Obviously, this tends to strengthen the resilience of the local population but the more tenuous, but even more important, effects in the wider network is downplayed. Locations with high values as sources and sinks are therefore possibly important as resilient refugia, but the long-distance dependencies in the network and the resilience of the dendritic network depends upon many nodes and corridors, even more valuable as they already may be weak and transparent in the analysis.

Thus, this method tends to identify potentially strong patches, important as refugia, but tends to omit the weaker nodes in the dendritic network needed for long-distance dispersal and colonization. This is very obvious when it comes to *Mytilus spp*. Many locations with resilient *Mytilus spp*. now and in the future are located on elevated ridges in the central Baltic. As these are relatively isolated from the coastal habitats, which in turn form a more coherent and connected network, the sink/source values of these deeper and isolated *Mytilus spp*. habitats are low. Yet, one could hypothesize that these more isolated patches are extremely important in forming “bridgeheads”, refugia or nodes, essential for genetic dispersal and recolonization over larger areas. In future studies we aim to include a dynamic network perspective using methods based on eigenvectors of the connectivity matrix, which may reveal also important stepping stones within a metapopulation (Jonsson et al. 2016).

To conclude, the results from this analysis aim to pinpoint climate refugia important to protect and promote from a local and quantitative aspect, but with weaker inference on essential nodes in network connectivity.

3.3. Assessing habitat change and identifying climate refugia

The main goal is to identify future hotspots, resilient areas and/or patches on the geographical fringe of the existence of the species; i.e. climate refugia. To be relevant, an SDM should in this context point out hotspots of particular strength, resilience or abundance. As it is impossible to validate results describing the future and as species depend on very complex ecological relationships, it is not obvious what values the chosen criteria (strength, probability etc.) should have to denote a hotspot or refugium. Furthermore, as the selected SDM tool does not provide a function to assess habitat quality, the only option is to use probability of presence (conformity with a typical viable ecological “ideal model niche”) as a proxy for habitat quality. Using an *ad hoc* approach, and considering the resolution of 250 meters (see section below on confidence and uncertainties), the results can be evaluated using a simplistic scheme, see table 1.

As a consequence, it is advisable to retain the continuous probability or strength models and judge these on an *ad-hoc* basis, where importance can be assessed from localized results in relation to regional or supra-regional distribution of probabilities (uniqueness, local sum, network distribution). Examples of probabilities are given in appendix B and the relative gain or loss is presented in appendix C. The result from appendix B is weighted with connectivity and presented in appendix D. Predicted future habitat changes (appendix C), gives indications of the transition from one “quality class” to another for each area.

Table 1. Suggested interpretation key for probability scores, translated to predicted habitat quality.

Probability score	Quality class
0-20%	Probable absence in the cell
21-40%	Probable presence in the cell, but of weak quality
41-60%	Presence in the cell, of good quality
61-80%	Presence in the cell, rich quality, abundance or cover
81%+	Presence in the cell, area with core qualities and resilience

What constitutes a future climate refugium is not analytically obvious. For some species, like *Mytilus spp.,* the modelled effects from climate change will rather be a reduced habitat quality overall and the spatial distribution will not have any obvious “last stands” or refugia. On the other hand, by ocular inspection it will be possible to use expert judgement to identify locations probably important in the future. These could be designated refugia and observed in MSP and conservation. In appendices A-D, the investigated habitats are presented in various ways to facilitate assessing future distribution, strength and importance. It is unrealistic to analytically single out certain areas as key habitats for the future. Poorly understood processes, dependencies and model uncertainties make such an analysis meaningless.

One concrete way to use the results, then, would be to analyze local hotspots vs. the complete model, or a sum of probabilities/strengths per area, administrative unit or water body, and study the trend in terms of percentage loss or gain per pixel, area or areal unit. In the same manner as one can make a sum or average of probabilities of strengths for different habitats and areas, it would be possible to use these “heat maps” to assess or model the strength of ecosystem services based on these habitats. If habitats are modelled for several different time slots in the future, it might even b possible to assess when the most radical shifts in species and habitat distribution will occur, i.e. ecological tipping points. This, however, is something that falls outside of the aims of this project. And require further scientific scrutiny.

3.3.1. A note on confidence and uncertainties

Selection of climate and nutrient models

Projections have been made for two different climate gas emission scenarios RCP 4.5 and RCP 8.5. In the RCP 4.5 scenario, the carbon dioxide emission peak around 2060 and the radiative forcing are then stabilised at 4.5 W/m^2 and has an expected global atmospheric warming of 1.1-2.6°C (IPCC, 2013, Table SPM.2). RCP 8.5 is slightly different, with an almost linear increase of the carbon dioxide emission until 2100, and with an expected global warming of 2.6-4.8°C. While the RCP 4.5 roughly corresponds to an ambitious societal effort to tackle climate change. the RCP 8.5 represents the more probable *laissez faire* scenario, ”business as usual”. It is not clear which projection is most probable as this depends on societal, economic and political developments and, consequently, the path which society takes. However, the significant differences in climate projections under the different emissions scenarios versus the differences between competing climate models makes it clear that uncertainty of future ecological impact is dominated primarily by these developments rather than model uncertainties.

Scenarios used to model nutrients and oxygen reflect future societal strategies and associated emission levels. These comprise (i) the Baltic Sea Action Plan (BSAP), (ii) Reference (REF), and (iii) Worst case (Worst) scenarios of which REF was used in this project. We obviously do not know how society will handle nutrient discharge in the future. The selected nutrient load scenario, "REF", represents a “no change” scenario, e.g. business as usual. If the BSAP scenario is selected, representing a situation where the countries around the Baltic has successfully implemented the Baltic Sea Action Plan proposed by HELCOM (2007, 2013), the model will result in reduced nutrient load and improved water clarity and the projected distribution of many species will be increased, e.g. with an improved ecology. If the worst-case scenario is used, it will result in opposite model results and impoverished habitats for most important habitat-forming species. As we do not know if the nations around the Baltic will successfully implement the Baltic Sea Action Plan and we must assume that it is indeed probable that ongoing mitigation efforts (and current slight improvements nutrient input to the Baltic, see Helcom 2015, Gustafsson et al. 2012, Savchuk et al. 2012) will not lead to a worst-case scenario, the “business as usual” model seems feasible to work with as a first test. Further on, it would be important to model future ecosystems using the different nutrient load scenarios and compare the results.

Nutrient load as such was not included in the habitat models for two reasons. First, the parameters are more relevant in the BSAP or worst-case scenarios, where they will lead to noticeable predicted habitat changes. Secondly nutrient load is particularly volatile, and any modelling including such predictors needs to consider the concurrency of species samples and environmental conditions. It would perhaps be possible to use short-term trends in environmental status to get in situ data to drive models of future broad-scale effects of changes in water quality and nutrient load. From the Copernicus data archive, datasets showing forecasts and hindcasts of nutrients (NH4, PO3, Chl, NO3) can be used both to try to find relevant biota samples correlating with nutrient load. But as of this writing and within this pilot project, neither data nor methods are mature enough to establish species sensitivity to changes in nutrient load and to produce qualified data to drive modelling of future conditions of habitats given changes in nutrient load.

Model precision

The pixel size of 250 meters was selected because it harmonized with (a) the best freely available bathymetry (EMODnet v. 3), (b) the Symphony tool and datasets, and (c) was deemed plausible to work with due to limited access to military classified information. At this level, each pixel represents an average of micro-environments of considerably varying character and contents. Thus, on a pixel-by-pixel level, results from such modelling cannot be used to assess the precise contents of each pixel. But given the complexity of the model and the large number of training samples, habitat suitability models capture typical or suitable habitats with a high level or confidence. Many of the underlying modelling runs yield results with an accuracy of higher than 90%, for both user and producer accuracy. Technical performance is included in the deliverables. An example is given in the table below.

What this means is that both in scale and content, the relatively coarse model results can only be used as a screening device, to assess and quantify the suitability of habitats on a regional level. This is also intuitive given the coarse climate projections and models for salinity, temperature etc.

Table 2. Quality of ensemble model for *Zostera marina*. Average of model means weighted by TSS.

Method	Testing.data	Cutoff	Sensitivity	Specificity
KAPPA	0.835	356.0	97.486	83.585
TSS	0.858	699.0	89.868	95.921
ROC	0.982	696.5	89.944	97.08

Environmental variables

The primary results of the modelling process are models of the dependence of habitat on the environmental variables. Especially in the complex coastal zone, the low resolution (1 or 2 nm) of predictors such as temperature and salinity affect the results, as data is resampled to 250 meters. Given concentrated efforts to model environmental conditions in higher detail, the habitat models could be applied not only to future climate scenarios but also to predictors of higher resolution, thus enabling local habitat models. Thus, after the screening process, it would be feasible to select sub regions for more detailed studies, but that would require improvements in hydrodynamic models, models of nutrient flows and salinity gradients etc.

4. Results from modelling

4.1. General observations

As has been proven previously in several other instances (e.g. Kniebusch et al. 2019, Vuorinen et al. 2015), salt-dependent species will retreat quite dramatically to the southwest in the Baltic, given that climate projections are valid. Thus, *Zostera marina* and *Fucus serratus* might become almost completely extinct from the Baltic Sea, *Fucus vesiculosus* will retreat from the Archipelago Sea and in the Bothnian Sea to the Baltic proper, and *Fucus radicans* to advance and to some extent replace *Fucus vesiculosus* along the Bothnian coast and central Baltic Archipelago Sea.

However, *F. radicans* does not form habitats of the richness as *F. vesiculosus* and *Stuckenia pectinata* will not be able to replace *Zostera marina* on sandy bottoms, according to the models. Thus, reduced quality of ecosystem services is to be expected. If anything, *S. pectinata* shows a little decrease overall in probability due to a combination of temperature, salinity and water quality.

Likewise, *Mytilus spp.* retreats in the northern and central Baltic. Increased temperatures could have a minor positive effect on *Mytilus* spp. in the southern Baltic but due to the fact that this area is sandy, silty and muddy, with less suitable substrates for *Mytilus* spp., the net gain in mussel beds is here predicted to be small and primarily confined to Danish waters.

Maps over modelled habitats today and at the year 2100 @ RCP 4.5 and RCP 8.5 can be found in appendix B.

4.2. Climate refugia

Given models predicting the probability of occurrence on a continuous scale (%), it is unclear where to suggest future climate refugia or limits of presence. Below are some general conclusions made per species and detailed maps over key areas are presented. Maps over predicted habitat loss and predicted habitat strength with suitability weighted with connectivity source/sink, on a Baltic Sea-scale, are present in the appendices.

4.2.1. Fucus vesiculosus

This habitat is projected to disappear from the Bothnian Sea at scenario RCP 4.5 and to further weaken and disappear from much of the central Archipelago Sea and between Åland and Sweden. Patches of “refugia” will possibly be found as shown in figure 3 below.

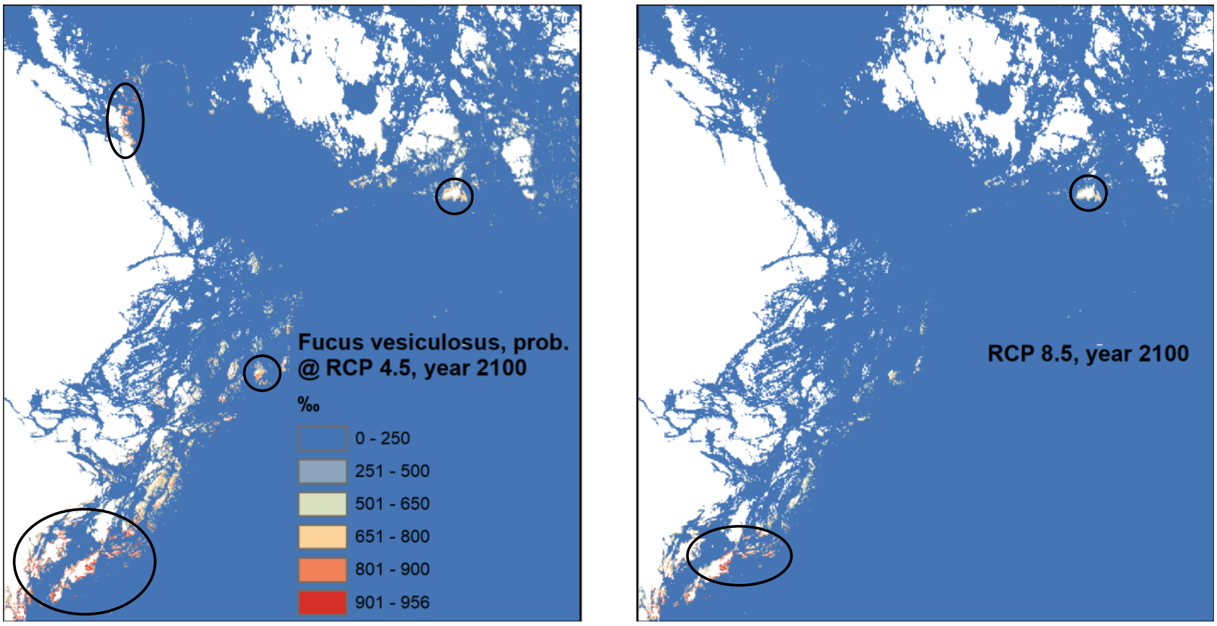


Figure 3. Detail over predicted habitat suitability at the fringes of the distribution of *Fucus vesiculosus*, RCP 4.5 and RCP 8.5 at year 2100. Yellow-red pixels, denoting 50% or greater probability, indicate areas possibly functioning as refugia. A subjective selection of probable areas of importance encircled. Larger maps are present in appendix B.

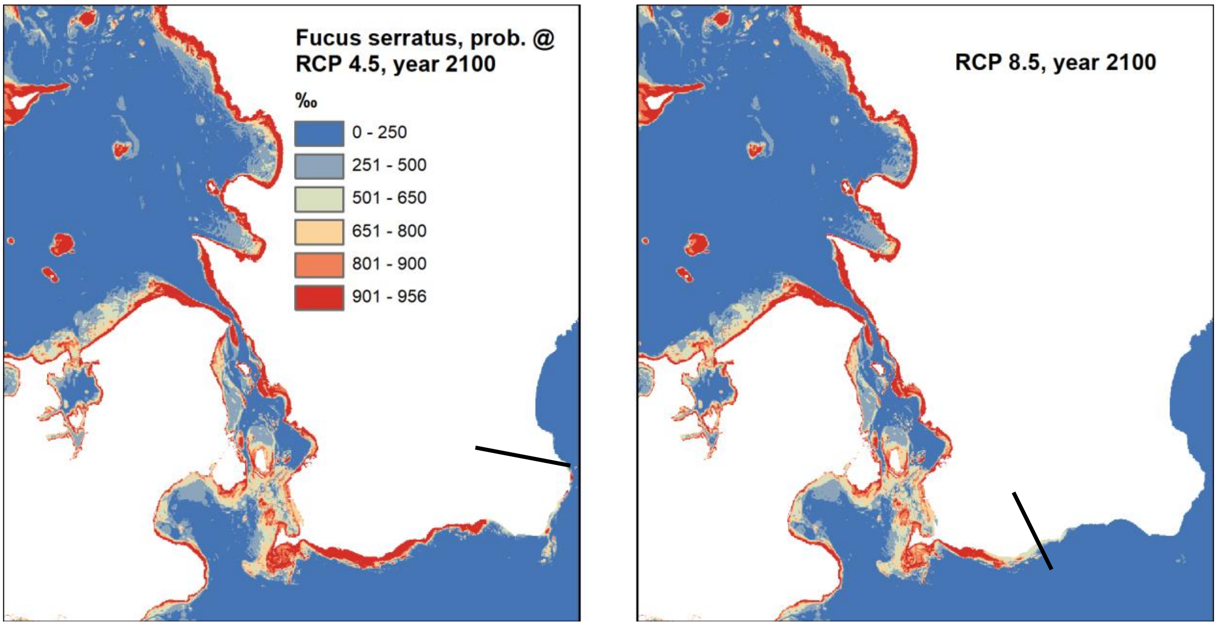


Figure 4. Detail over predicted habitat suitability at the fringes of the distribution of *Fucus serratus*, RCP 4.5 and RCP 8.5 at year 2100. Yellow-red pixels, denoting 50% or greater probability, indicate areas possibly functioning as refugia. Easternmost modelled distribution indicated with a black line. Larger maps are present in appendix B.

4.2.2. Zostera marina

The eelgrass will most probably disappear entirely north of Öland (below, left). Strong habitats and possible refugia can be predicted to Kalmar sound and southern/eastern Gotland. At RCP 8.5, only weak and fragmented habitats seem to be left in Kalmar sound. See figure 6 below.

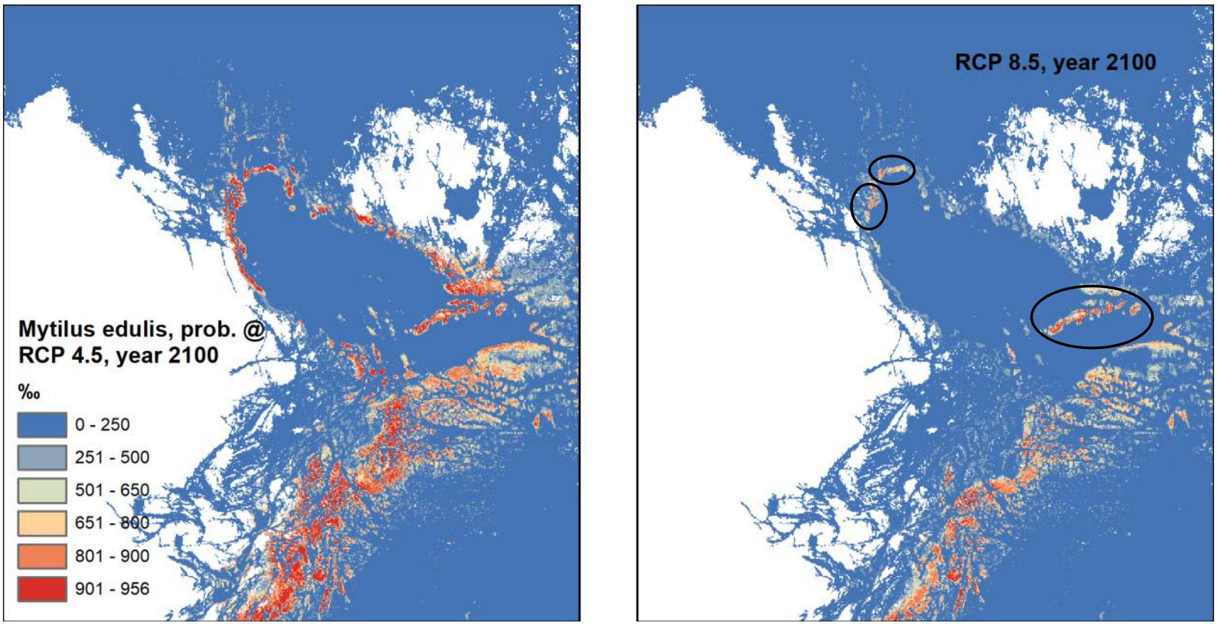


Figure 5. Detail over predicted habitat suitability at the fringes of the distribution for *Mytilus edulis/trossulus.* The area seems to provide a functioning network, at RCP 8.5 severely weakened. Possible climate refugia encircled in the RCP 8.5 scenario. Larger maps are present in appendix B.

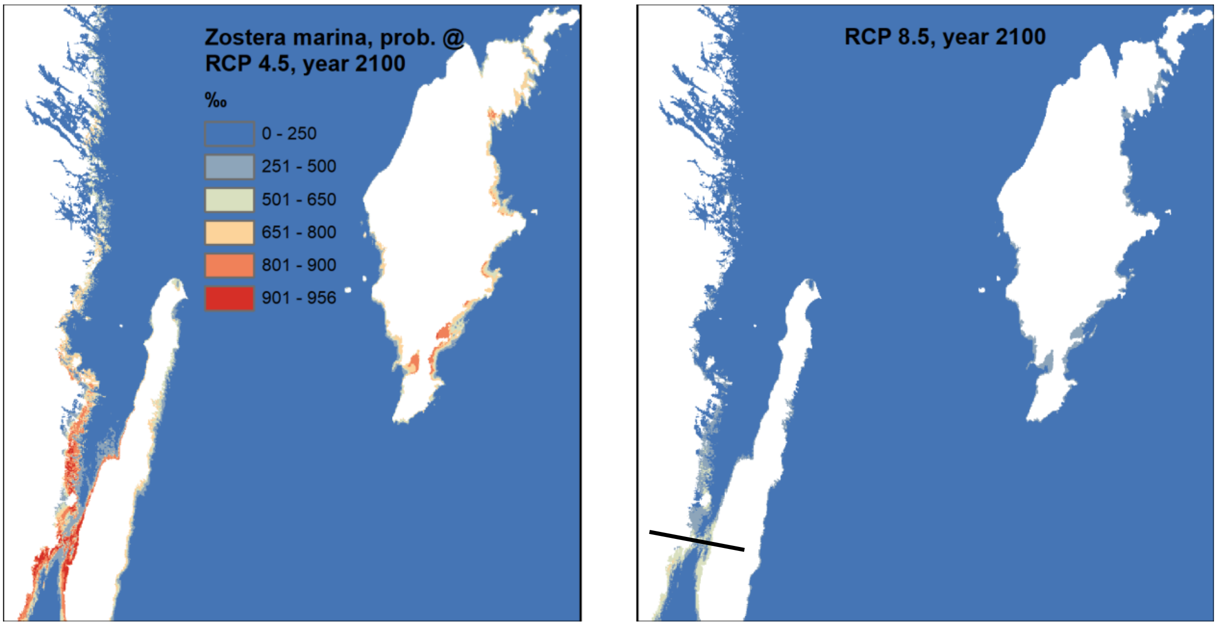


Figure 6. Detail over predicted habitat suitability at the fringes of the distribution for *Zostera marina*. The species will probably be severly weakened north of Öland, and at RCP 8.5 by almost completely gone north of Kalmar (indicated with a black line). Larger maps are present in appendix B.

4.2.3. Stuckenia pectinata

There has been a discussion of if *Stuckenia pectinata* would be able to colonize and take over areas previously occupied by other habitat forming macrophytes, e.g. Z*ostera marina*. The logic is that this species is tolerant to freshwater. However, according to the current model this species will gain little If any ground and generally rather be slightly weakened, possibly depending on degraded water quality/Secchi depth. At the same time, this species prefers softer bottoms and more sheltered areas compared to *Zostera marina* and *Fucus spp*. so there are not many new areas to gain for this species.

5. Evaluating previous efforts at assessing climate refugia

To supplement the key species analyzed in this project (above), a complementary task was to evaluate previous efforts of assessing climate refugia (Hammar & Mattson 2017). It was decided that both the new climate models that have become available through the ClimeMarine project (Saraiva, et al. 2018, 2019a, 2019b, cf. Meier et al. 2019) as well as the new modelling technique adopted in the current report (Guisan et al. 2017) warranted this evaluation. This previous effort included refugia for:

1. Eelgrass (*Zostera marina*)
2. Blue mussels (*Mytilus edulis/trossulus*)
3. Bladderwrack *(Fucus vesiculosus)*
4. Herring (*Clupea harengus membras*)
5. "Skorv" (*Saduria entomon*)
6. Ringed seal (*Phoca hispida*)

Numbers 1–3 in this list are modelled by the method presented in the previous chapters. For No 4–7, the GIS-based method in the previous effort was reproduced with the new climate models and the results are presented below. To complement models for essential fish habitats within Pan Baltic Scope, nursery areas for European flounder was also analyzed using simple environmental windows.

5.1.1. Herring

Using modelled probability of soft bottoms (<50%), salinity (> 3.5 psu), oxygen (> 2.1 ml/l) and light at the seabed (>=0.1%), the GIS-based model of Hammar & Mattson (2017) was re-iterated. As with the previous model, herring reproduction seems to disappear from the Bothnian Bay and largely the west coast of the Bothnian Sea but new data on primarily bottom salinity resulted in a model that does not rule out reproduction of herring on the east coast the Bothnian Sea, in contrast to the previous model. Likewise, better data on the photic zone broadens modelled areas to include deeper areas in the archipelagoes. Any specific climate refugia cannot be identified.

A map of current modelled nursery areas together with projected distribution for RCP 4.5 and 8.5 is present in appendix A.

5.1.2. Cod

The method employed was slightly different to the preceding attempt (Hammar & Mattson 2017). This time, suitable water volumes for larvae were calculated in 3D by computing the environmental window for each geographical area (pixel). This was done by selecting cells from the 3D model for salinity and temperature that meet requirements (salinity > 14.5 psu, oxygen > 2.1 ml/l) and calculating the total depth of these cells, in meters. The result shows, in meters, the "thickness" of the water column suitable for larval survival.

The results agree with previous results. At RCP 4.5, only a small area in the Arkona basin near Kriegers flak seems like a suitable nursery area in the Baltic proper. Suitable areas are otherwise confined to Öresund and around Lolland and further to the west/north. The new model is a little more discriminating, which means that the small patch of suitable water in practice cannot be viewed as a climate refugium. It is simply too small. Thus, even at RCP 4.5, no cod will reproduce in the Baltic.

At RCP 8.5 the situation is even worse, and the small patch is gone completely. Potential climate refugia are obviously the easternmost parts of Öresund and south of Grønsund/Falster.

A map of current modelled suitability index based on water column thickness together with projected suitability for RCP 4.5 and 8.5 is present in appendix A.

5.1.3. "Skorv"

The model agrees broadly with the previous model. Using the envelope bottom oxygen > 2.1, hard bottom < 50% and mean summer bottom temperature < 15°C, the "skorv" (*Saduria entomon*) disappears from the shallow areas of primarily the eastern and southern Baltic but not from the waters of Finland to the extent that was previously suggested. No specific climate refugia can be identified.

A map of current modelled probable distribution of "skorv" together with projected distribution for RCP 4.5 and 8.5 is present in appendix A.

5.1.4. Ringed seal

Suitable breeding habitats for the ringed seal were calculated from a yearly ice cover of 10% from which were subtracted areas cleared of ice or otherwise severely disturbed by shipping traffic during winter time (using data from Symphony, winter shipping noise @125 Hz > 105db). As from the previous attempt, a severe reduction in suitable habitats can be identified. The results show that for RCP 4.5, suitable habitats form primarily along the west coast of the Bothnian Bay, southwards to Kåge, with absence in and near shipping lanes and harbors. At RCP 8.5, only the innermost archipelagoes near Råne, Haparanda and east of Kemi carry suitable habitats. These are obvious choices for climate refugia.

A map of current modelled suitable ice sheets for breeding together with predicted ice extent at RCP 4.5 and 8.5 is present in appendix A. A graph showing the reduction in suitable habitats is presented in figure 7 below.

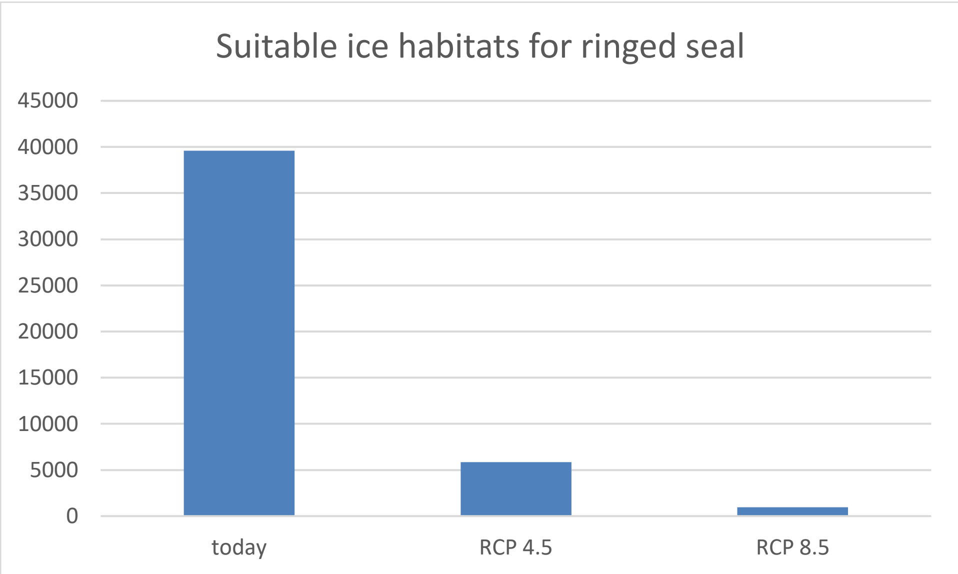


Figure 7. Suitable habitats for ringed seal (square kilometres), based on ice cover and absence of shipping, for today, at RCP 4.5 and RCP 8.5 shows a drastic reduction of suitable habitats for breeding.

5.1.5. Flounder

To give current models of essential fish habitats some perspective, future suitable nurseries for flounder (*Platichthys flesus* and *P. solemdali*) was modelled purely based on salinity and bathymetry. With a threshold of 6 psu and for parts of the sea where depth is less than 30 meters, the species will retreat to the southwest for RCP 4.5 and even further for RCP 8.5. The area is not negligible; based on the whole Baltic area including Denmark and the Swedish west coast (OSPAR/HELCOM area), it seems that roughly 25% of the area is lost at RCP 4.5 and from the remaining area a further 15% at RCP 8.5, resulting in a loss of c. 40% of suitable habitats at the *laissez-faire* scenario (see figure 8 below). For the Baltic alone, the projected loss is even more dramatic with less than a third of the nurseries preserved.

A map of current modelled possible nursery areas for Flounder together with projected distribution for RCP 4.5 and 8.5 is present in appendix A. A graph showing the reduction in suitable nurseries is presented in figure 8 below.

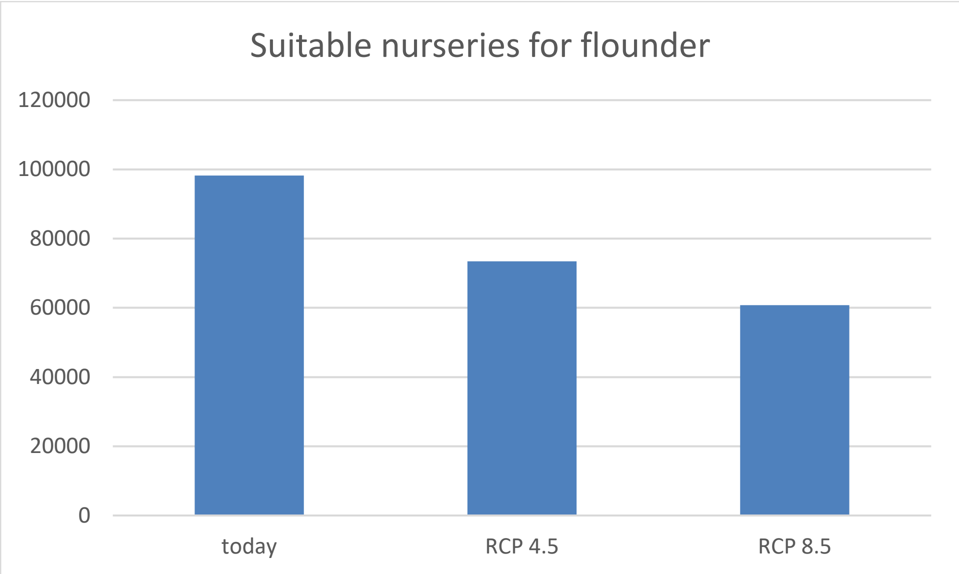


Figure 8. A simple model of suitable habitats (square kilometres) for flounder nurseries show a decline of about 40% at RCP 8.5, 25% at RCP 4.5 for the combined area of the Baltic and western Swedish/Danish waters. For the Baltic alone, the situation is modelled to become much worse.

6. Project results and conclusions

6.1. Results and recommendations

The results show that with some certainty the Baltic Sea will function quite differently in the future, when taking climate change and societal development into account, as encapsulated by the RCP 4.5 and RCP 8.5 climate model scenarios (Saraiva et al. 2019b). The area will most probably undergo drastic ecological regime shifts, which in turn will reshape the ecological basis for not only the ecological food-webs, but, as a consequence also with implications for economic, cultural and recreational ecosystem services.

In absolute terms, the area will likely experience drastic reduction in food production that relies on brackish water, e.g. cod, and perhaps some increase in functions/services/goods relying on fresh water. In any way, this implies profound changes for not only professional fishery but also leisure fishing, recreation and tourism. One example is the loss of water filtration services offered by blue mussels that can affect water quality and with cascading effects causing loss of e.g. fish and seabirds (through loss of macroalgae, loss of fish and mussels), which will reduce the experienced environmental quality. Other examples are the loss of macrophytes like *Fucus* spp. And *Zostera marina* which act as foundation species and form habitats for many associated species, including juvenile fish.

To be able to plan actions for environmental protection and to some extent to mitigate adverse effects of climate change, it would most be effective to analyze likely future hotspots for biodiversity and ecosystem services and to protect, restore and develop these, using local measures and careful marine spatial planning. A starting point for such planning and mitigation efforts would be to produce detailed predictions of future distribution and strength (modelled abundance and connectivity strength) of all major species and habitats that are important for the ecosystem services identified in published reports (e.g. Bryhn et al. 2015, Ivarsson et al. 2017) and highly valued according to various valuation schemes such as MOSAIC (Hogfors et al. *in prep*).

6.2. Deliverables

The project har produced raster datasets in 250-meter resolution, covering the whole HELCOM/OSPAR area. Technical format is GeoTIFF (EPSG 3035) and the datasets comprise the data for the maps in appendices A–D.

6.3. Possible future improvements

To improve the model of future climate refugia, improvements could be done for the predictors, the modelling method, and the collection of species occurrence data. It is also possible to sketch future ways to use models like these and what those new areas of application would require.

Predictors and scale

As for the model predictors the following areas of improvement are deemed feasible:

- Improved substrate model, using a larger number of substrate samples from nations other than Sweden, from which data is readily available.
- Improved salinity model with greater accuracy in the complex archipelagoes / coastal zones.
- Improved model of the photic zone using temporally and spatially high-resolution data on Secchi depth from Copernicus.
- A careful selection of predictors describing nutrients and/or trends in nutrient load, based on an evaluation of applicability, as training data (observations) and impact from nutrients must be correlated in time to be meaningful in the modelling process.

An urgent area of development is nutrient load water quality. As these determinants are volatile, any modelling needs to consider the concurrency of species samples and environmental conditions. It would perhaps be possible to use short-term trends in environmental status to get model results for future broad-scale effects of changes in water quality and nutrient load. From the Copernicus data archive, datasets showing forecasts and hindcasts of nutrients (NH4, PO3, Chl, NO3) can be used both to try to find relevant biota samples correlating with nutrient load, and to calculate local trends that may correlate with local presence or absence of species and habitats.

Concerning the selection of predictors, a study of the dependencies between predictors (collinearity) and a careful removal of some predictors that introduce over-estimation or overfitting could give better models. This is a general challenge when modelling marine environments as a few variables, mainly depth and wave exposure, heavily affect all others. A simple approach to identify collinearity among explanatory variables is the use of variance inflation factors (VIF).

Lastly, the scale of geographic units (pixels) greatly affects the results of the model and its usability. As each cell receives some sort of mean or median value of features inherent to the pixel, it is not obvious that this average value is representative of actual features at the location. For instance, bathymetry values within a rocky and steep cell of large size, in this case 250 m, can vary considerably, sometimes over 50 meters, while the mean value of such a cell might suggest a relatively shallow area suitable for shallow water habitats. To mitigate this possible source of error, it is imperative to introduce predictors that captures each cell's characteristics. In this example, a slope or rugosity layer would help the modelling algorithm to discern the pixel from real shallow habitats. In this context, it is important to stress the fact that a large proportion of the shallow coastal zone has not been bathymetrically mapped with an adequate resolution or quality, a fact which calls for action.

Model

As for the modelling method, it would be effective to continue running the model and tuning parameters, trying different selection of modelling algorithms and parameters within the ensemble.

For species showing dependencies between each other or competition among each other, or otherwise occupy different ecological niches, relevant species models (dependent, competitive or excluding) could be tried as predictors, using what is known as JDSM, joint species distribution models (e.g. Ovaskainen & Abrego 2020).

Species samples

As the procedure to assemble presence and absence data is based on subsampling occurrence records and creating absence records from stratified random sampling and through conjecture, the actual selected samples need to be investigated to see if they are representative of actual presence/absence through relevant environmental gradients.

Usage

A plausible future development is to use the models to calculate total and regional capacity for different ecosystem services; production of biomass, nursery areas for fish, filtration capacity of mussels etc. Such applications require the model to shift from probability of presence, with or without connectivity factors, to a model of areal cover, density or biomass per area unit.

It would also be useful if the absolute predicted capacity could be compared to the total, regional and local requirements from coastal fish recruitment, filtration of nutrients etc. This, however, would require both predicted abundance/biomass as well as quantifiable ecological models.

From presence to abundance

As a last but very important point of development, future efforts should try to assess abundance (% cover, weight, species size) to better present a measure of ecological productivity. Probability of presence is an often useful but not perfect proxy for species biomass (Pearce & Boyce 2005, Gutiérrez et al. 2013). For instance, concering salinity-dependent macro algae in the Baltic, their abundance (often measuread as % cover) varies with salinity much more profoundly than the probaibility of presence.

However, data on cover, weight or other measure of abundance is scarce compared to presence-only data.

7. References

Ahtiainen, H. & Öhman, M.C. 2014. *Ecosystem Services in the Baltic Sea: Valuation of Marine and Coastal Ecosystem Services in the Baltic Sea*. Nordisk Ministerråd, Copenhagen.

Bryhn, A., Lindegarth, M., Bergström, L & Bergström, U. 2015. *Ekosystemtjänster från svenska hav. Status och påverkansfaktorer*. Havs- och vattenmyndighetens rapport 2015:12.

Cameron A, Askew N (2011) EUSeaMap - Preparatory Action for development and assessment of a European broad-scale seabed habitat map final report. In: *Technical appendix No 1 – Light data and thresholds*. pp Page, EMODnet.

Conversi, A., Dakos, V., Gårdmark, A., Ling, S., Folke, C., Mumby, P.J., Greene, C., Edwards, M., Bleckner, T., Casini, M., Pershing, A. & Möllmann, C. 2015. A holistic view of marine regime shifts. *Philosophical Transactions Royal Society, Series B*, 370 (5), 2013.0279.

Corell, H., Moksnes, P.O., Engqvist, A., Döös, K. & Jonsson, P.R. 2012. Depth distribution of larvae critically affects their dispersal and the efficiency of marine protected areas. *Marine Ecology Progress Series* 467:29-46.

De Vries, P. & Döös, K. 2001. Calculating Lagrangian trajectories using time-dependent velocity fields. *Journal of the Atmospheric Sciences* 18:1092-1101.

Elith, J., Kearney, M. & Phillips, S. 2010. The art of modelling range-shifting species. *Methods in Ecology & Evolution* 2010, 1, 330–342

Esfahani, M.T. 2008. *Predictive vegetation modelling: Comparison of Methods, Effects of Sampling Design and Application on Different Scales*. Diss., Friedrich-Schiller-Universität Jena.

Franklin, J. & Miller, J.A. 2009. Mapping species distributions. Cambridge university press, Cambridge.

Garpe, K. 2008. *Ecosystem services provided by the Baltic Sea and Skagerrak*. Report 5873, Naturvårdsverket, Stockholm.

Guisan, A., W. Thuiller, and N. E. Zimmermann. 2017. *Habitat suitability and distribution models*. Cambridge University Press, Cambridge.

Gustafsson, B.G., Schenk, F., Blenckner, T., Eilola, K., Meier, H.E.M., Müller-Karulis, B., Neumann, T. Ruoho-Airola, T. Savchuk, O.P. & Zorita, E. 2012. Reconstructing the Development of Baltic Sea Eutrophication 1850–2006. *Ambio* 41: 534–548.

Gutiérrez, D, Harcourt, J., Díez, S. Illán, J. & Wilson, R. 2013. Models of presence-absence estimate abundance as well as (or even better than) models of abundance: The case of the butterfly Parnassius apollo. *Landscape Ecology*. 28. 10.1007/s10980-013-9847-3.

Hammar, J. & Mattson, M. 2017. *Möjliga klimatrefugier i Östersjön baserat på två olika scenarier. Kunskapsunderlag för havsplanering*. Havs- och vattenmyndighetens rapport 2017:37.

Hammar, L., Schmidtbauer Crona, J., Kågesten, G., Hume, D., Pålsson, J., Aarsrud, M., Mattsson, D., Åberg, F., Hallberg, M. & Johansson, T. 2018. *Symphony. Integrerat planeringsstöd för statlig havsplanering utifrån en ekosystemansats*. Havs-och vattenmyndighetens rapport 2018:1

Hammar, L., Molander, S., Pålsson, J., Schmidtbauer Crona, J., Carneiro, C., Johansson, T., Hume, D., Kågesten, G., Mattsson, D., Törnqvist, O., Snowball, L., Mattsson, M., Bergström, U., Perry, D., Andersen, J. & Caldow, C. 2019. Cumulative impact assessment in support of ecosystem-based marine spatial planning. Paper submitted to Frontiers in Ecology and the Environment.

HaV 2013. *State of the Baltic Sea. Background Paper*. Havs- och vattenmyndighetens rapport 2013:4.

Helcom 2007. Toward a Baltic Sea unaffected by eutrophication. Background document to Helcom Ministerial Meeting, Krakow, Poland, Tech. Rep., Helsinki Commission, Helsinki, Finland.

Helcom 2013a. Summary report on the development of revised Maximum Allowable Inputs (MAI) and updated Country Allocated Reduction Targets (CART) of the Baltic Sea Action Plan. In: Tech. rep. (ed Commission H), Copenhagen, Denmark.

Helcom 2013b. Climate change in the Baltic Sea Area. HELCOM thematic assessment in 2013.

Helcom 2015. Updated Fifth Baltic Sea pollution load compilation (PLC-5.5). Baltic Sea Environment Proceedings 145.

Hogfors, H., Fyhr, F. & Nyström Sandman, A. *in prep*. *Mosaic – ramverk för naturvärdesbedömning i marin miljö*. Havs- och vattenmyndighetens rapport.

Hordoir, R., Axell, L., Höglund, A., Dieterich, C., Fransner, F., Gröger, M., Liu, Y., Pemberton, P., Schimanke, S., Andersson, H., Ljungemyr, P., Nygren, P., Falahat, S., Nord, A., Jönsson, A., Lake, I., Döös, K., Hieronymus, M., Dietze, H., Löptien, U., Kuznetsov, I., Westerlund, A., Tuomi, L. & Haapala, J. 2019. Nemo-Nordic 1.0: a NEMO-based ocean model for the Baltic and North seas – research and operational applications. *Geoscientific Model Development* 12:363-386.

Hurrell, J. W., & Deser, C. 2009. North Atlantic climate variability: The role of the North Atlantic Oscillation. *Journal of Marine Systems* 78:28-41.

IPCC 2013. *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley), Cambridge University Press, Cambridge & New York.

Ivarsson, M., Magnussen, K., Heiskanen, A-S., Navrud, S. & Viitasalo, M. 2017. *Ecosystem services in MSP Ecosystem services approach as a common Nordic under-standing for MSP*. Nordic Council of Ministers.

Jahnke M, Jonsson PR, Moksnes P-O, Loo L-O, Nilsson Jacobi M and Olsen JL. 2018. Seascape genetics and biophysical connectivity modelling support conservation of the seagrass *Zostera marina* in the eastern North Sea. *Evolutionary Applications* 11: 645-661.

Jonsson, P. R., Nilsson Jacobi, M. & Moksnes, P.O. 2016. How to select networks of marine protected areas for multiple species with different dispersal strategies. *Diversity and Distributions* 22:161-173.

Jonsson, P. R., Kotta, J., Andersson, H. C., Herkül, K., Virtanen, E., Nyström Sandman, A. & Johannesson, K. 2018. High climate velocity and population fragmentation may constrain range shift of the key habitat former Fucus vesiculosus in the Baltic Sea. *Diversity and Distributions* 24:892–905.

Kniebusch, M., Meier, M. & Radtke, H. 2019. Changing Salinity Gradients in the Baltic Sea As a Consequence of Altered Freshwater Budgets. Geophysical research letters 46:16, 9739-9747

Kuhn, M. & Johnson, K. 2013. Applied Predictive Modeling. Springer, New York Heidelberg Dordrecht London.

Ovaskainen, O. & Abrego, N. 2020. *Joint Species Distribution Modelling with Applications in R*. Cambridge University Press.

Pearce, J.L. & Boyce, M.S. 2005. Modelling distribution and abundance with presence-only data. Journal of Applied Ecology. 43:3, 405–412.

Pearson, R. & Dawson, T.P. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology & Biogeography* (2003) 12, 361–371

Meier, H.E.M., Dietrich, C., Eilola, K. Gröger, M., Höglund, A., Saraiva, S. & Wåhlström, I. 2019. Future projections of record-breaking sea surface temperature and cyanobacteria bloom events in the Baltic Sea. *Ambio* 48:11, 1362–1376.

Reiss, H., Cunze, S., König, K., Neumann, H. & Kröncke, I. 2011. Species distribution modelling of marine benthos: A North Sea case study. *Marine Ecology Progress Series*. 442. 71. 10.3354/meps09391.

Roberts, D.R. & Hamann, A. Predicting potential climate change impacts with bioclimate envelope models: a palaeoecological perspective. *Global Ecology and Biogeography* (2012) 21, 121–133.

Saraiva, S., Meier, M., Andersson, H., Höglund, A., Dieterich, C., Gröger, M, Hordoir, R. & Eilola, K. 2019b. Uncertainties in Projections of the Baltic Sea Ecosystem Driven by an Ensemble of Global Climate Models. *Frontiers in earth science* 6, DOI: 10.3389/feart.2018.00244.

Saraiva, S., Meier, M., Andersson, H., Höglund, A., Dieterich, C., Gröger, M., Hordoir,R. & Eilola, K. 2019b. Baltic Sea ecosystem response to various nutrient load scenarios in present and future climates. *Climate Dynamics* 52:3369-3387.

Saupe, E.E., Barve, V., Myers, C.E., Soberón, J., Barve, N., Hensz, C.M., Peterson, A.t., Owens, H.L. & Lira-Noriega, A. 2012. Variation in niche and distribution model performance: The need for a priori assessment of key causal factors. Ecological Modelling Volumes 237–238, 10 July 2012, 11-22.

Savchuk, O.P., Eilola, K., Gustafsson, B.G., Rodriguez Medina, M. & Ruoho-Airola, T. 2012. Long-term reconstruction of nutrient loads to the Baltic Sea 1850-2006. Baltic Nest Institute Technical report 6:9. www.balticnest.org

Shabani, F., Kumar, L. & Ahmadi, M. 2016. A comparison of absolute performance of different correlative and mechanistic species distribution models in an independent area. *Ecology and Evolution* 2016; 6(16): 5973–5986.

Tarkesh, M. & Jetschke, G. 2012. Comparison of six correlative models in predictive vegetation mapping on a local scale. *Environ Ecol Stat* (2012) 19:437–457.

Uppala, S. M., Källberg, P. W., Simmons, A. J., Andrae, U., Da Costa Bechtold, V., Fiorino, M. Gibson, J. K., Haseler, J., Hernandez, A., X. Li, K. G.A., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Chevallier, C. S. F., Dethof, A., Dragosavac, M., Fisher, M. Fuentes, M., Hagemann, S., Holm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., Mcnally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Saunders, R. W., Simon, P., Ster, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P. & Woollen, J. 2005. The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society* 131:2961-3012.

Vuorinen, I., Häninnen, J., Rajasilta, M., Laine, P., Eklund, J., Montesino-Pouzols, F., Corona, F., Junker K., Meier, H.E.M., Dippner, J.W. (2015) Scenario simulations of future salinity and ecological consequences in the Baltic Sea and adjacent North Sea areas - implications for environmental monitoring. *Ecological Indicators*, 50, 196-205.

Watson, J. R., Mitarai, S., Siegel, D. A., Caselle, J. E., Dong, C. & McWilliams, J. C. 2010. Realized and potential larval connectivity in the Southern California Bight. *Marine Ecology Progress Series* 401:31-48.

Wijkmark, N. & Isæus M. 2010: *Wave exposure calculations for the Baltic Sea*, AquaBiota Report 2010:02. AquaBiota water research.

Appendix A: GIS-based modelled current and future habitats for select species and habitats

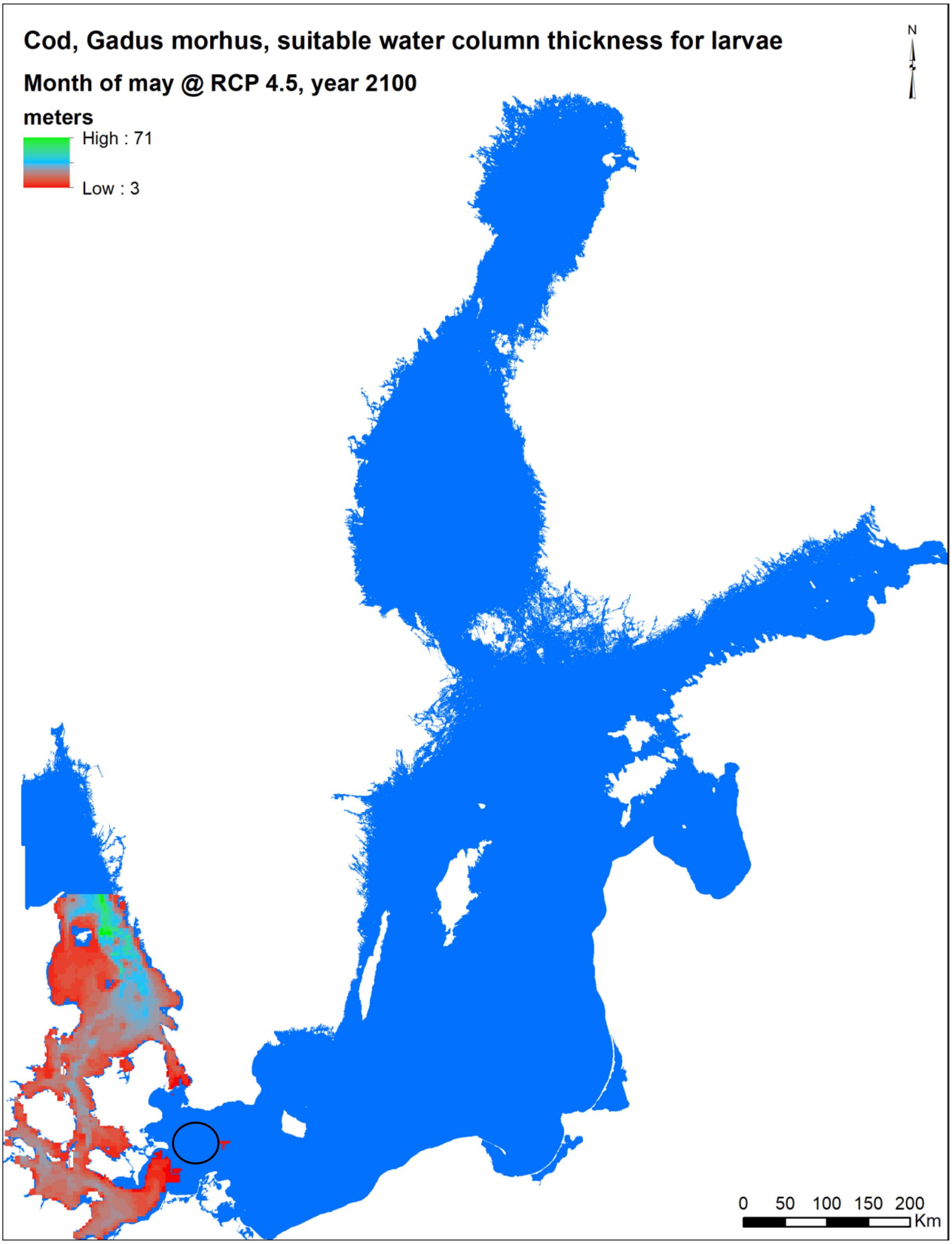


Figure 9. Modelled suitable nursery areas for cod based on salinity and oxygen, shows that the eastern stock of cod will most probably not breed even at RCP 4.5 in year 2100, as the area (encircled) of suitable habitat is very small and the factual conditions will vary, with probable periods of anoxia and insufficient sainity.

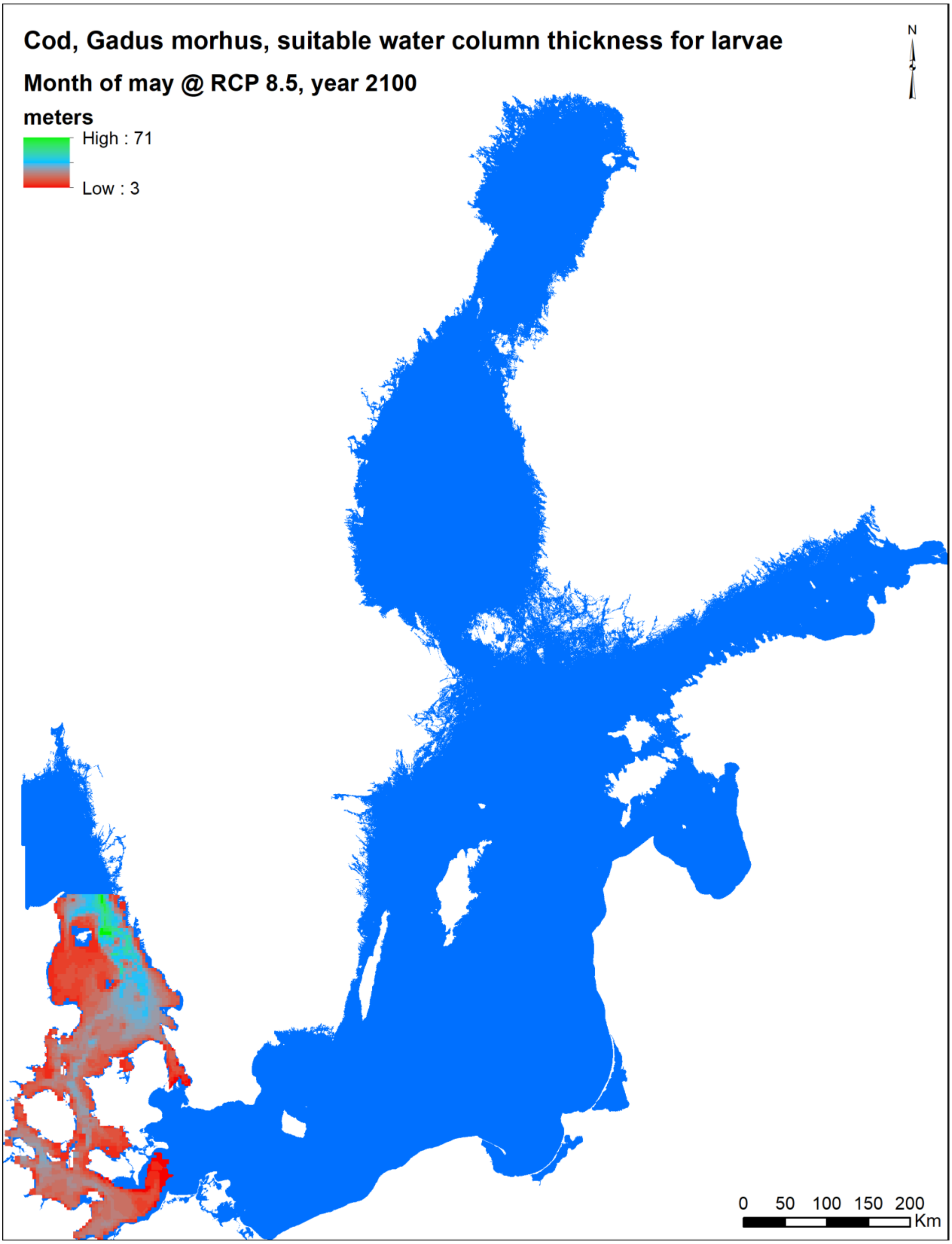


Figure 10. Modelled suitable nursery areas for cod based on salinity and oxygen, shows that the eastern stock of cod will most probably not breed at all in the Baltic at RCP 8.5 in year 2100.

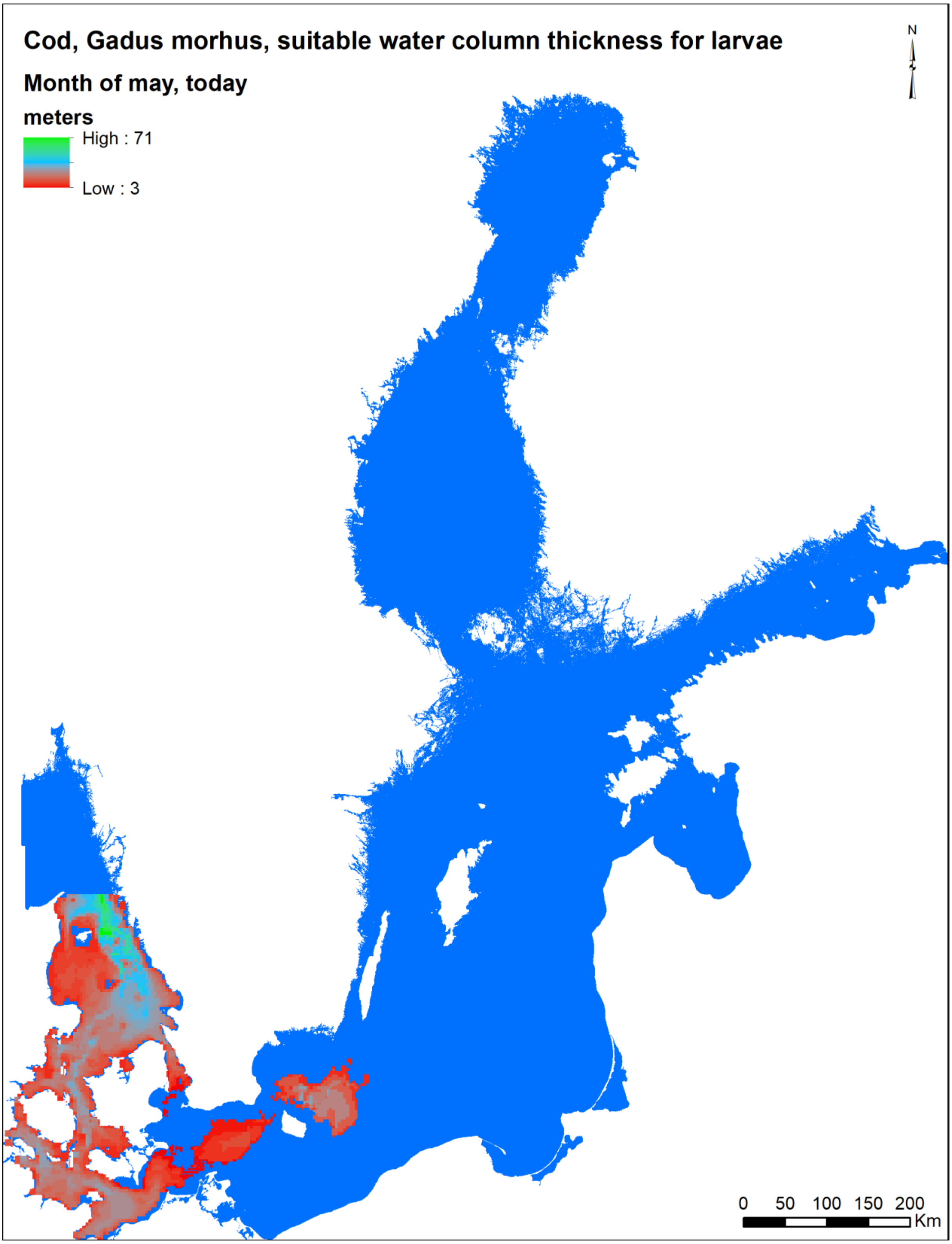


Figure 11. A model of suitable habitats for cod with sufficient salinity and oxygen today shows that the eastern stock of cod should be able to breed in large portions of the southwestern Baltic, even though only the area northeast of Bornholm has a deeper/taller water column, often reaching 15 – 25 meters. Comparing this model with the previous two, for RCP 4.5 and RCP 8.5 spectively, shows decisive differences.

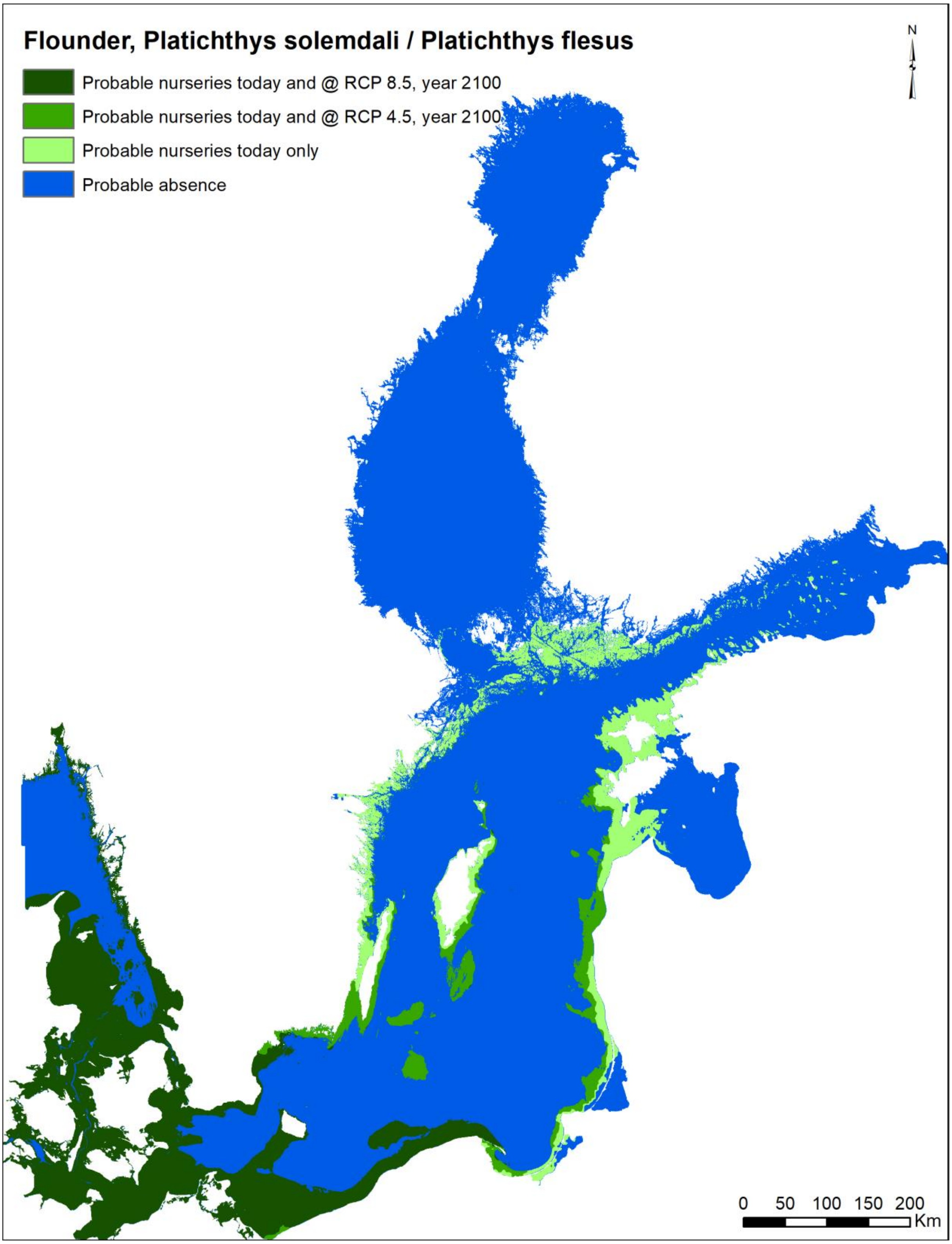


Figure 12. Modelled suitable nurseries for flounder, purely based on salinity and bathymetry, shows how the species will retreat to the southwest for RCP 4.5 and RCP 8.5.

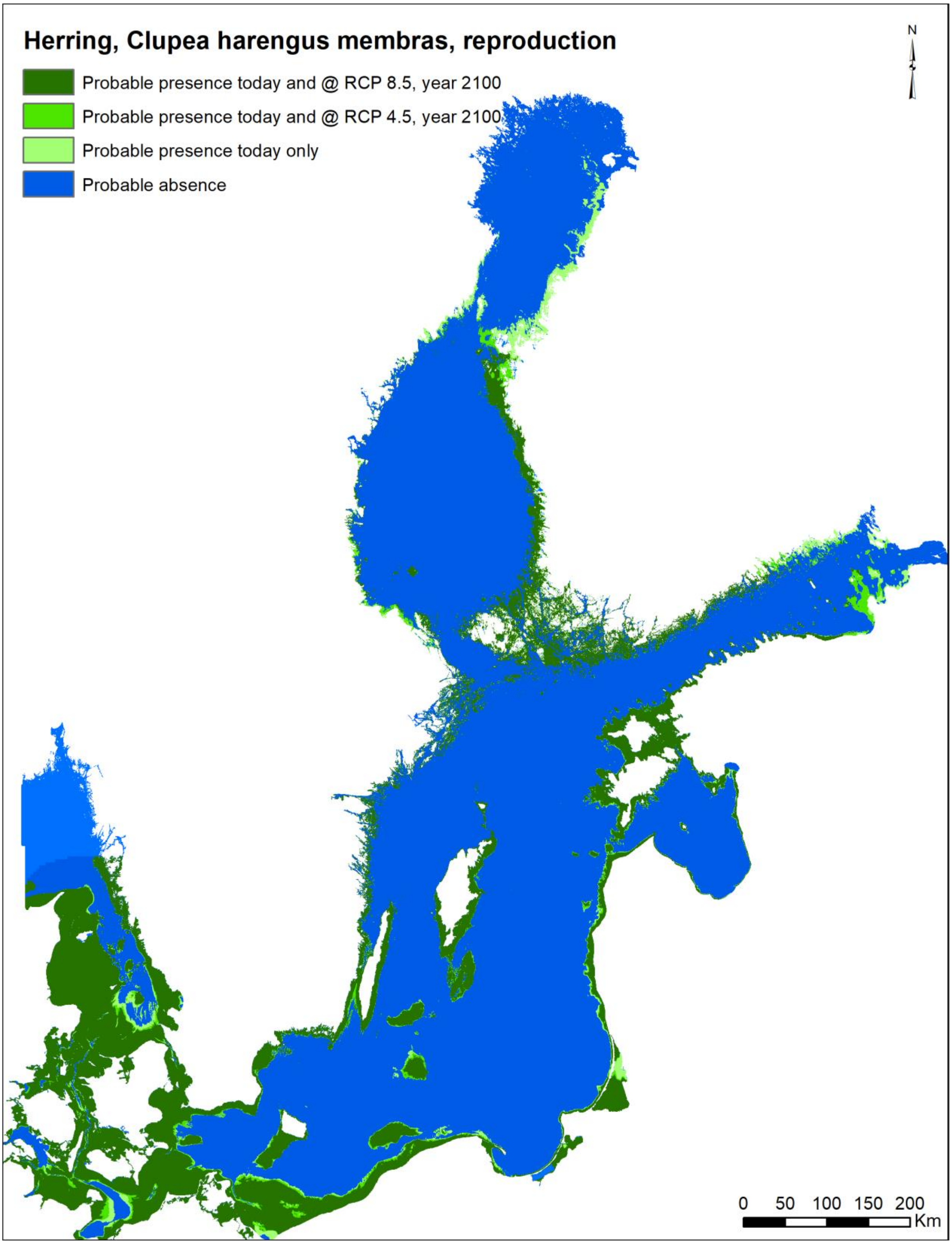


Figure 13. Modelled suitable habitats for the reproduction of herring, based on seabed substrate, salinity, photic zone and oxygen levels show that the species will probably disappear from the Bothnian Bay and easternmost pasrt of the Gulf of Finland at RCP 4.5. At RCP 8.5 the species will disappear from Kvarken and long the western paart of the Bothnian Bay. The species will also avoid the deeper portions of the current habitats, most notably in the southern Baltic.

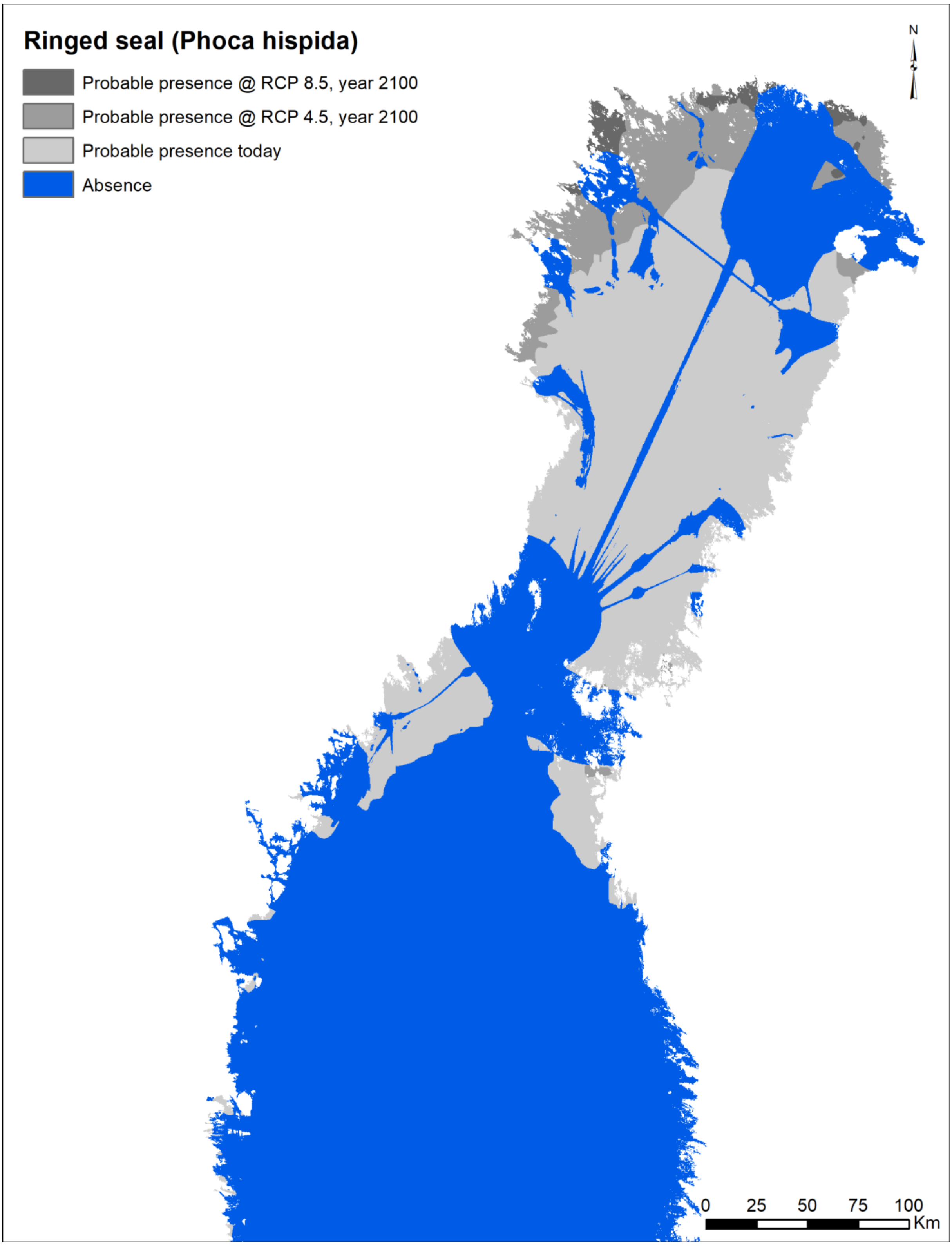


Figure 14. The modelled habitat of the ringed seal based on sea ice and noise and disturbance from maritime traffic shows that today, suitable ice sheets are often available down to Kvarken whereas at RCP 4.5 The area retreats to the north and northwest with focus on the archipelagoes of Norrbotten. At RCP 8.5 there are only a handful of areas near the coast where ice forms to a required degree.

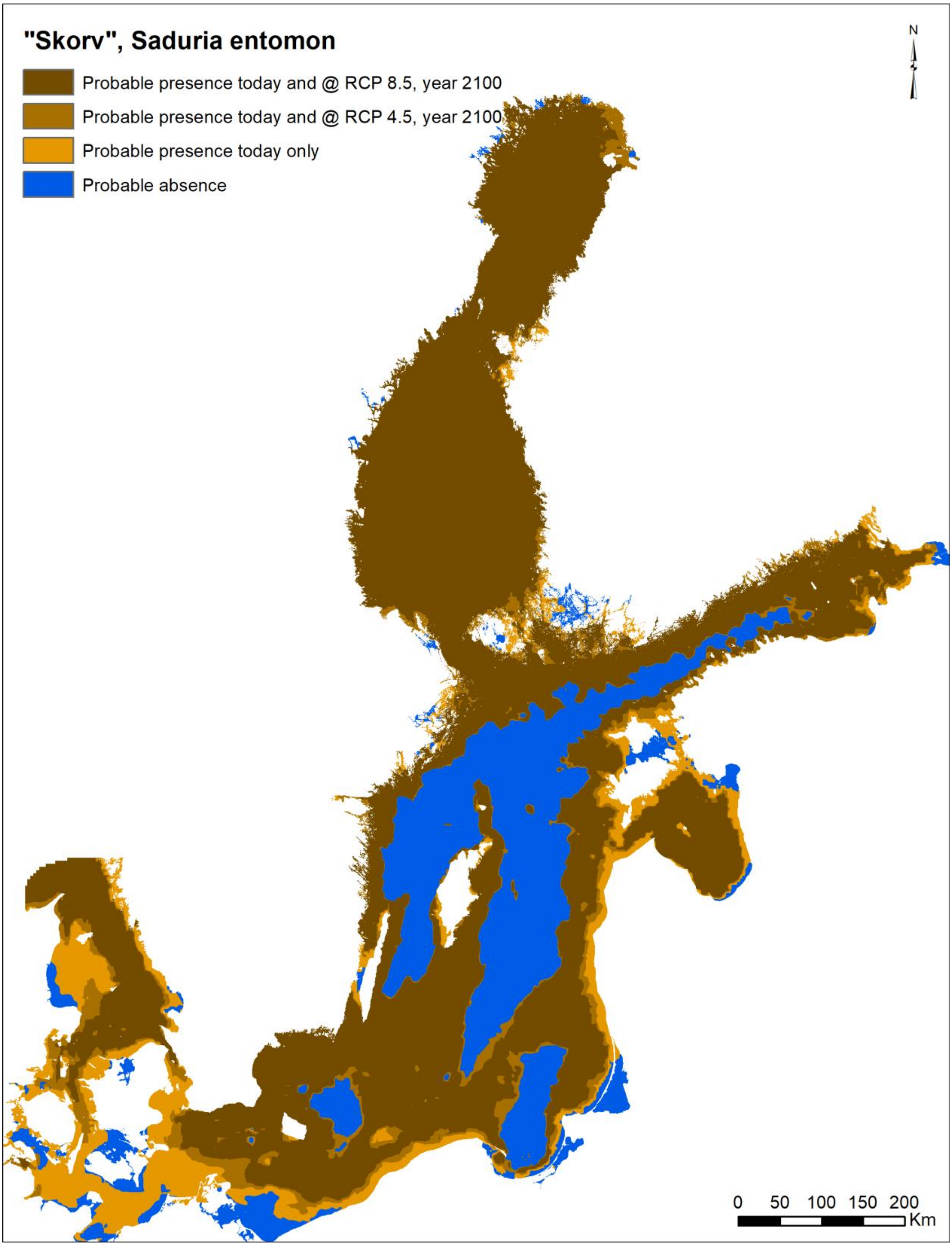


Figure 15. Skorv. Based on summer temperature at the seabed, seabed substrates and bottom oxygen, the skorv is predicted to disappear from mainly the southwesterns and eastern coasts of the Baltic, and the archipelago seas.

Appendix B: Ensemble modelling of current and future key foundation species

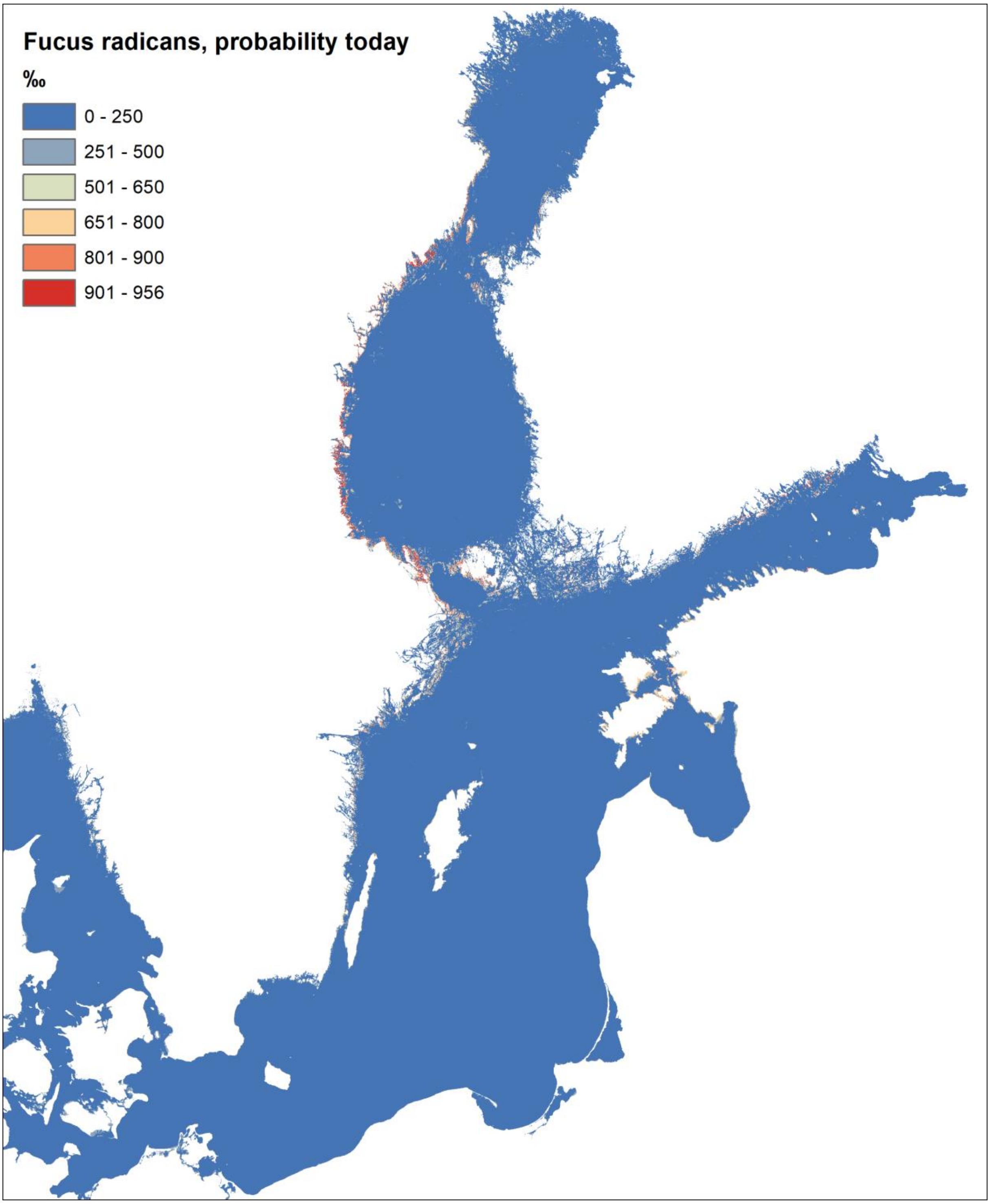


Figure 16. Modelled habitat suitability for *Fucus radicans*, today. Note the concentration on the west coast of the Bothnian sea.

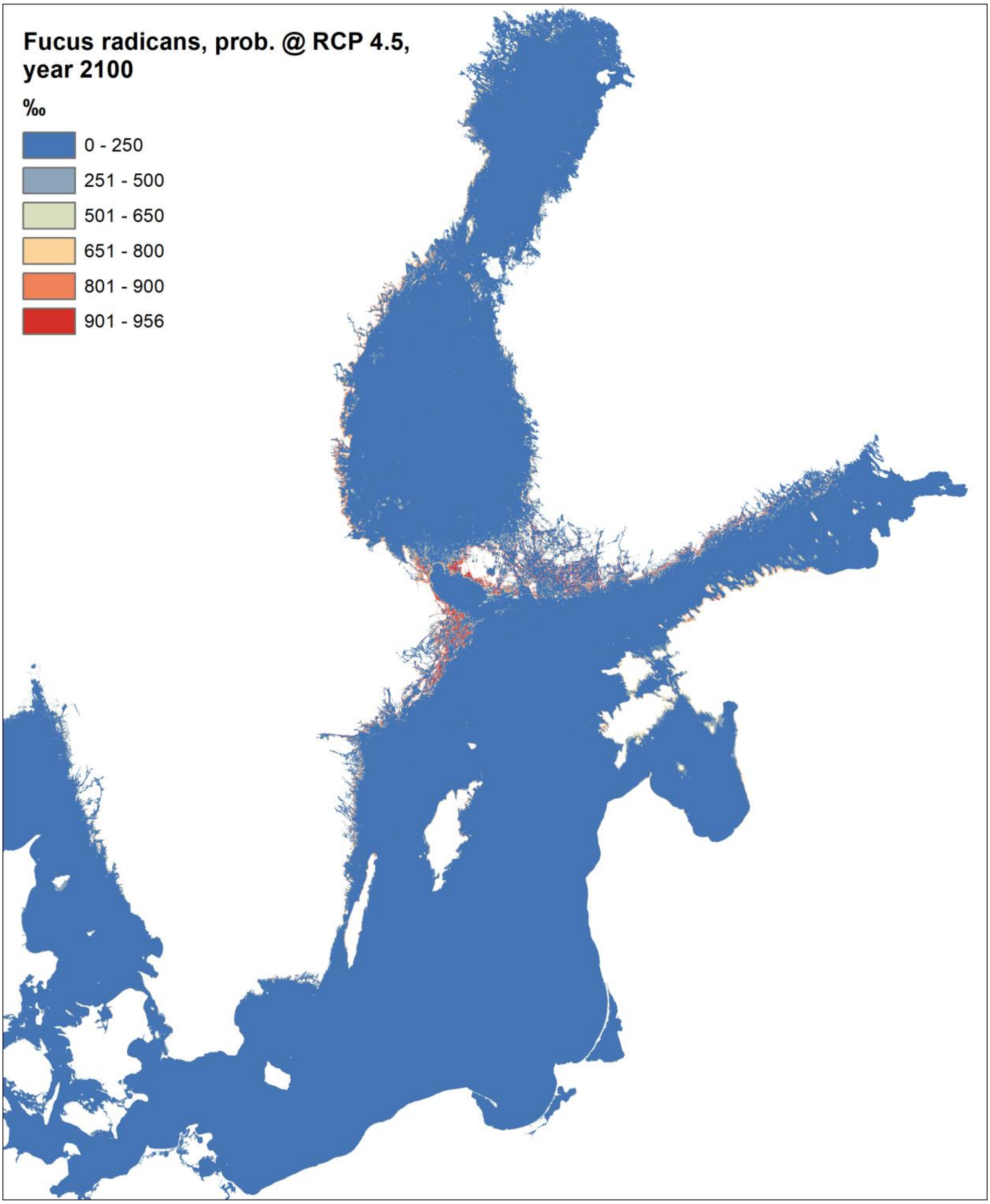


Figure 17. Modelled habitat suitability for *Fucus radicans*, given the climate scenario RCP 4.5, by the year 2100. Note the concentration in the central archiepelago sea.

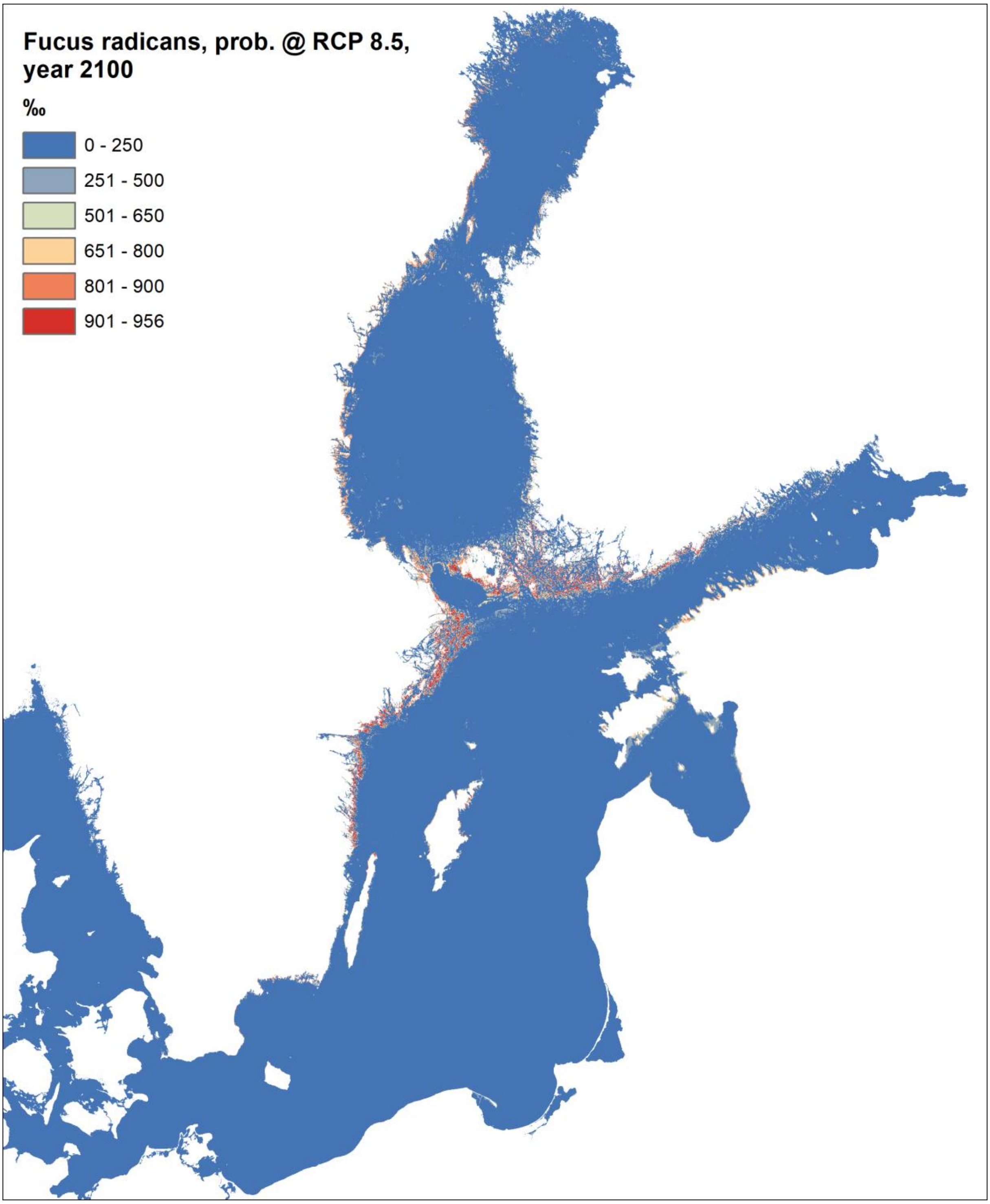


Figure 18. Modelled habitat suitability for *Fucus radicans*, given the climate scenario RCP 8.5, by the year 2100. Note the concentration in finnish and southern archiepelago seas.

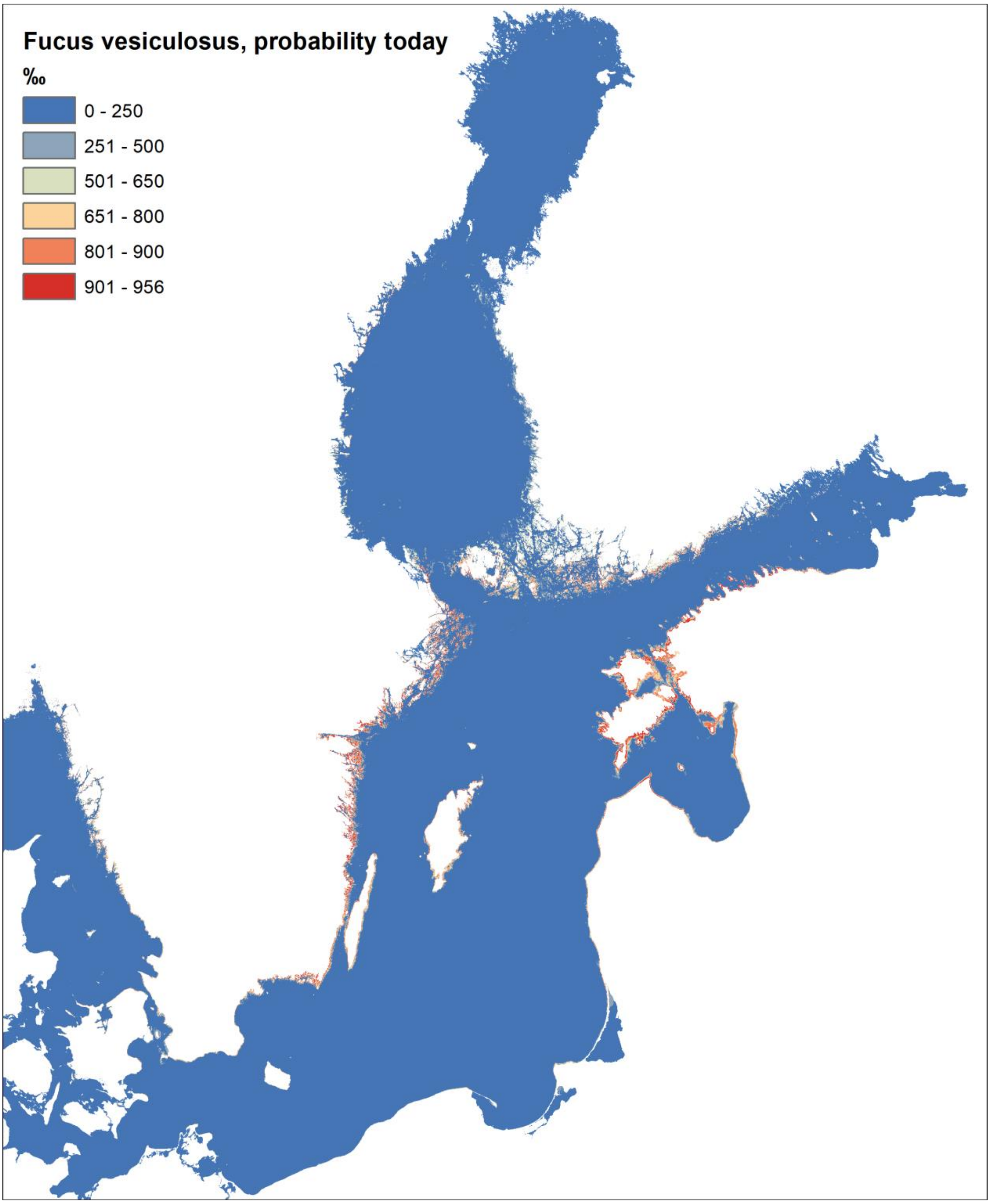


Figure 19. Modelled habitat suitability for *Fucus vesiculosus*, today. Note the concentration in the Baltic proper and in Estonia.

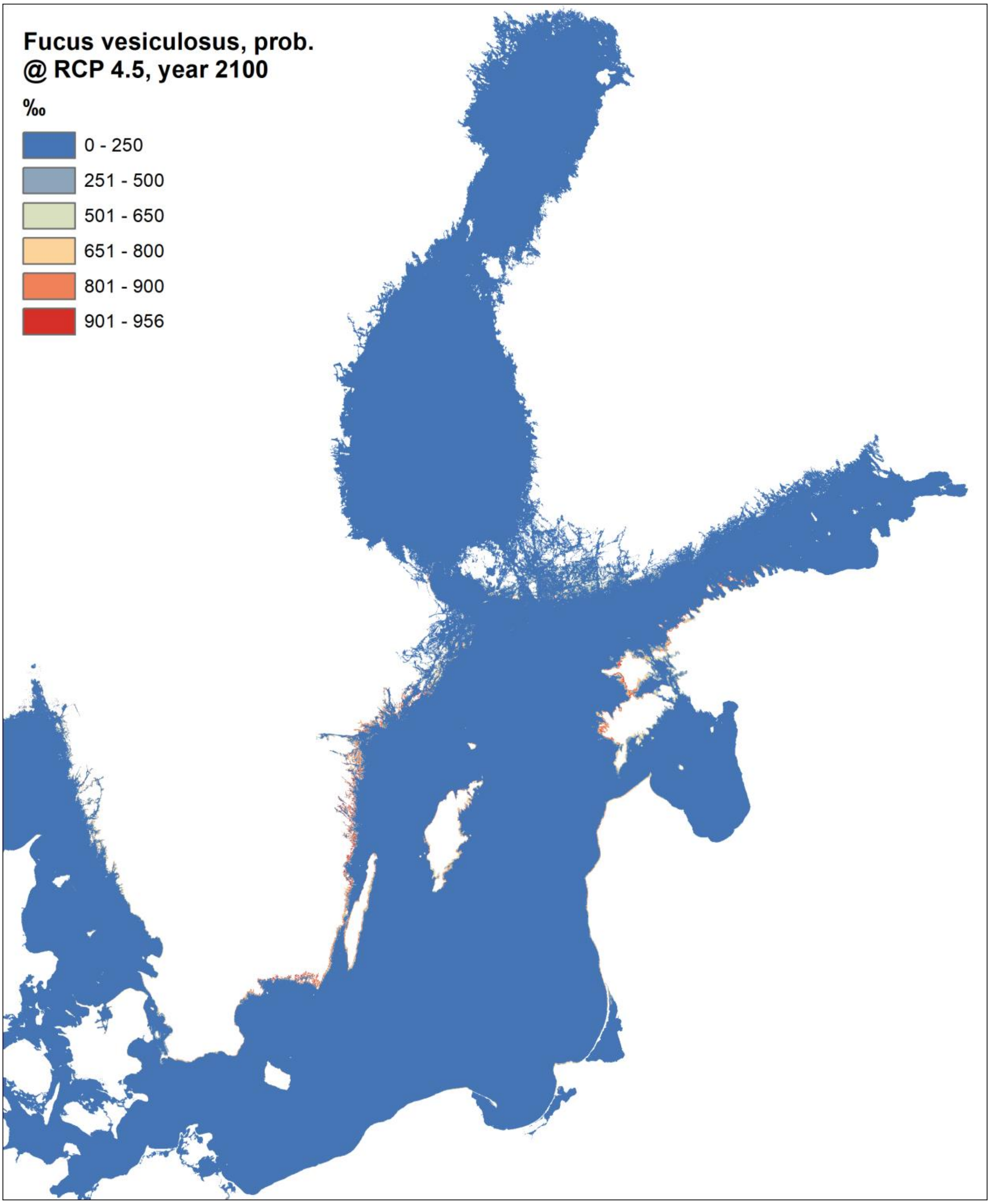


Figure 20. Modelled habitat suitability for *Fucus vesiculosus*, given the climate scenario RCP 4.5, by the year 2100. Note the concentration along the western coast of the Baltic proper and in western Estonia.

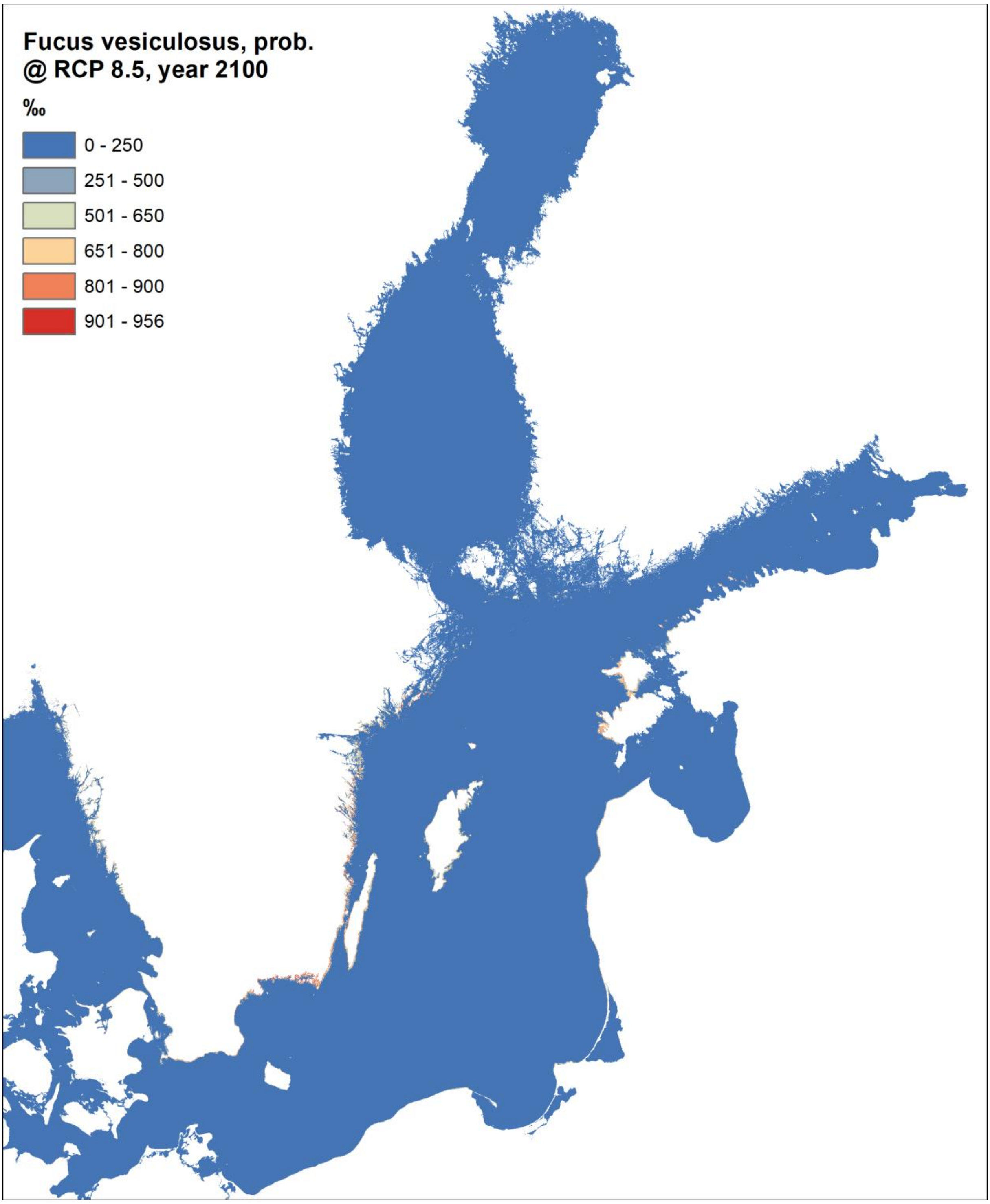


Figure 21. Modelled habitat suitability for *Fucus vesiculosus*, given the climate scenario RCP 8.5, by the year 2100. Note the concentration along the south/western coast of the Baltic proper.

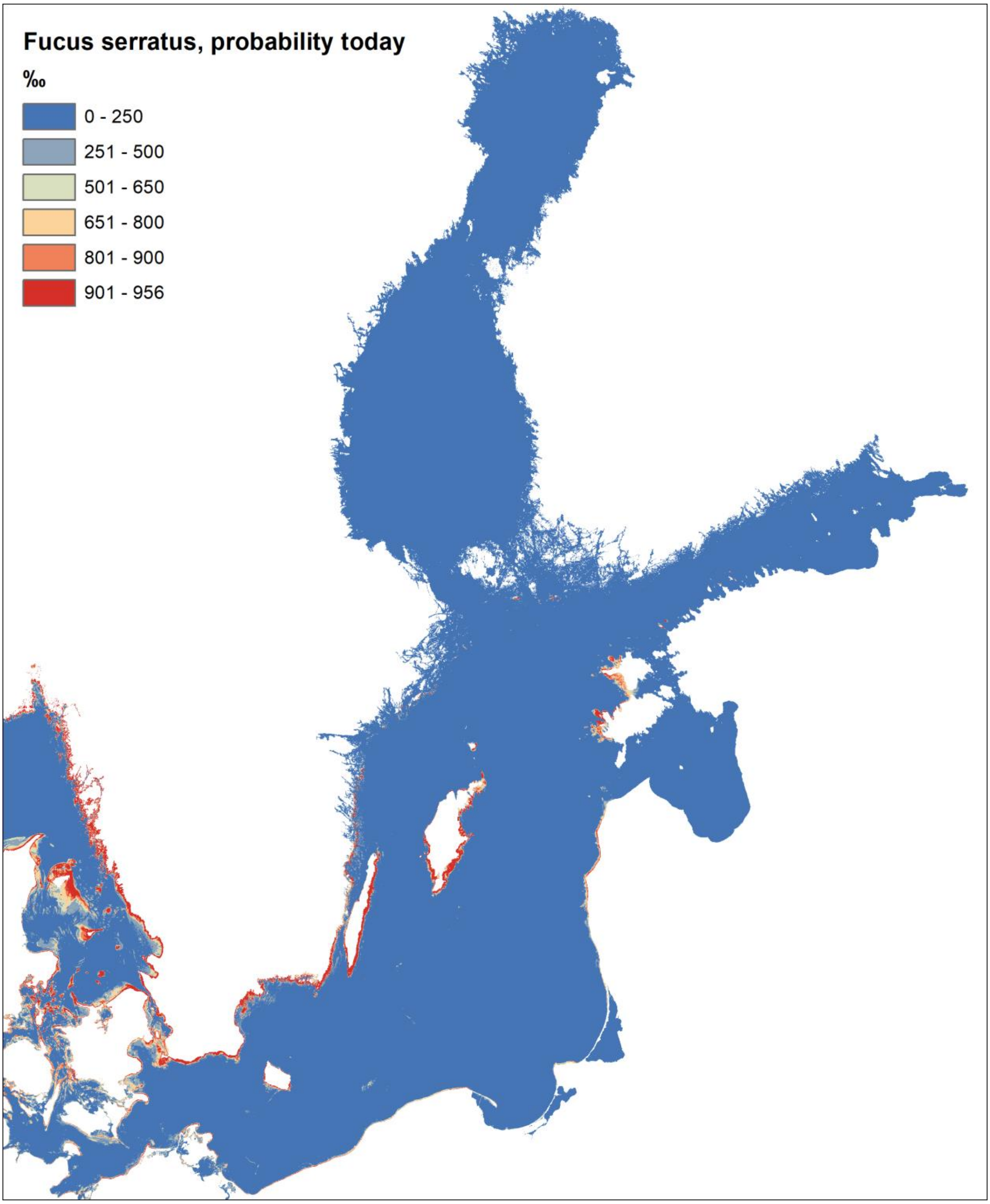


Figure 22. Modelled habitat suitability for *Fucus serratus*, today. Note the concentration in the central Baltic proper and further to the southwest.

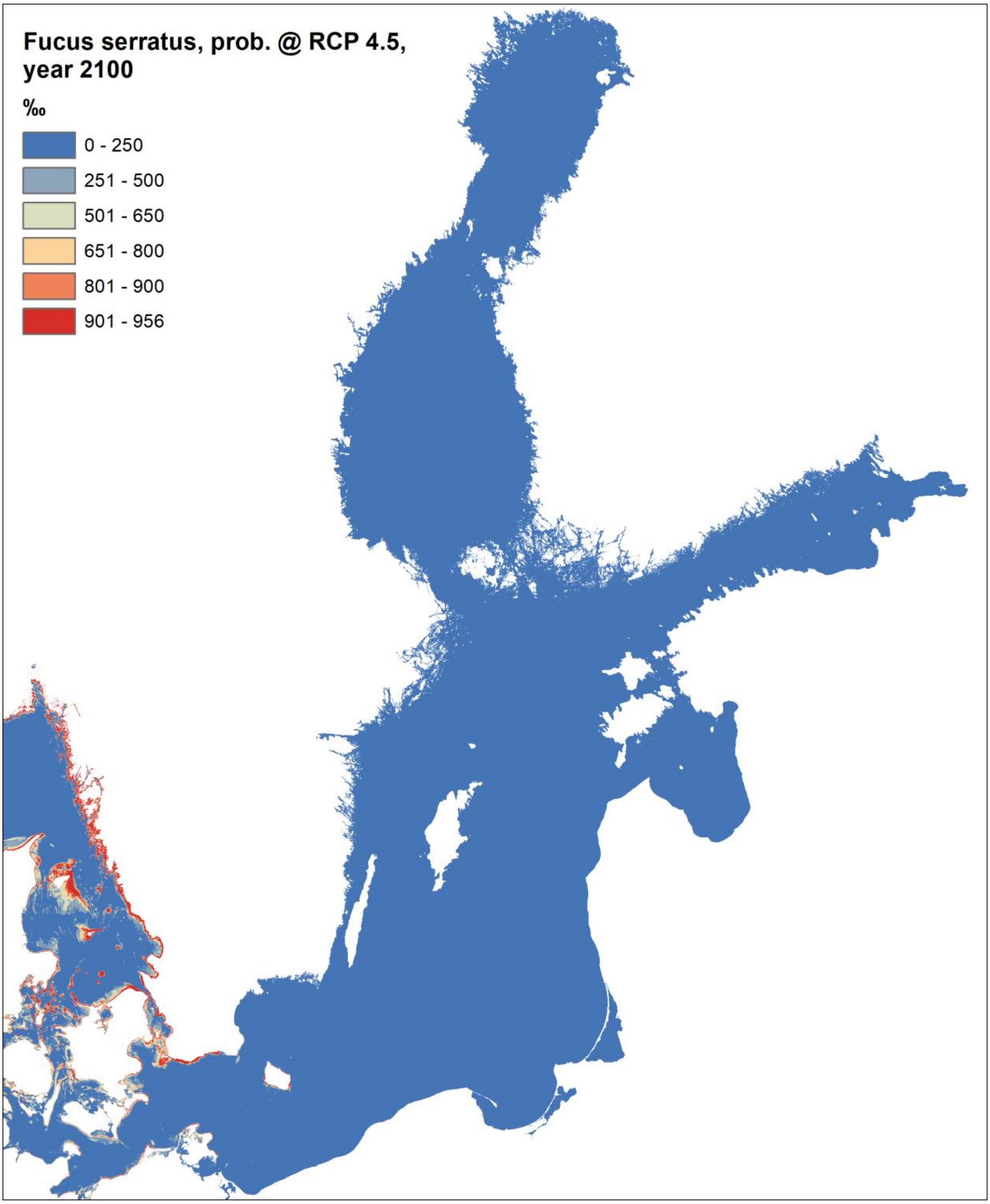


Figure 23. Modelled habitat suitability for *Fucus serratus*, given the climate scenario RCP 4.5, by the year 2100. Note the concentration along the southern coast of Skåne, Kattegatt and further to the west.

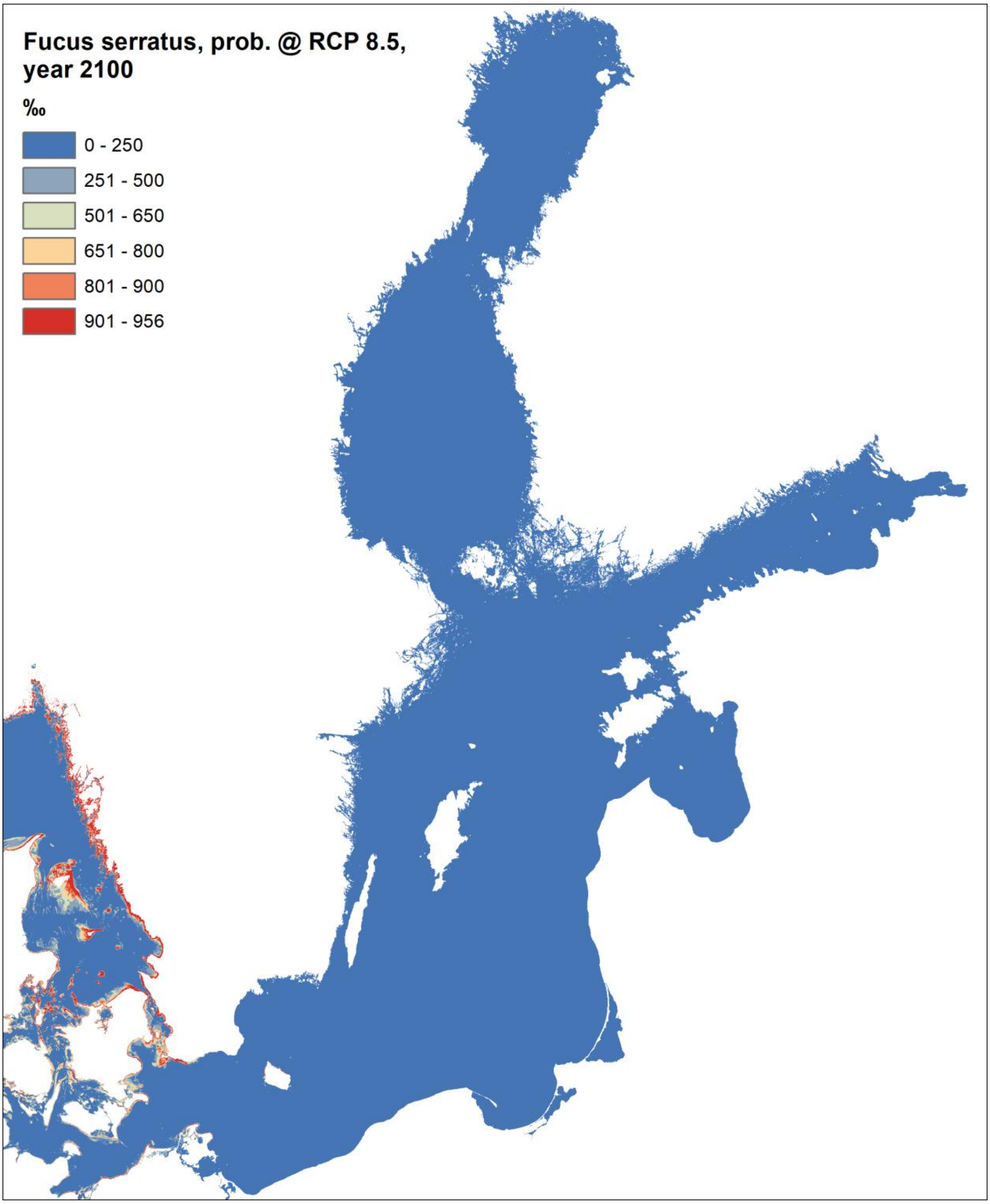


Figure 24. Modelled habitat suitability for *Fucus serratus*, given the climate scenario RCP 8.5, by the year 2100. Note the concentration in Kattegatt and further to the west.

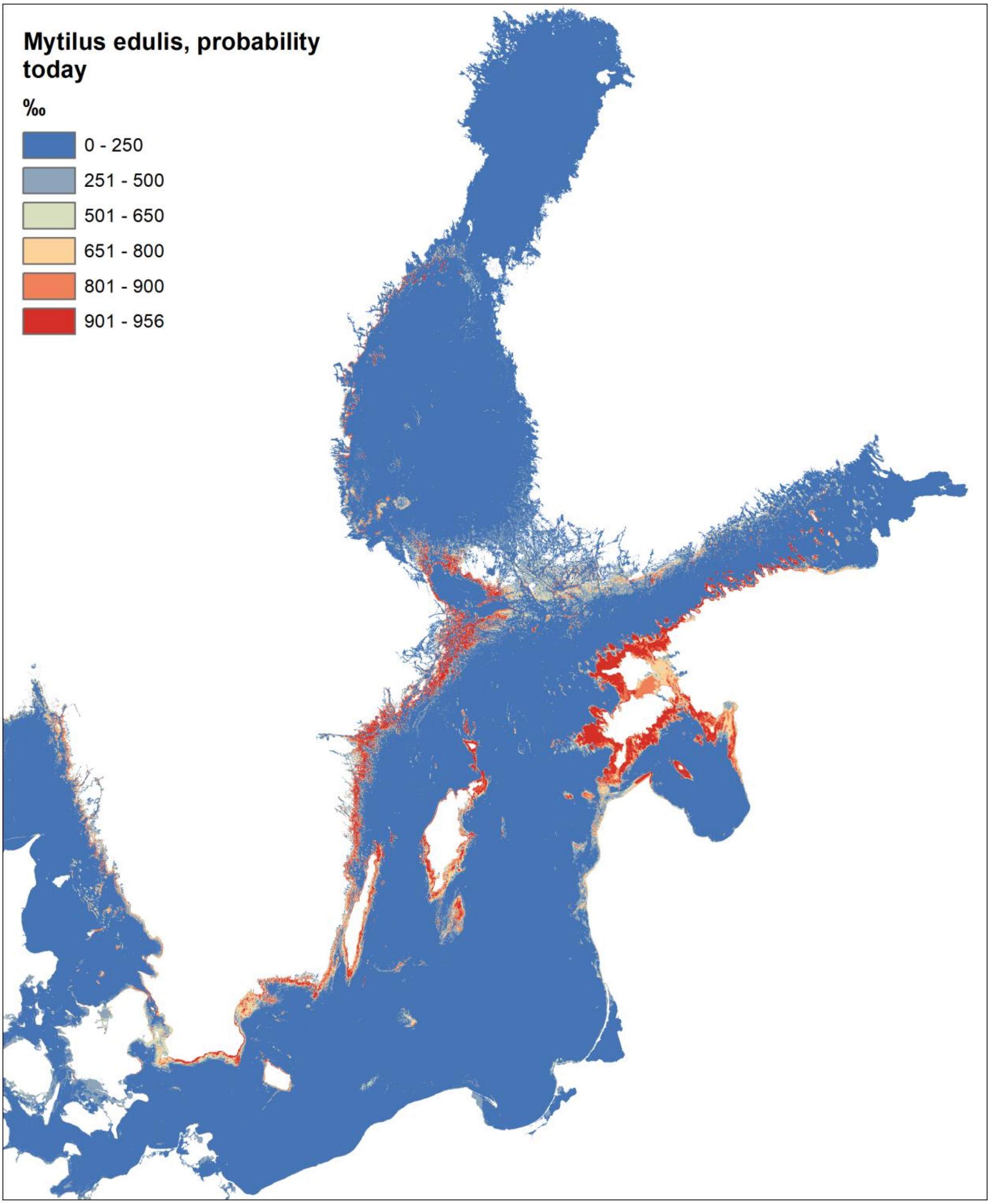


Figure 25. Modelled habitat suitability for *Mytilus edulis/trossulus* today. Note the concentration in the central Baltic proper.

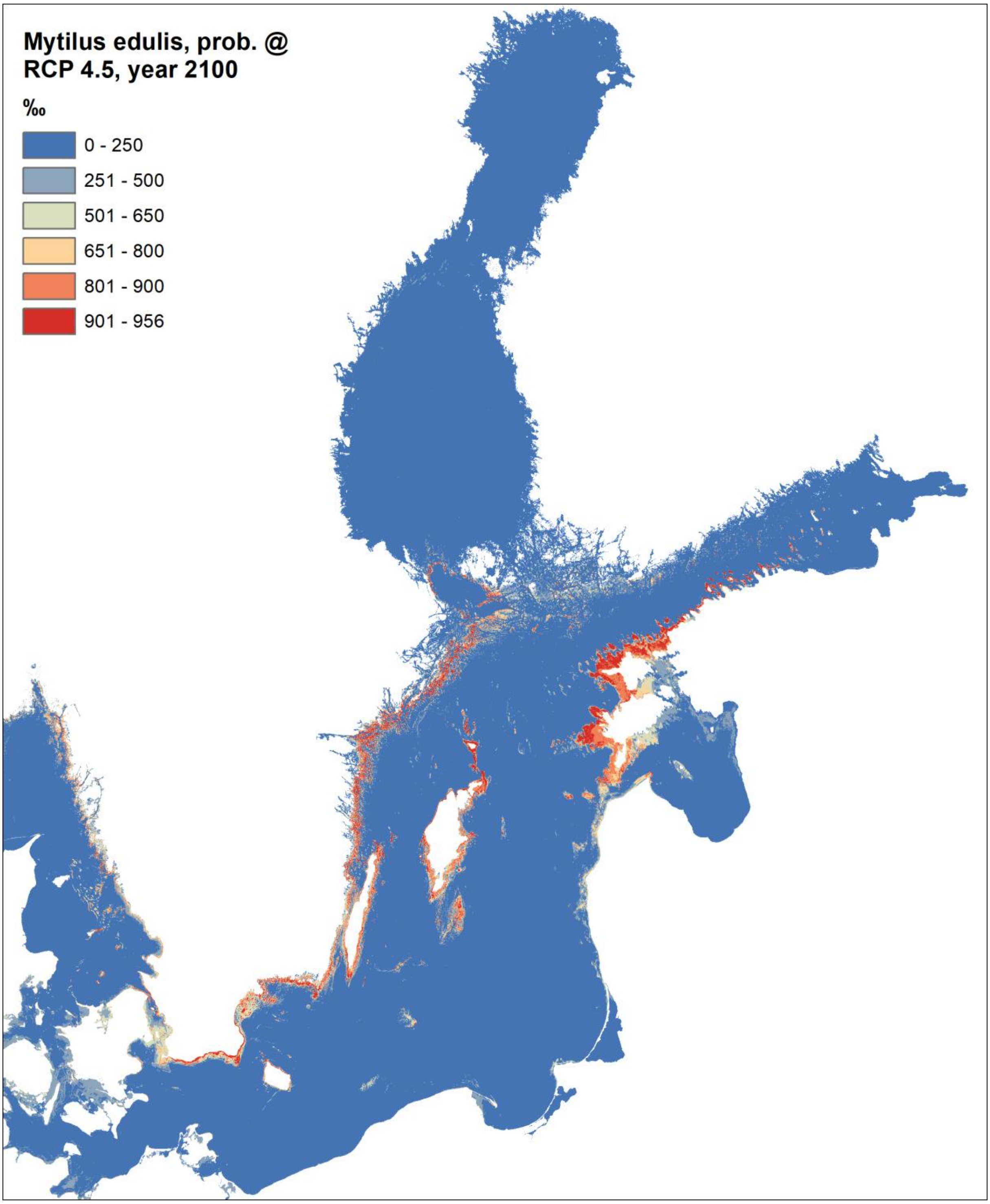


Figure 26. Modelled habitat suitability for *Mytilus edulis/trossulus*, given the climate scenario RCP 4.5, by the year 2100. Note reduction at northern and eastern limits.

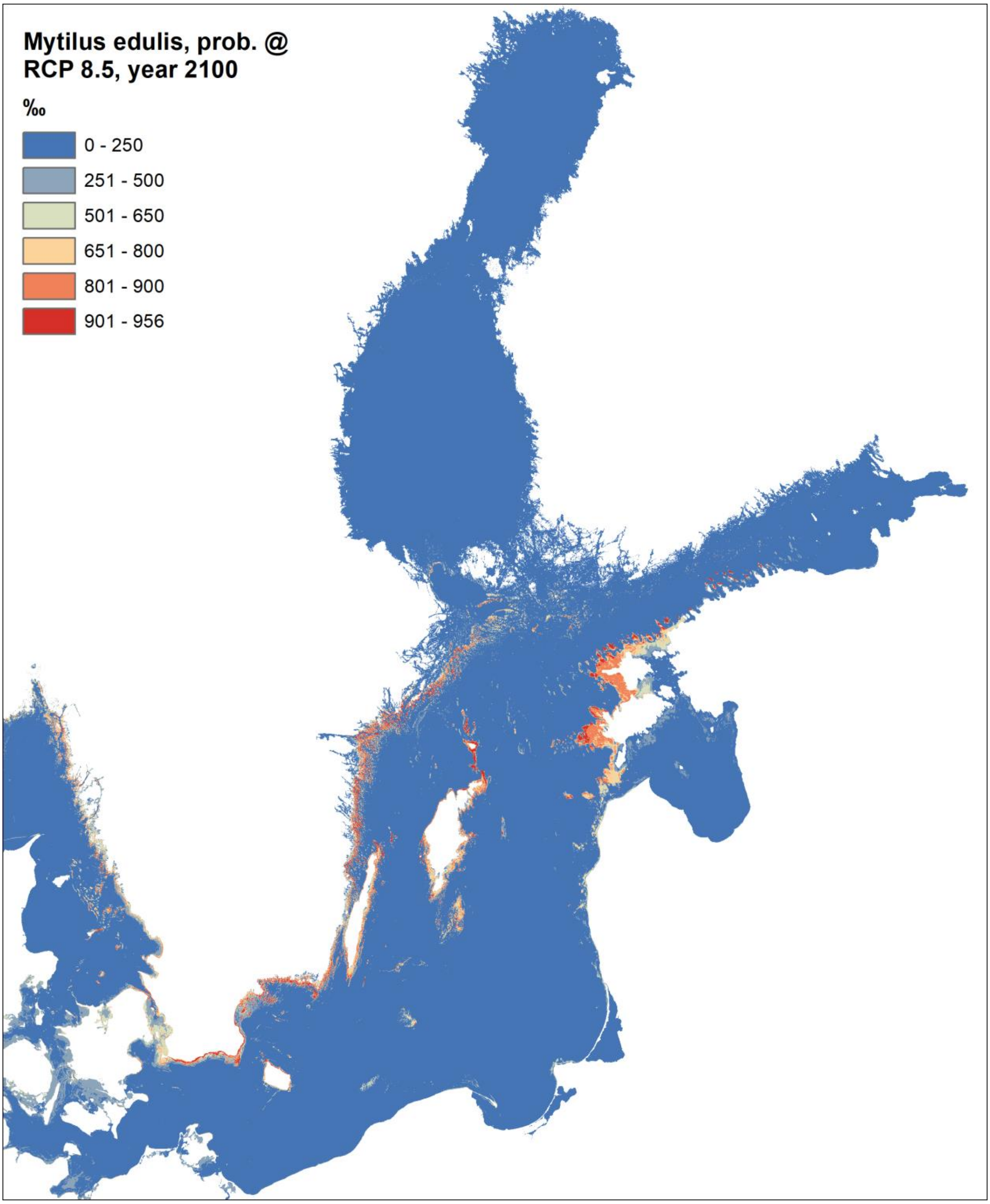


Figure 27. Modelled habitat suitability for *Mytilus edulis/trossulus*, today, given the climate scenario RCP 8.5, by the year 2100. Note severe reduction at northern and eastern limits.

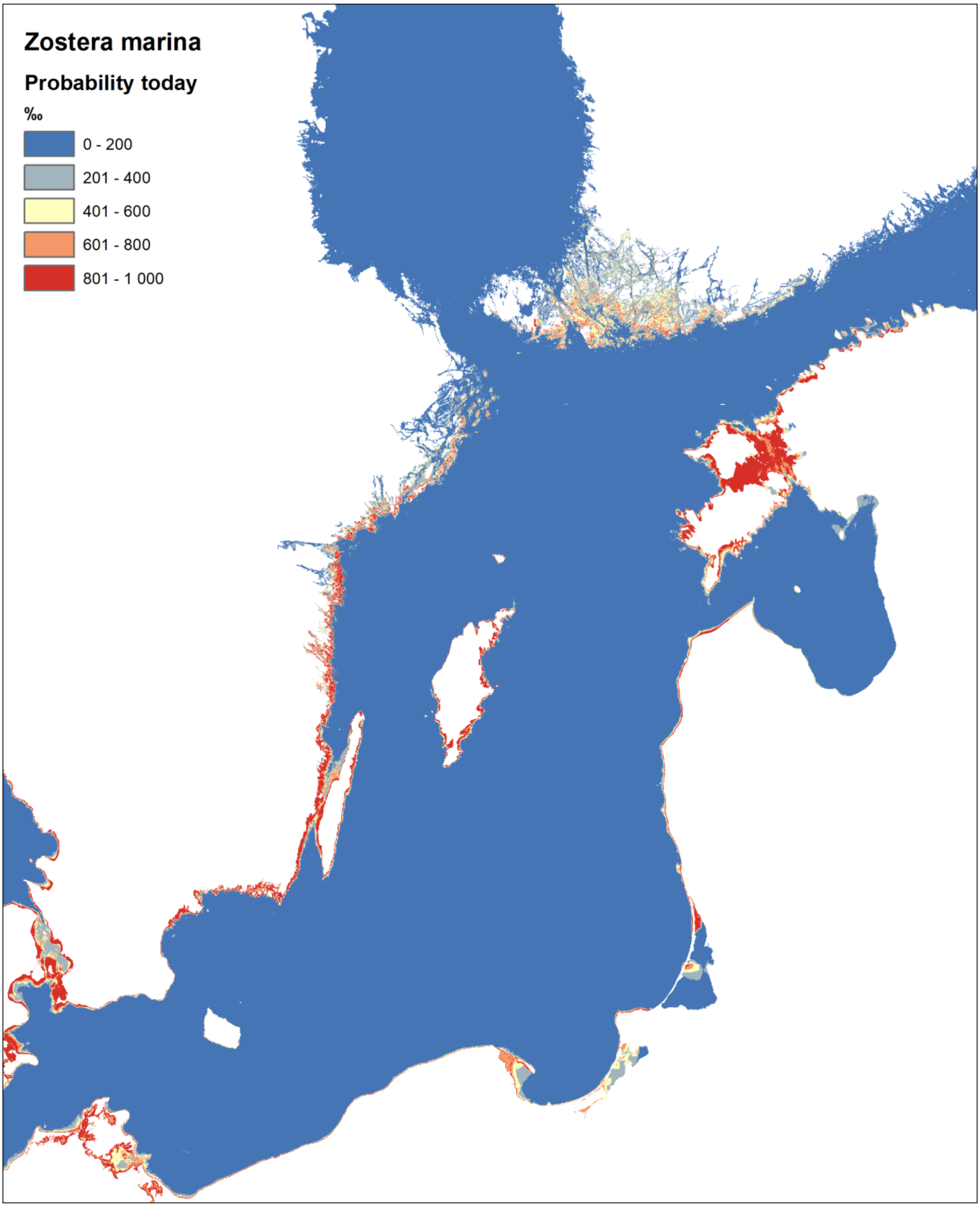


Figure 28. Modelled habitat suitability for *Zostera marina*, today.

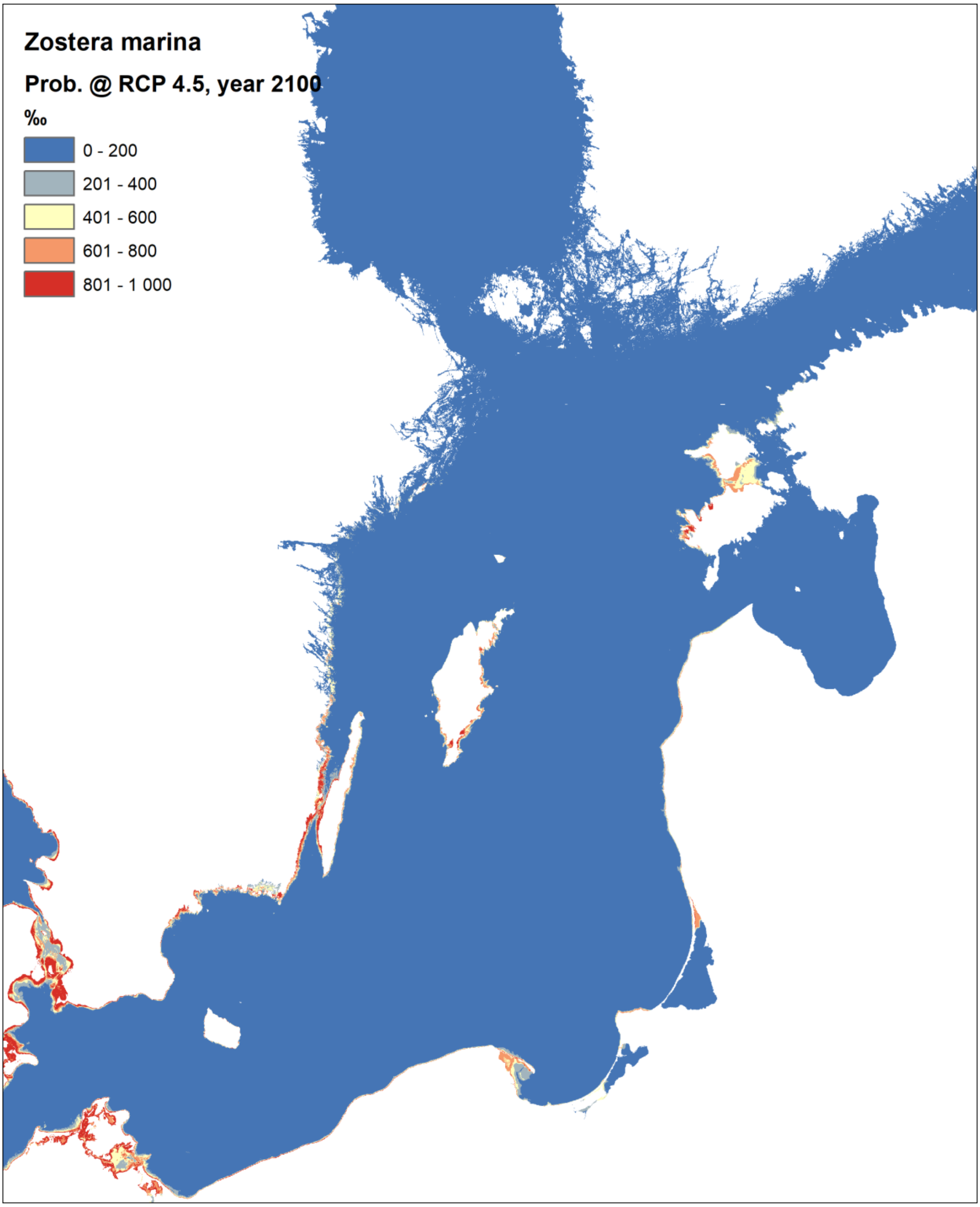


Figure 29. Modelled habitat suitability for *Zostera marina*, given the climate scenario RCP 4.5, by the year 2100. Note reduction in the central and Baltic and Gulf of Finland.

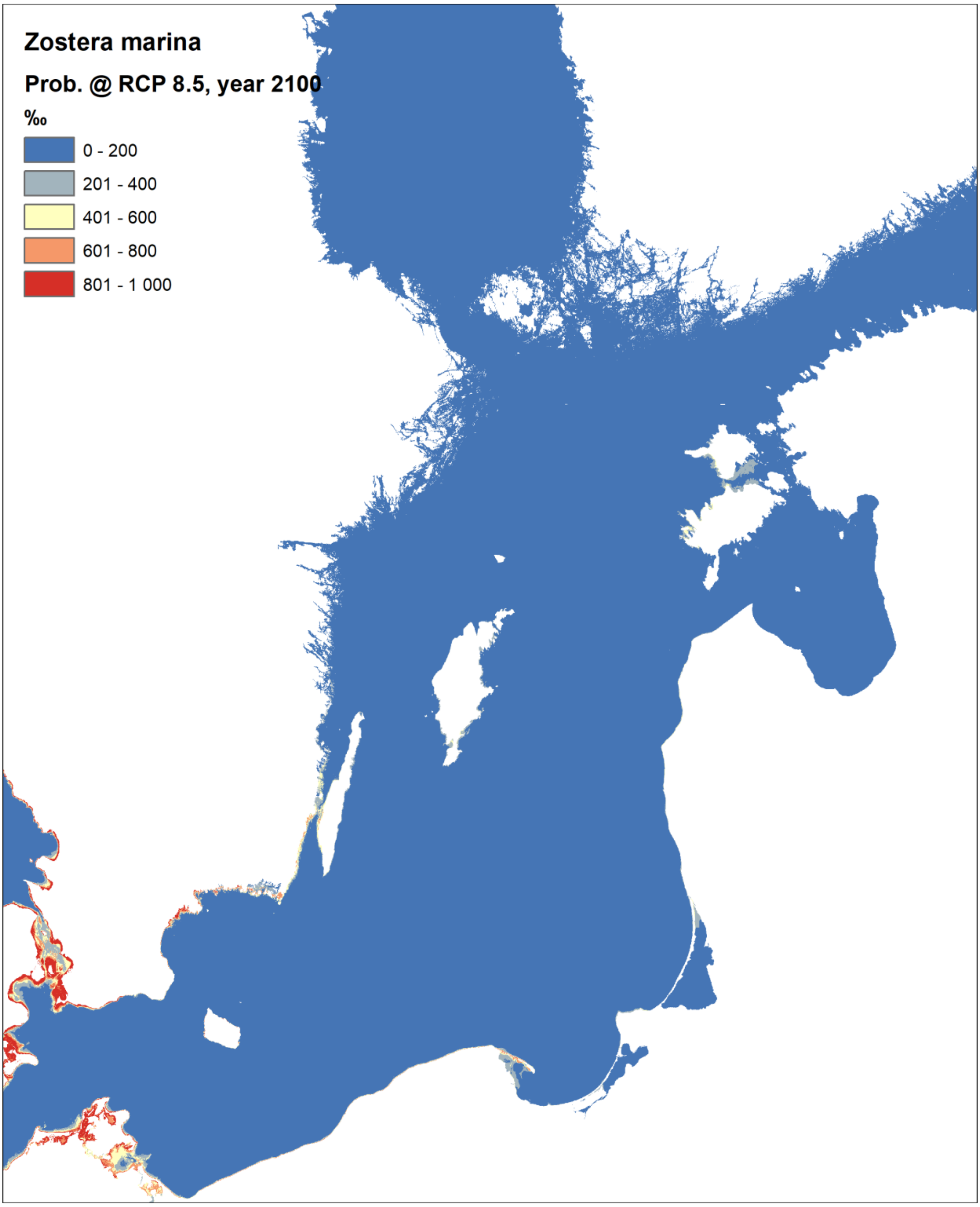


Figure 30. Modelled habitat suitability for *Zostera marina*, given the climate scenario RCP 8.5, by the year 2100. Note complete loss in the central and Baltic and Gulf of Finland and severe reduction in the rest of the Baltic.

Appendix C: Modelled habitat changes

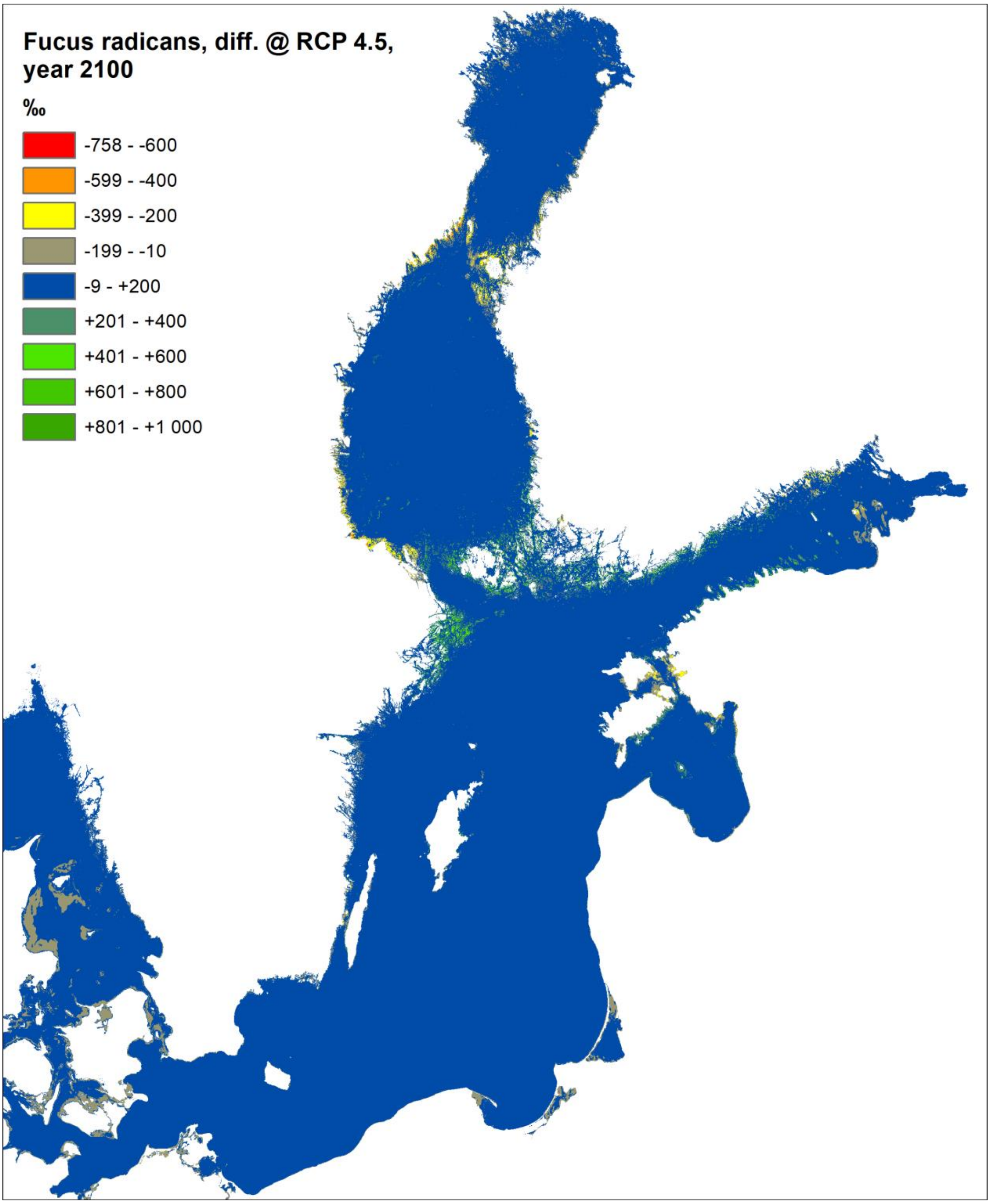


Figure 31. Modelled change in habitat sutability for *Fucus radicans*, given the climate scenario RCP 4.5, by the year 2100. Note increased suitability in the central archipelago seas; the species spreads southward in concert with a reduction of salinity.

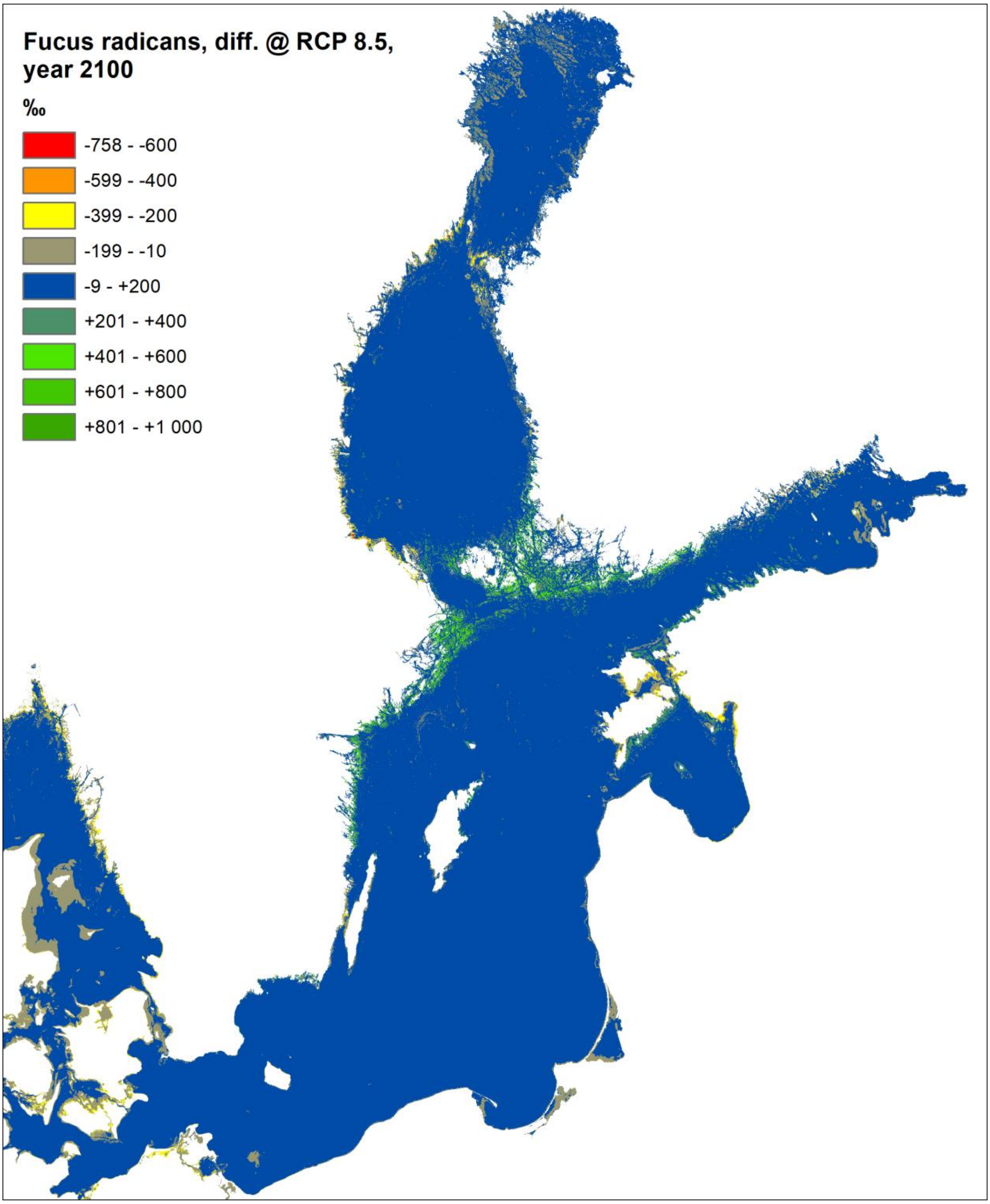


Figure 32. Modelled change in habitat sutability for *Fucus radicans*, given the climate scenario RCP 8.5, by the year 2100. Note increased suitability in the central archipelago seas and central Baltic proper; the species spreads southward in concert with a reduction of salinity.

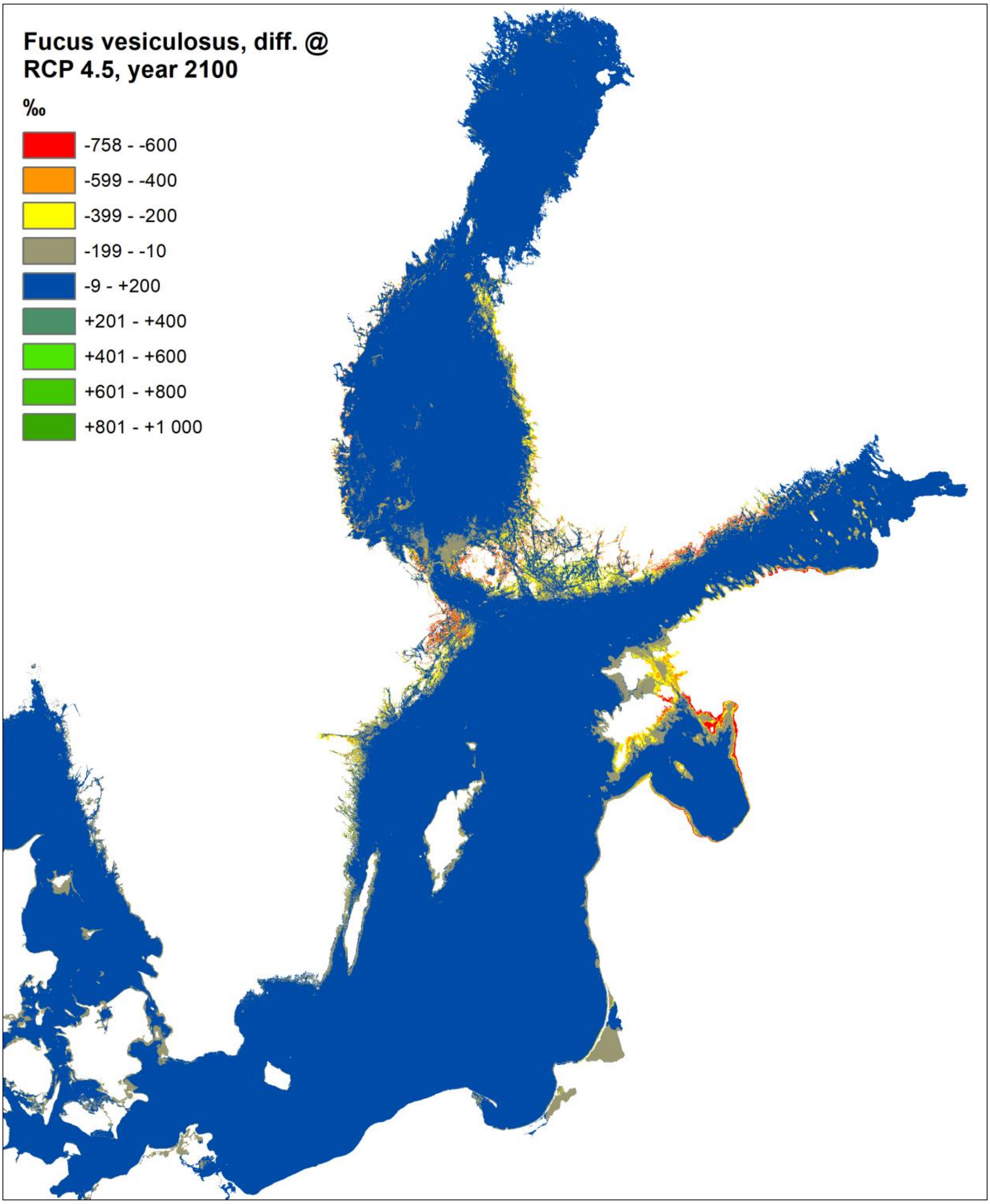


Figure 33. Modelled change in habitat suitability for *Fucus vesiculosus*, given the climate scenario RCP 4.5, by the year 2100. Note loss of suitable habitats in the central archipelago seas, Gulf of Finland and Estonia.

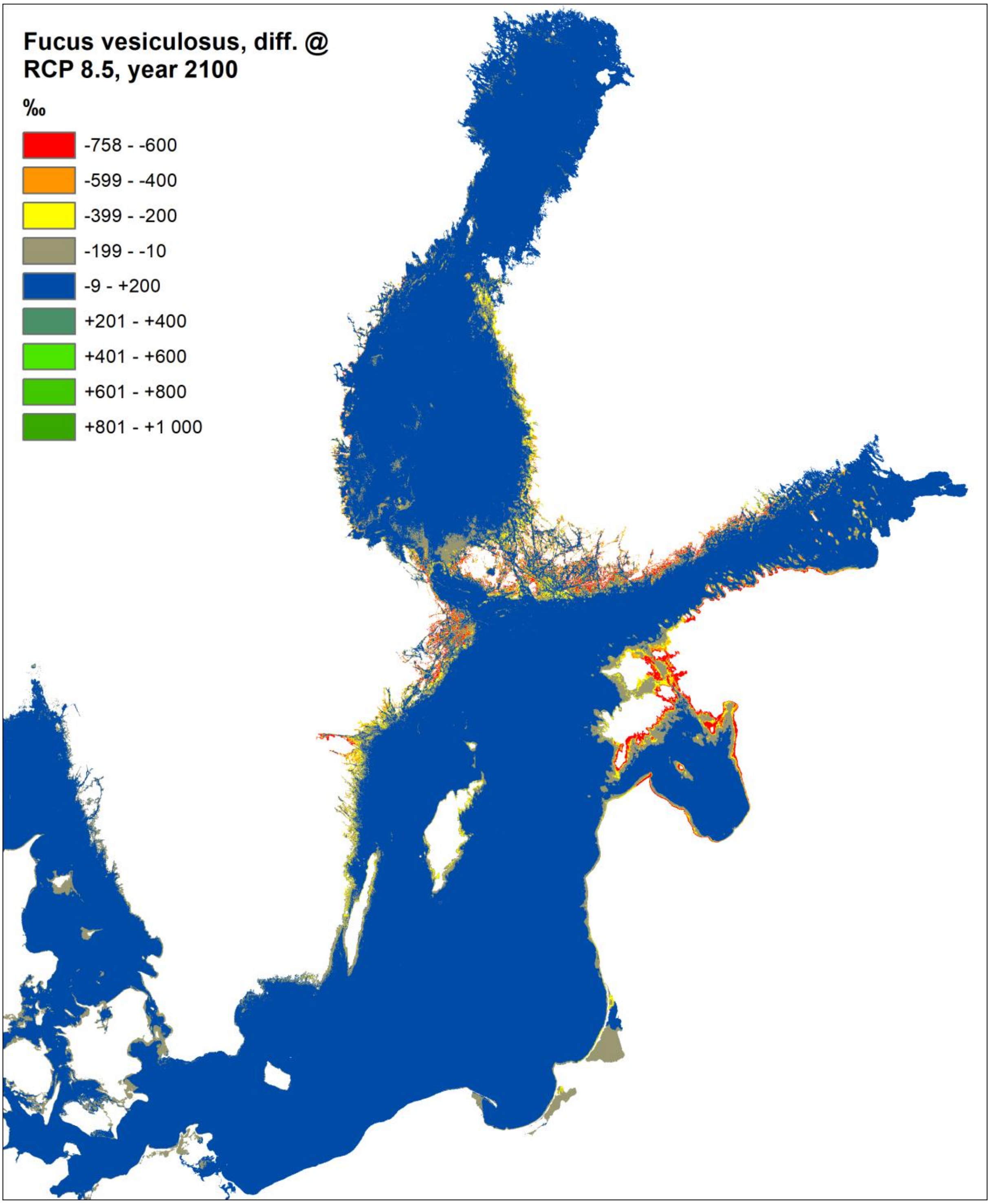


Figure 34. Modelled change in habitat suitability for *Fucus vesiculosus*, given the climate scenario RCP 8.5, by the year 2100. Note loss of suitable habitats in the central archipelago seas and Estonia.

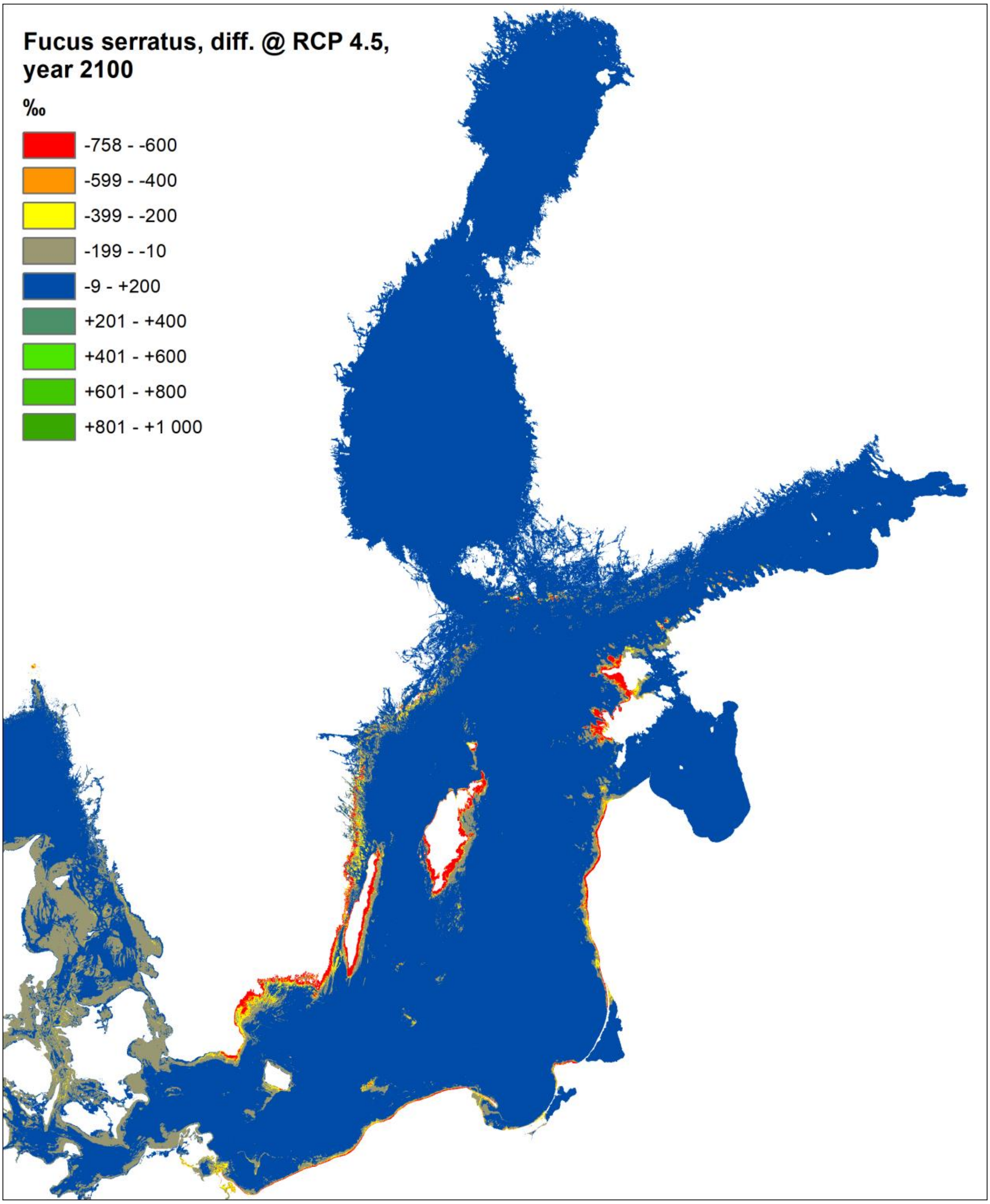


Figure 35. Modelled change in habitat suitability for *Fucus serratus*, given the climate scenario RCP 4.5, by the year 2100. Note loss of suitable habitats in the central Baltic proper and Estonia.

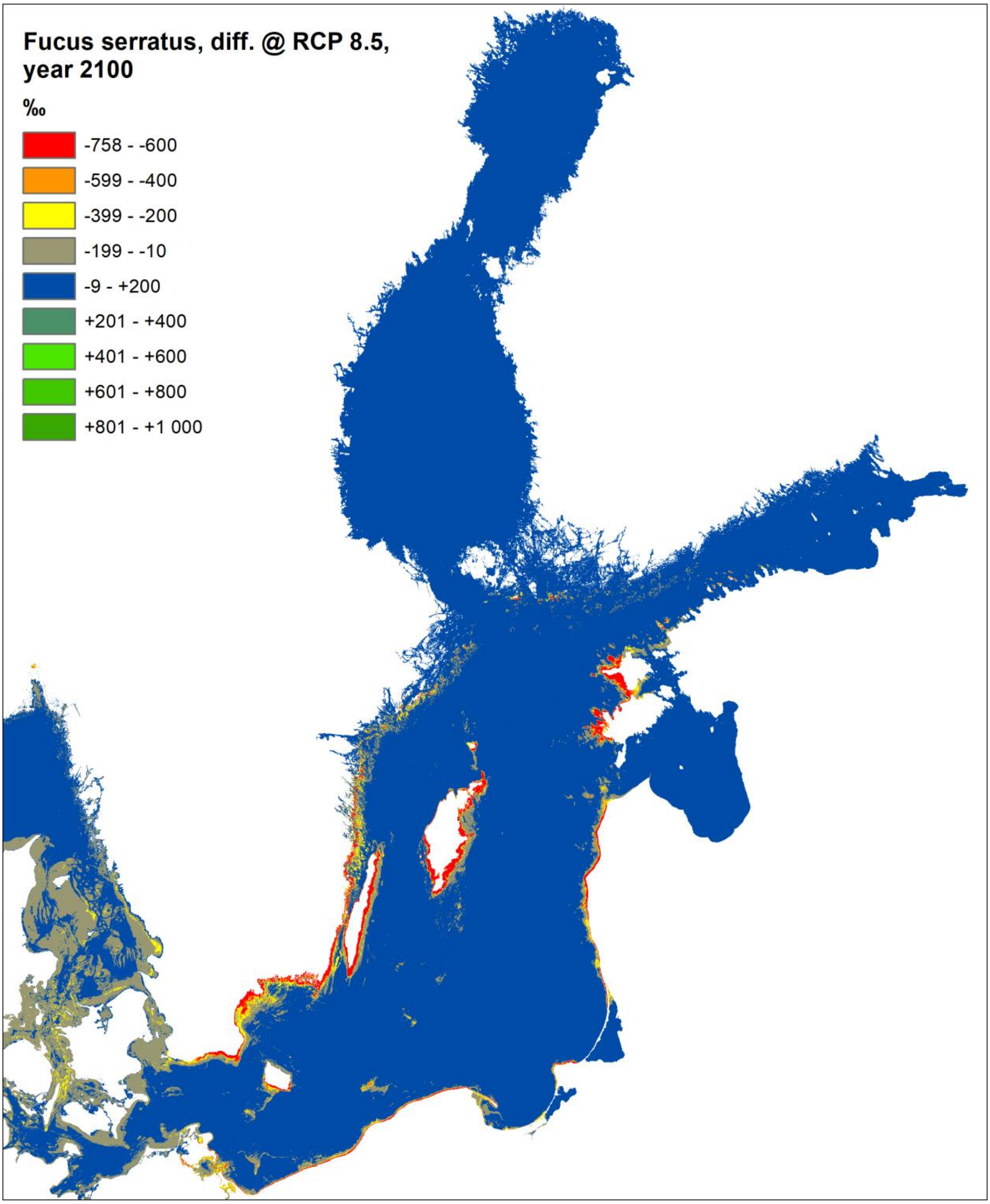


Figure 36. Modelled change in habitat suitability for *Fucus serratus*, given the climate scenario RCP 8.5, by the year 2100. Note loss of suitable habitats in the central Baltic proper and Estonia, with only difference with RCP 4.5. In reality, this small difference comes from the fact that the species will disappear almost entirely from the Baltic even at RCP 4.5, with only surviving populations in the southwest portion of Skåne.

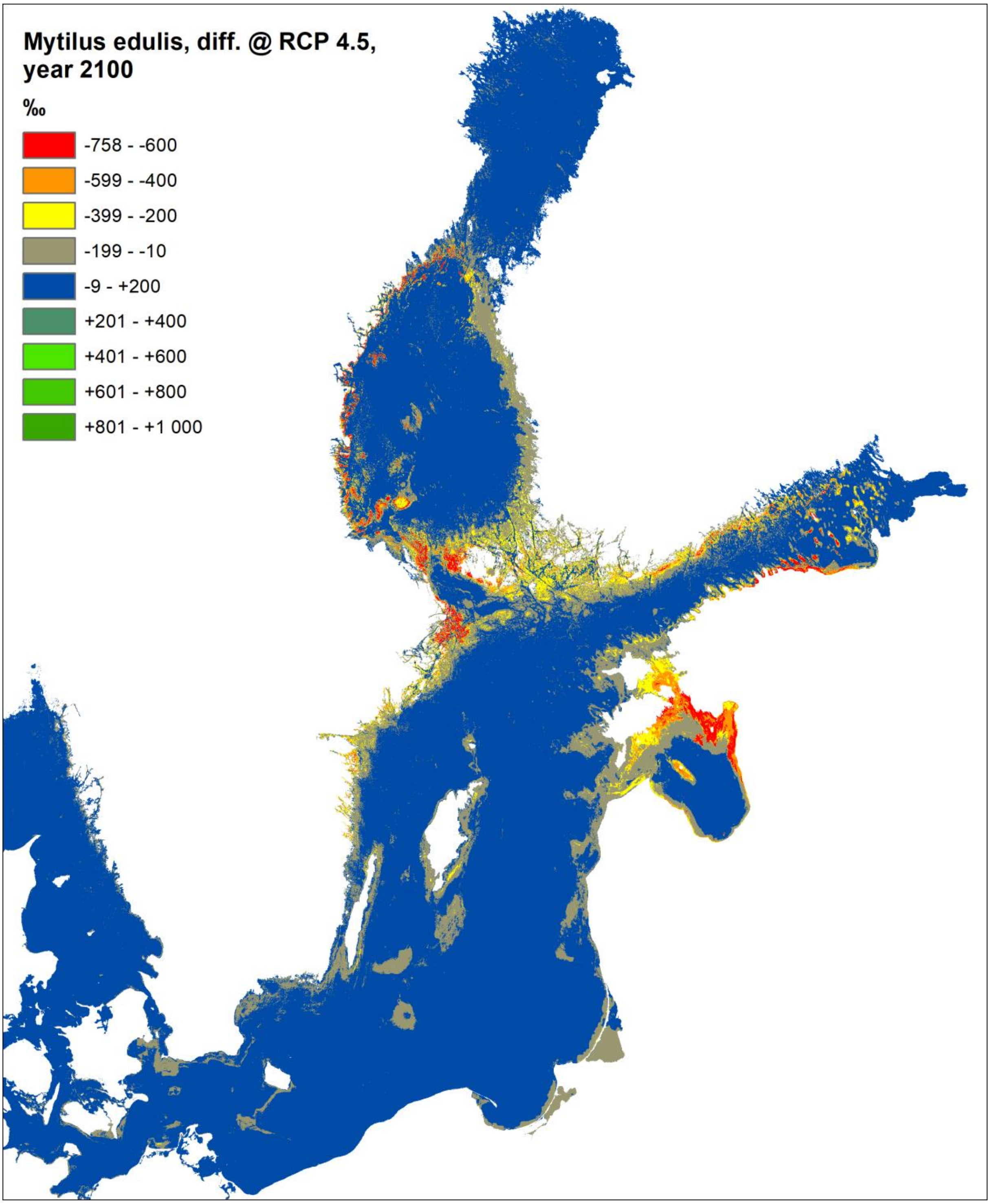


Figure 37. Modelled change in habitat suitability for *Mytilus edulis/trossulus*, given the climate scenario RCP 4.5, by the year 2100. Note loss of suitable habitats along the western coast of the Bothnian sea, in the central archipelago waters and in the Gulf of Riga.

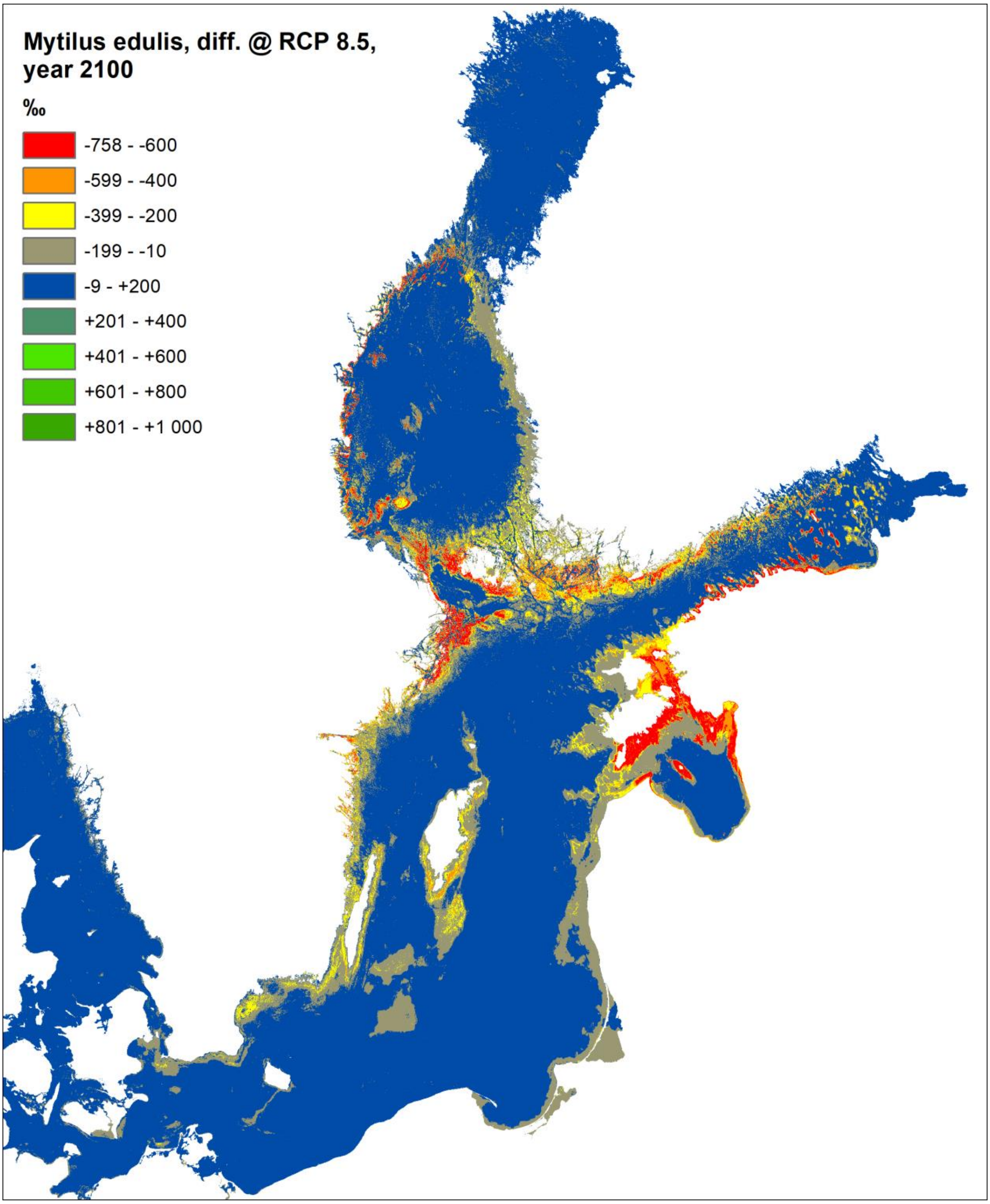


Figure 38. Modelled change in habitat suitability for *Mytilus edulis/trossulus*, given the climate scenario RCP 8.5, by the year 2100. Note further loss of suitable habitats along the western coast of the Bothnian sea, in the central archipelago waters and in around Estonia and the Gulf of Finland.

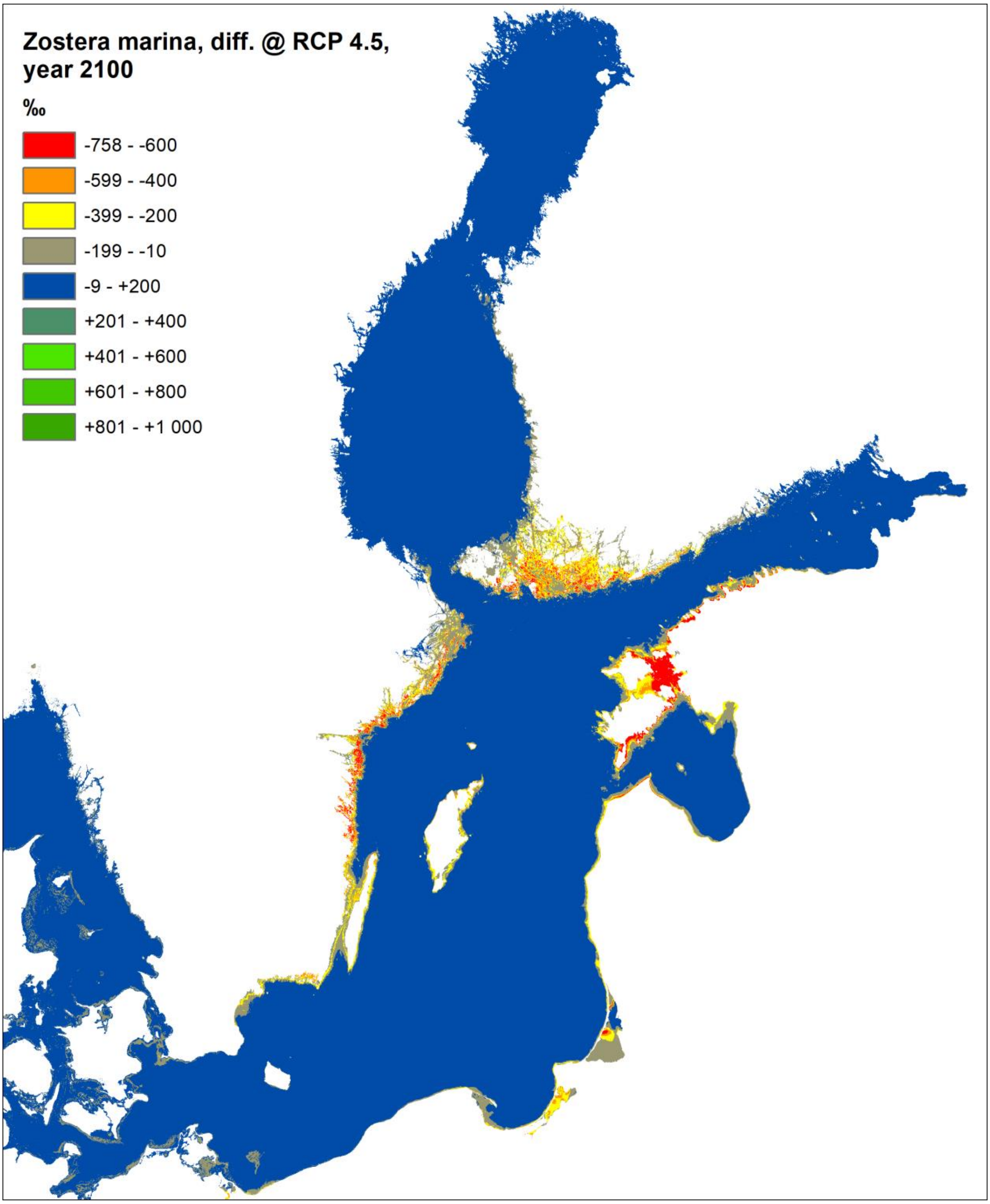


Figure 39. Modelled change in habitat suitability for *Zostera marina*, given the climate scenario RCP 4.5, by the year 2100. Note loss of suitable habitats along the western coast of the Baltic, in the Finnish archipelago waters and west of Estonia.

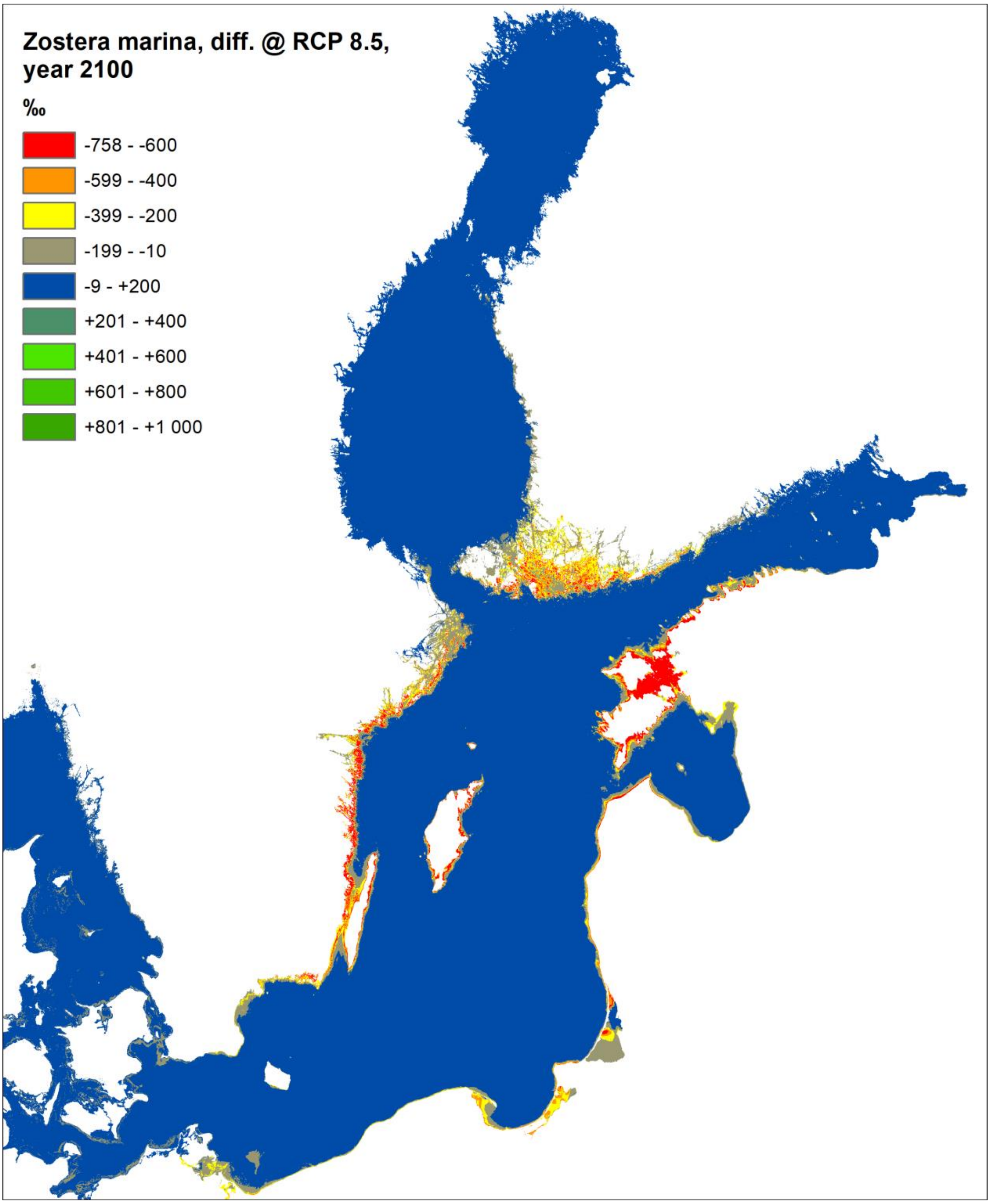


Figure 40. Modelled change in habitat suitability for *Zostera marina,* given the climate scenario RCP 8.5, by the year 2100. Note extended loss of suitable habitats along all coast of the Baltic area, with only Skåne and the southernmost coasts with limited reduction.

Appendix D: Modelled habitat strength

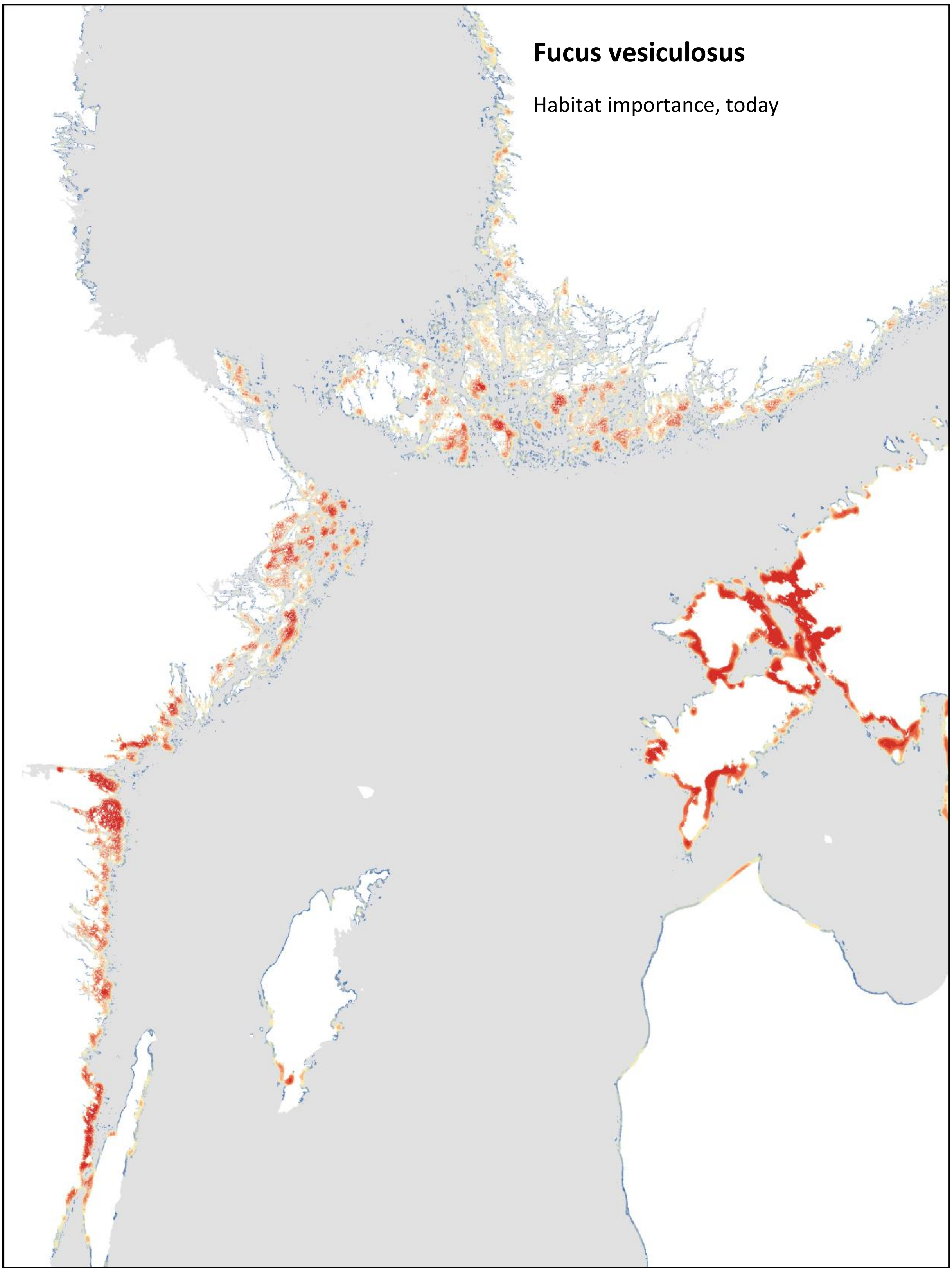


Figure 41. Modelled importance of *Fucus vesiculosus* communities in terms of habitat suitability weighted by the patch as source for the habitat network through connectivity. Red areas denote patches with high suitability and a positive contribution to the network.

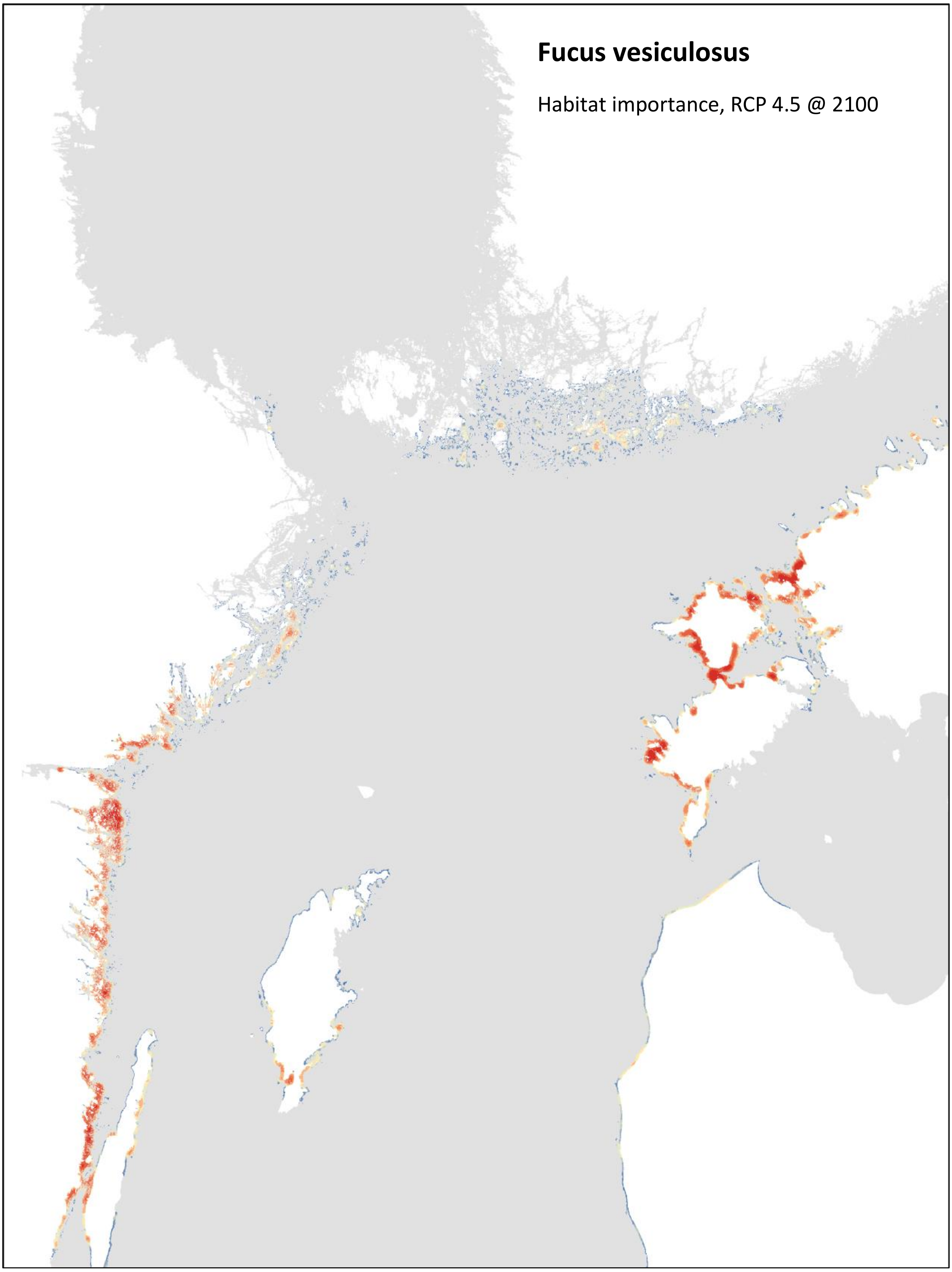


Figure 42. Modelled importance of *Fucus vesiculosus* in terms of habitat suitability weighted by the patch as source for the habitat network through connectivity. Predicted situation given RCP 4.5, at year 2100. Red areas denote patches with high suitability and a positive contribution to the network.

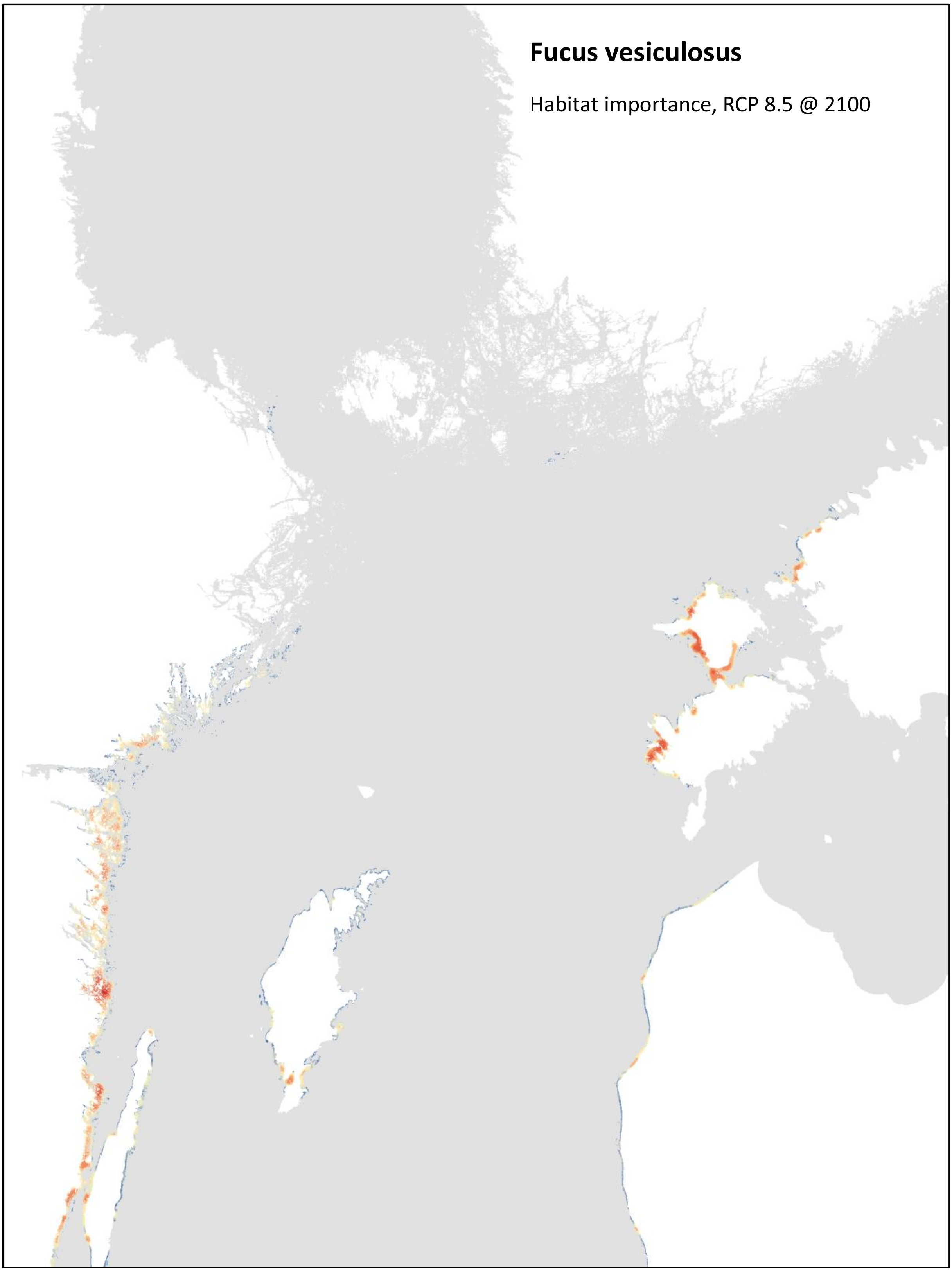


Figure 43. Modelled importance of *Fucus vesiculosus* in terms of habitat suitability weighted by the patch as source for the habitat network through connectivity. Predicted situation given RCP 8.5, at year 2100. Red areas denote patches with high suitability and a positive contribution to the network.

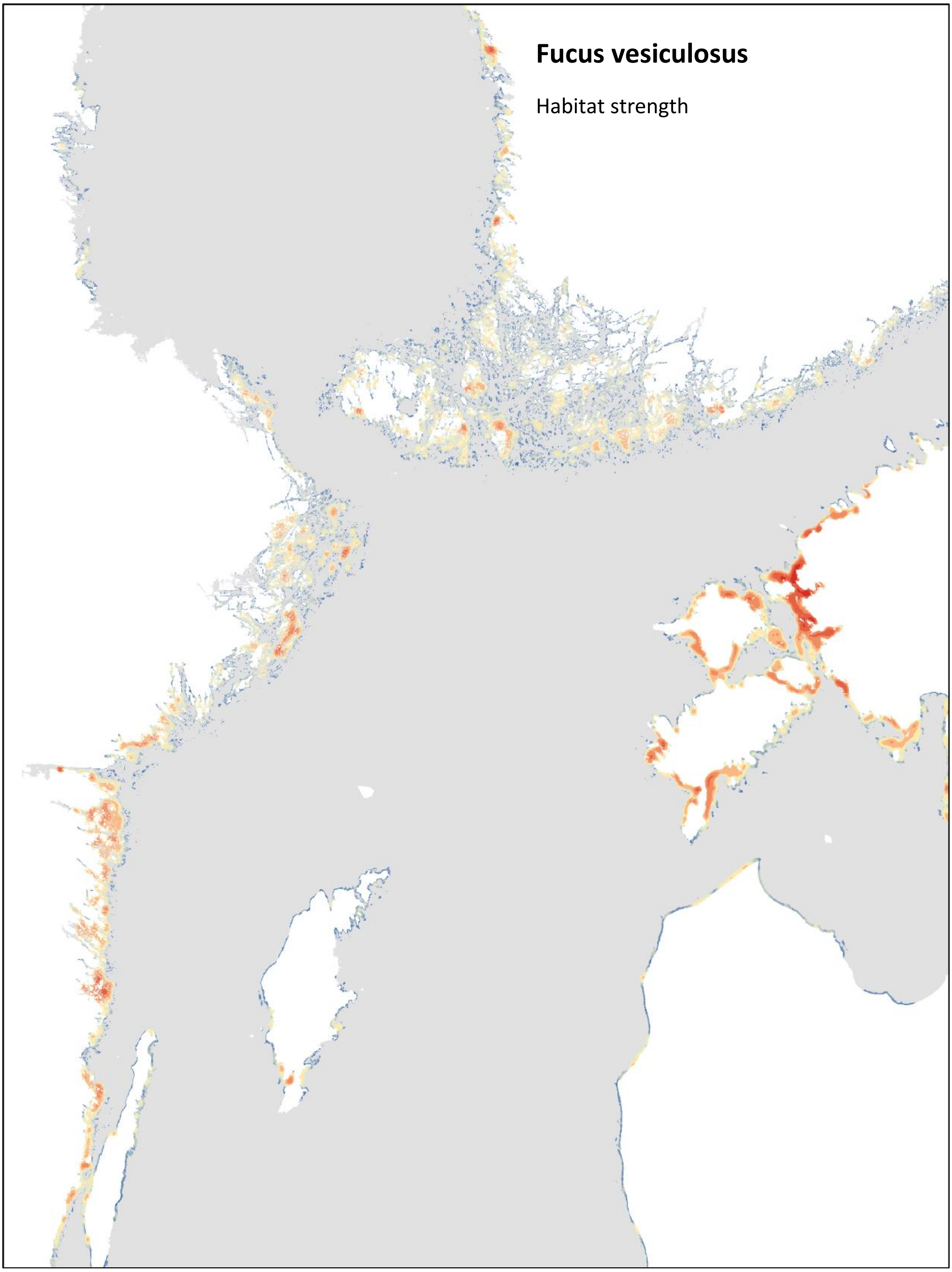


Figure 44. Modelled strength or resilience of *Fucus vesiculosus* in terms of habitat suitability weighted by the patch as sink for dispersal from the habitat network through connectivity. Red areas denote patches with high suitability and a positive contribution from the network.

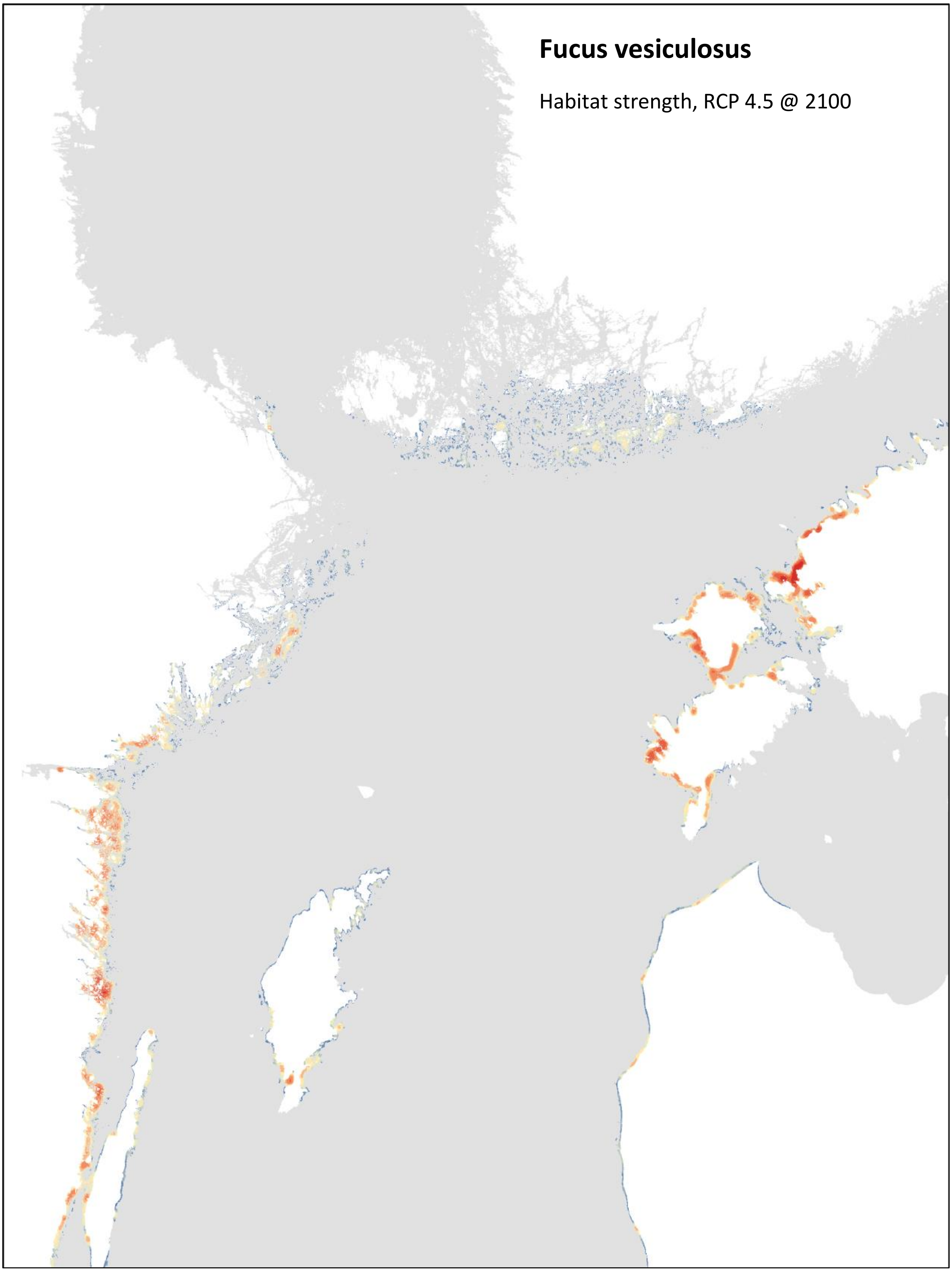


Figure 45. Modelled strength or resilience of *Fucus vesiculosus* in terms of habitat suitability weighted by the patch as sink for dispersal from the habitat network through connectivity. Predicted situation given RCP 4.5, at year 2100. Red areas denote patches with high suitability and a positive contribution from the network.

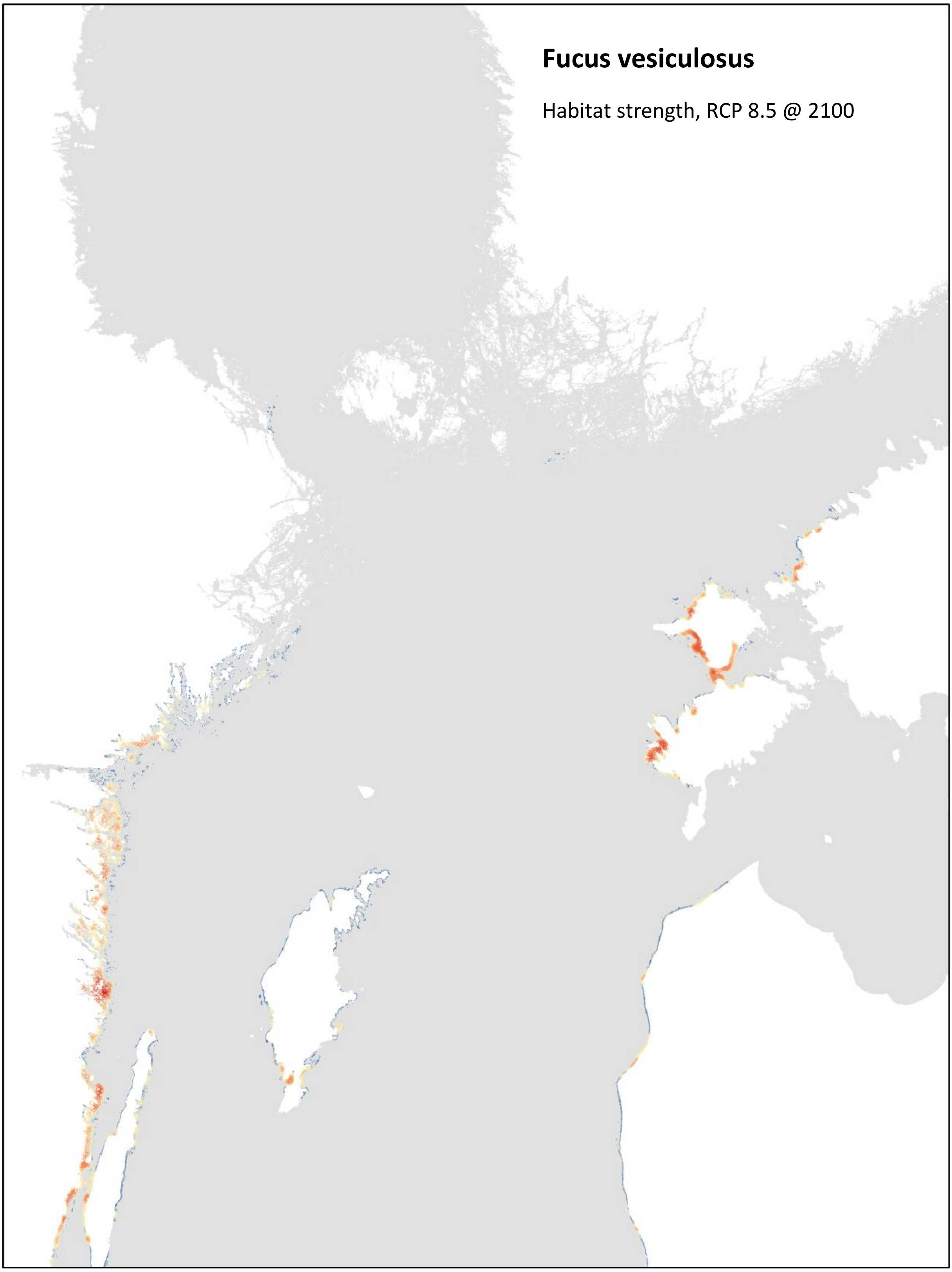


Figure 46. Modelled strength or resilience of *Fucus vesiculosus* in terms of habitat suitability weighted by the patch as sink for dispersal from the habitat network through connectivity. Predicted situation given RCP 8.5, at year 2100. Red areas denote patches with high suitability and a positive contribution from the network.

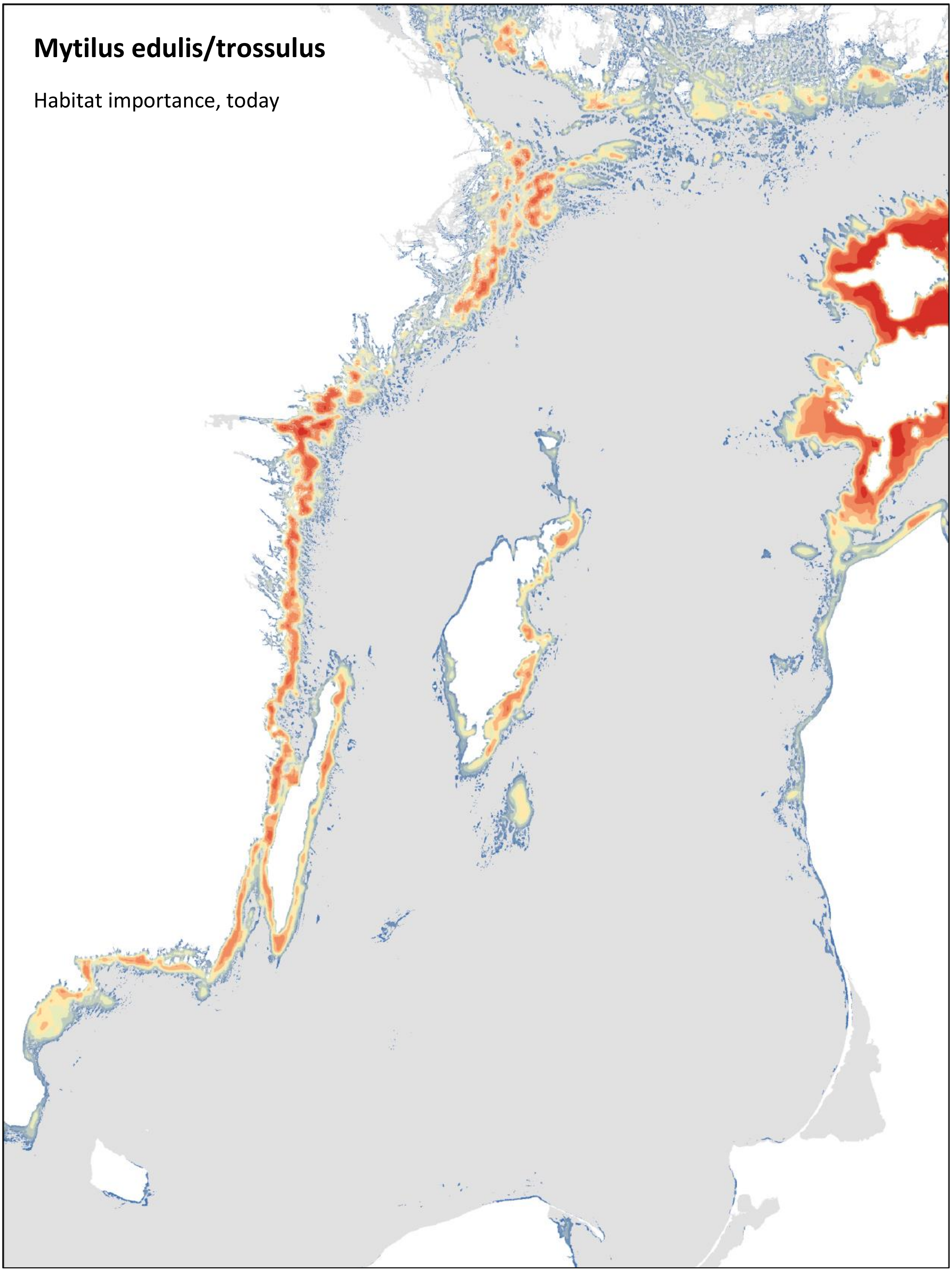


Figure 47. Modelled importance of *Mytilus* communities in terms of habitat suitability weighted by the patch as source for the habitat network through connectivity. Red areas denote patches with high suitability and a positive contribution to the network.

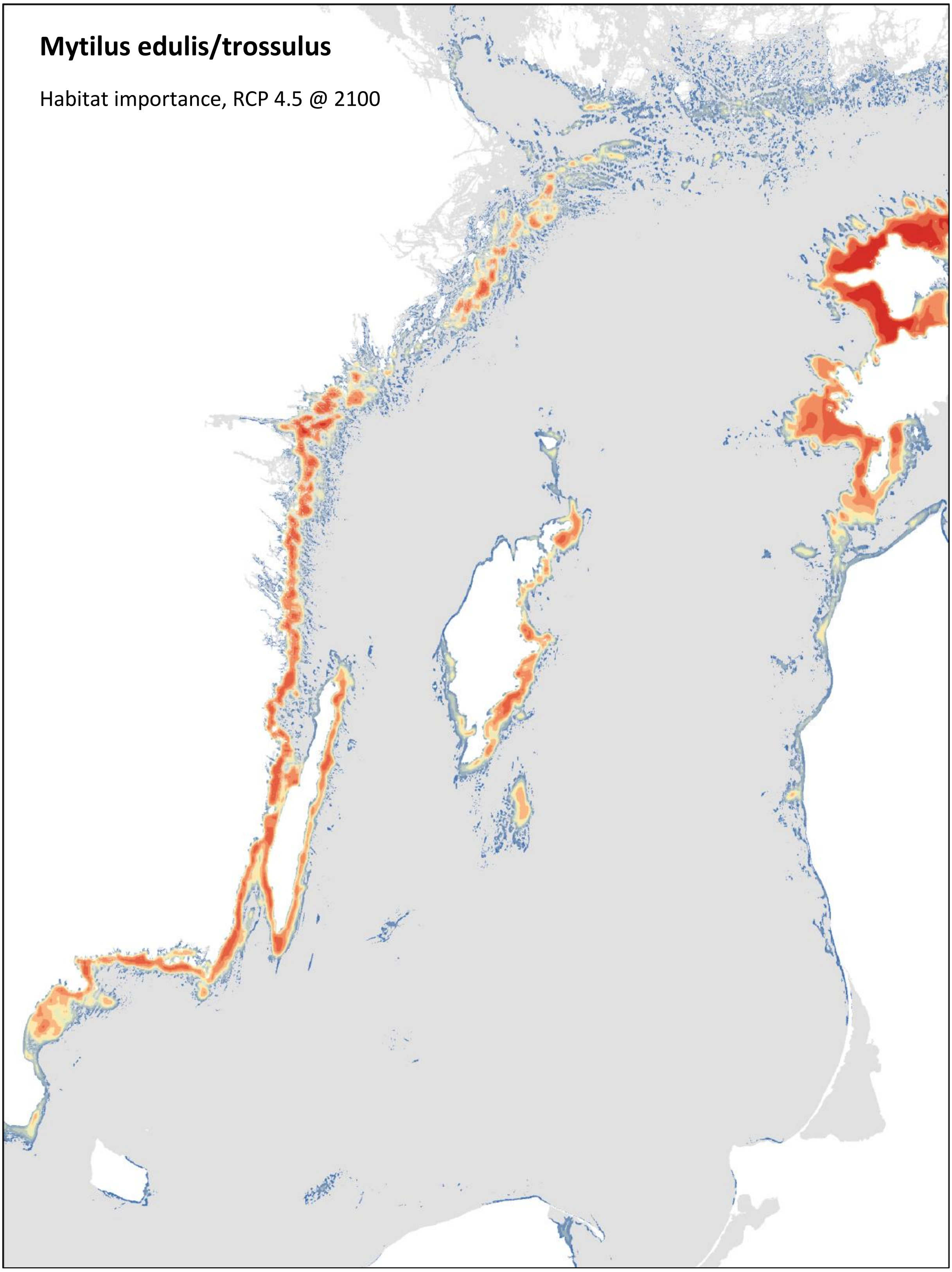


Figure 48. Modelled importance of *Mytilus* communities in terms of habitat suitability weighted by the patch as source for the habitat network through connectivity. Predicted situation given RCP 4.5, at year 2100. Red areas denote patches with high suitability and a positive contribution to the network.

Figure 49. Modelled importance of *Mytilus* communities in terms of habitat suitability weighted by the patch as source for the habitat network through connectivity. Predicted situation given RCP 8.5, at year 2100. Red areas denote patches with high suitability and a positive contribution to the network.

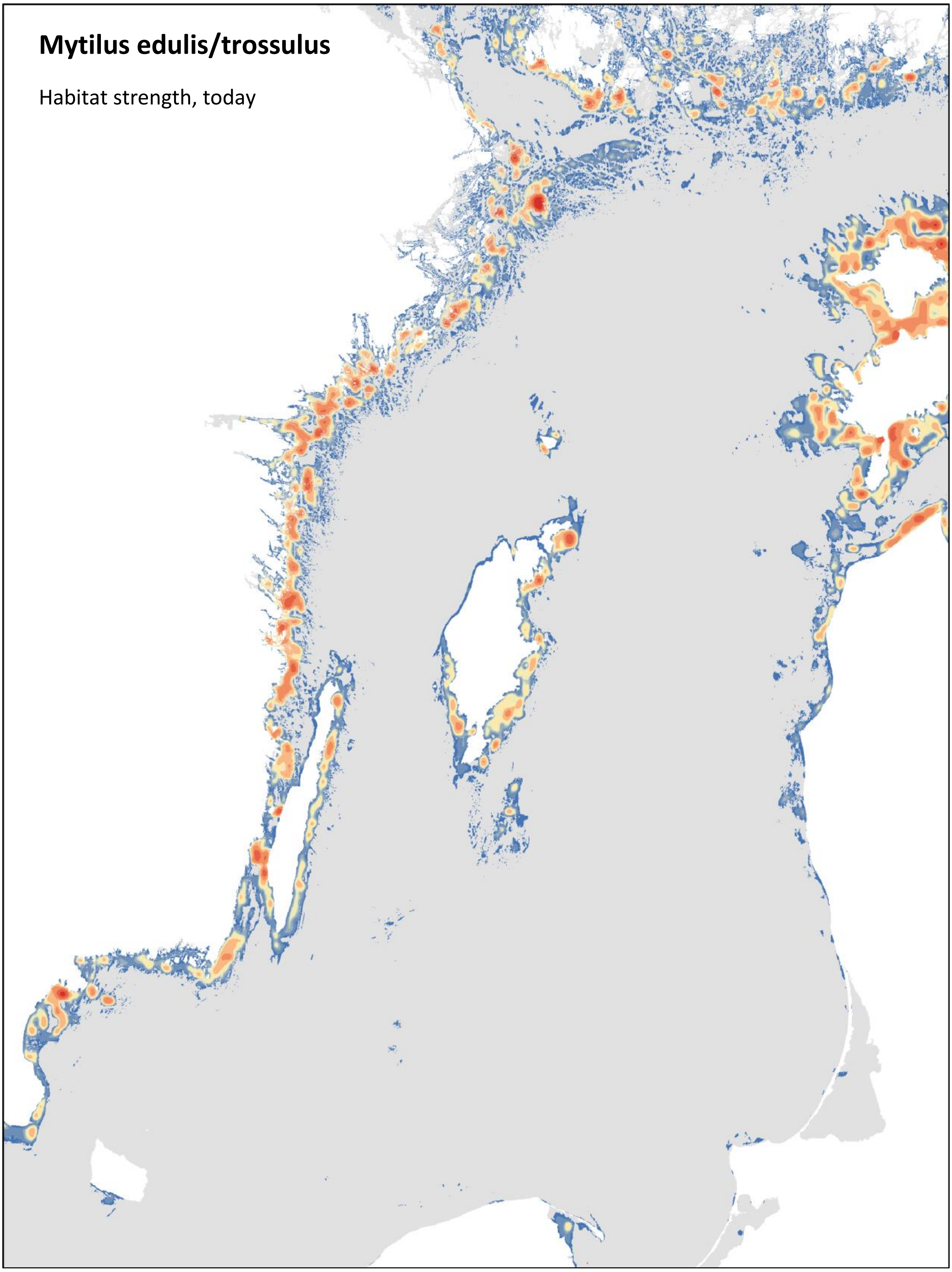


Figure 50. Modelled strength or resilience of *Mytilus* communities in terms of habitat suitability weighted by the patch as sink for dispersal from the habitat network through connectivity. Red areas denote patches with high suitability and a positive contribution from the network.

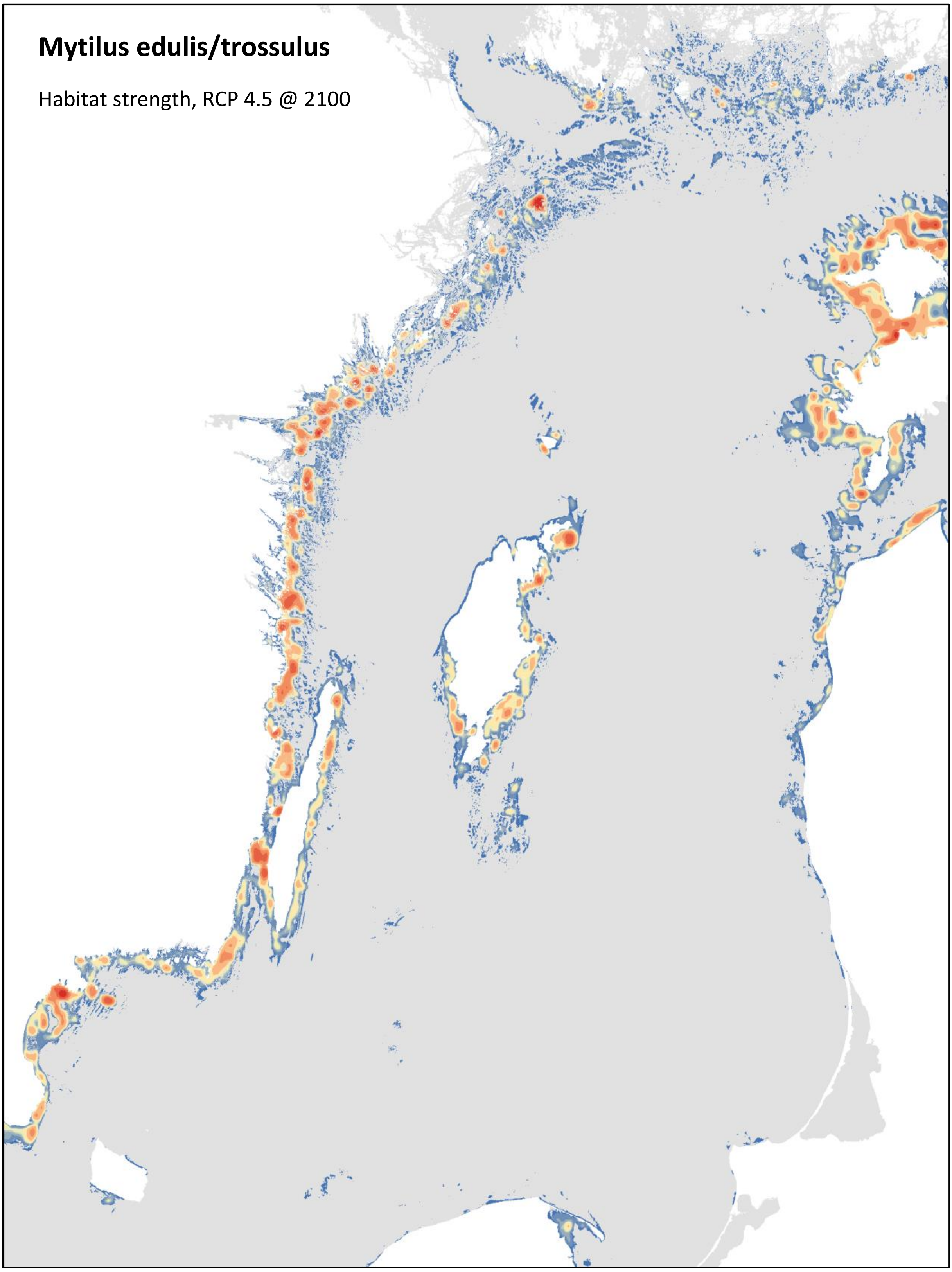


Figure 51. Modelled strength or resilience of *Mytilus* communities in terms of habitat suitability weighted by the patch as sink for dispersal from the habitat network through connectivity. Predicted situation given RCP 4.5, at year 2100. Red areas denote patches with high suitability and a positive contribution from the network.

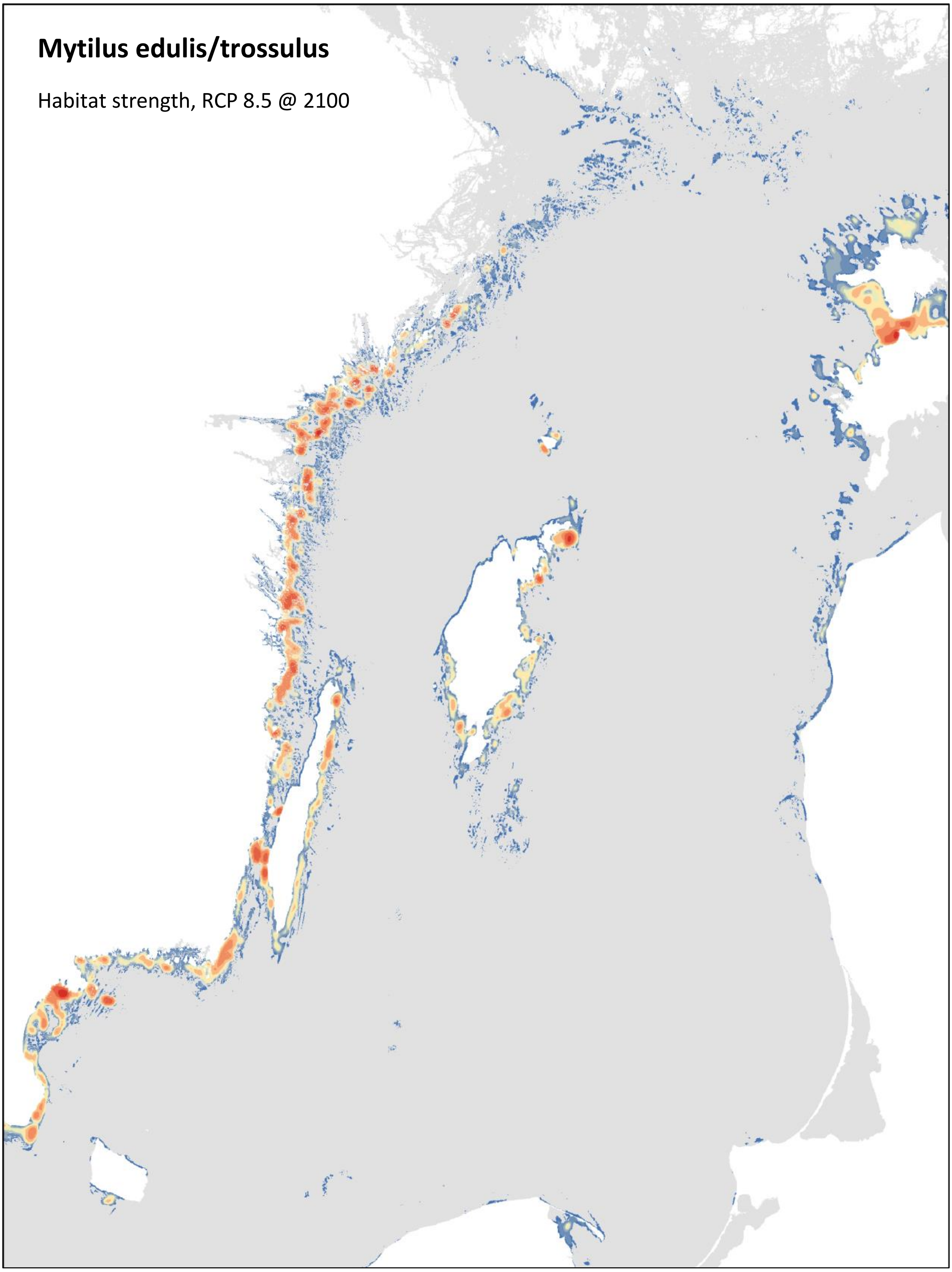


Figure 52. Modelled strength or resilience of *Mytilus* communities in terms of habitat suitability weighted by the patch as sink for dispersal from the habitat network through connectivity. Predicted situation given RCP 8.5, at year 2100. Red areas denote patches with high suitability and a positive contribution from the network.

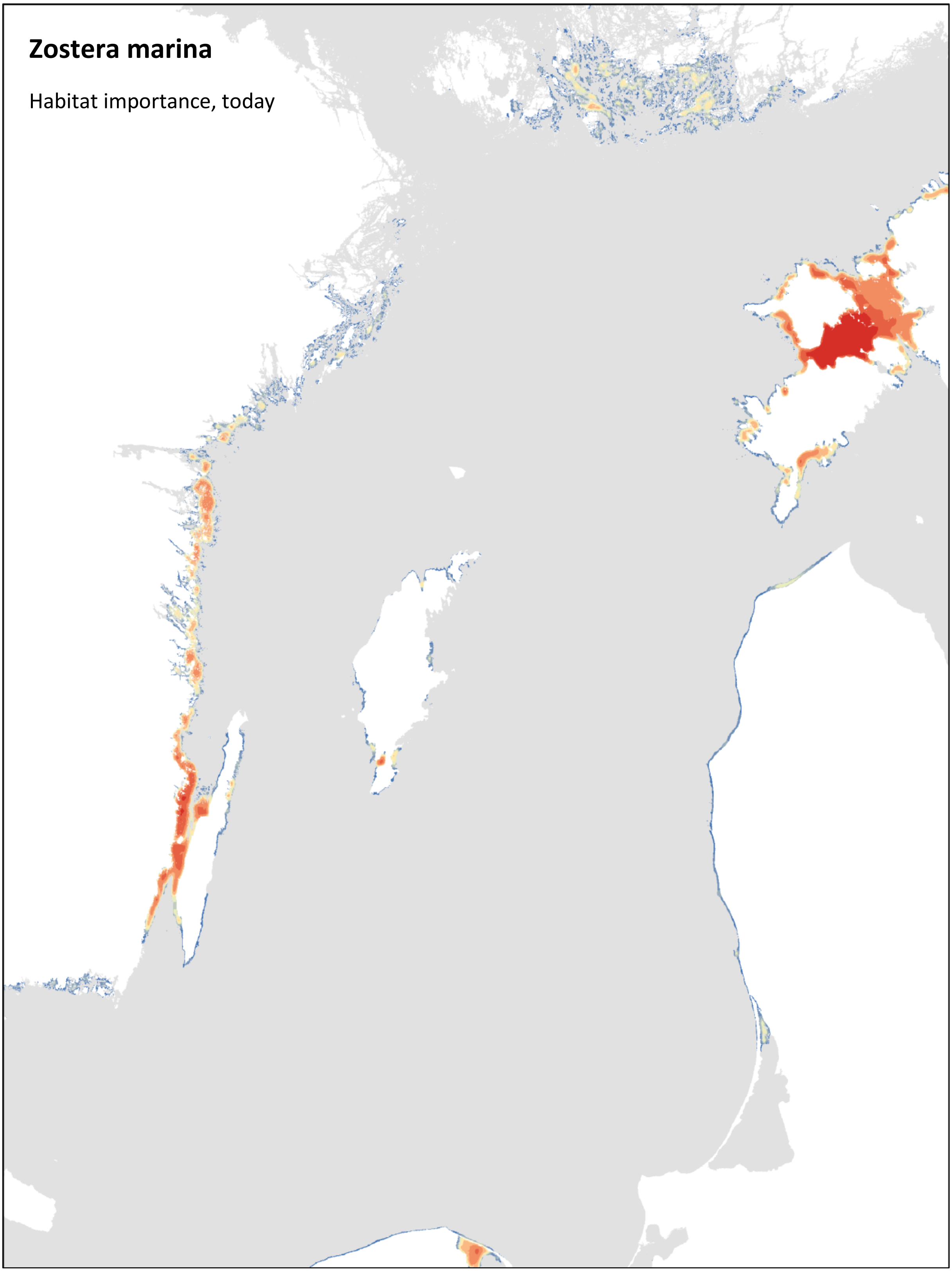


Figure 53. Modelled importance of *Zostera* communities in terms of habitat suitability weighted by the patch as source for the habitat network through connectivity. Red areas denote patches with high suitability and a positive contribution to the network.

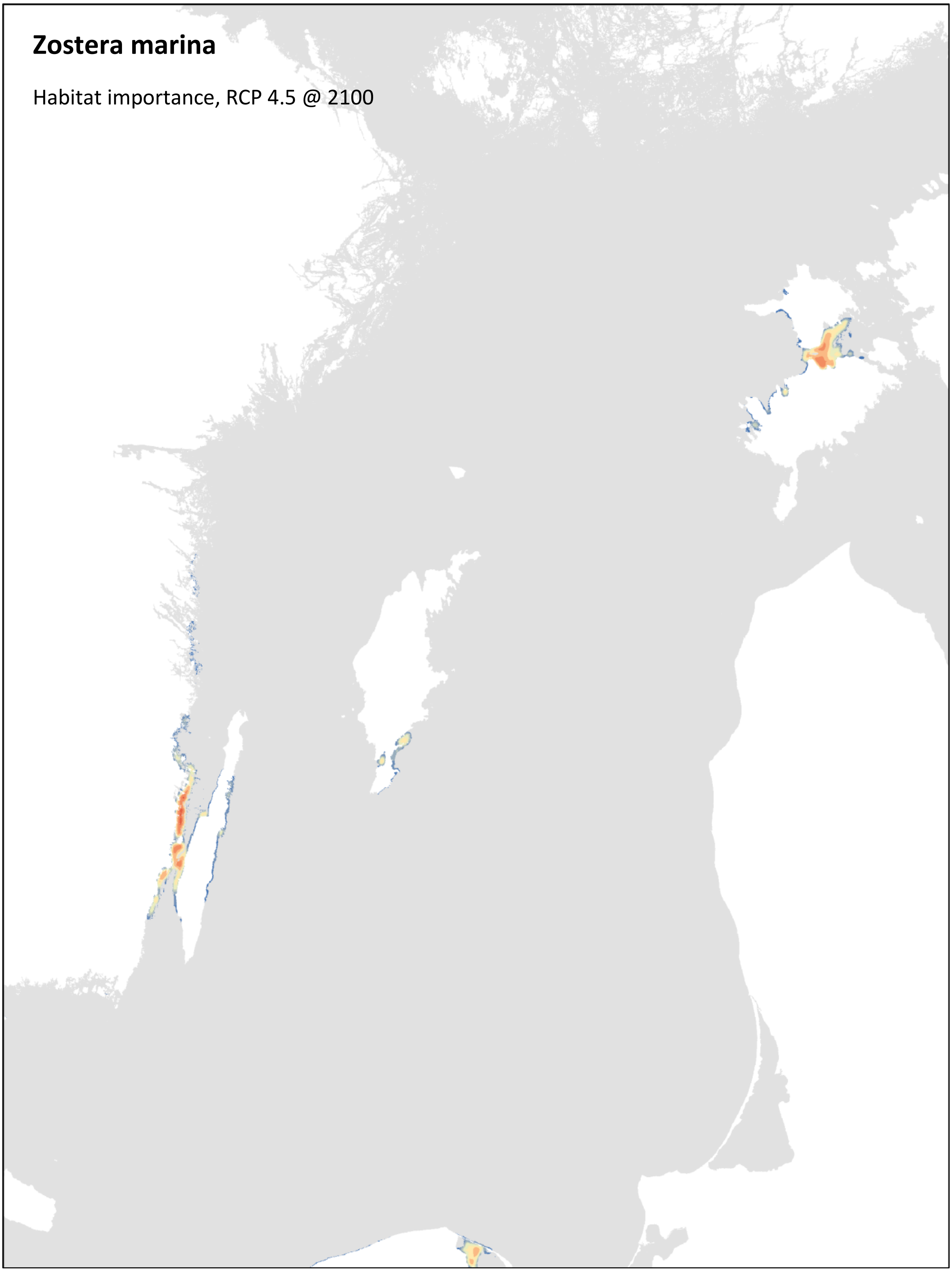


Figure 54. Modelled importance of *Zostera* communities in terms of habitat suitability weighted by the patch as source for the habitat network through connectivity. Predicted situation given RCP 4.5, at year 2100. Only few areas with (moderately) high suitability and a positive contribution from the network can be found, coloured yellow-orange-red in the map. These are plausible important future climate refugia.

Figure 55. Modelled importance of *Zostera* communities in terms of habitat suitability weighted by the patch as source for the habitat network through connectivity. Predicted situation given RCP 8.5, at year 2100. No patches with high suitability and a positive contribution to the network can be found.

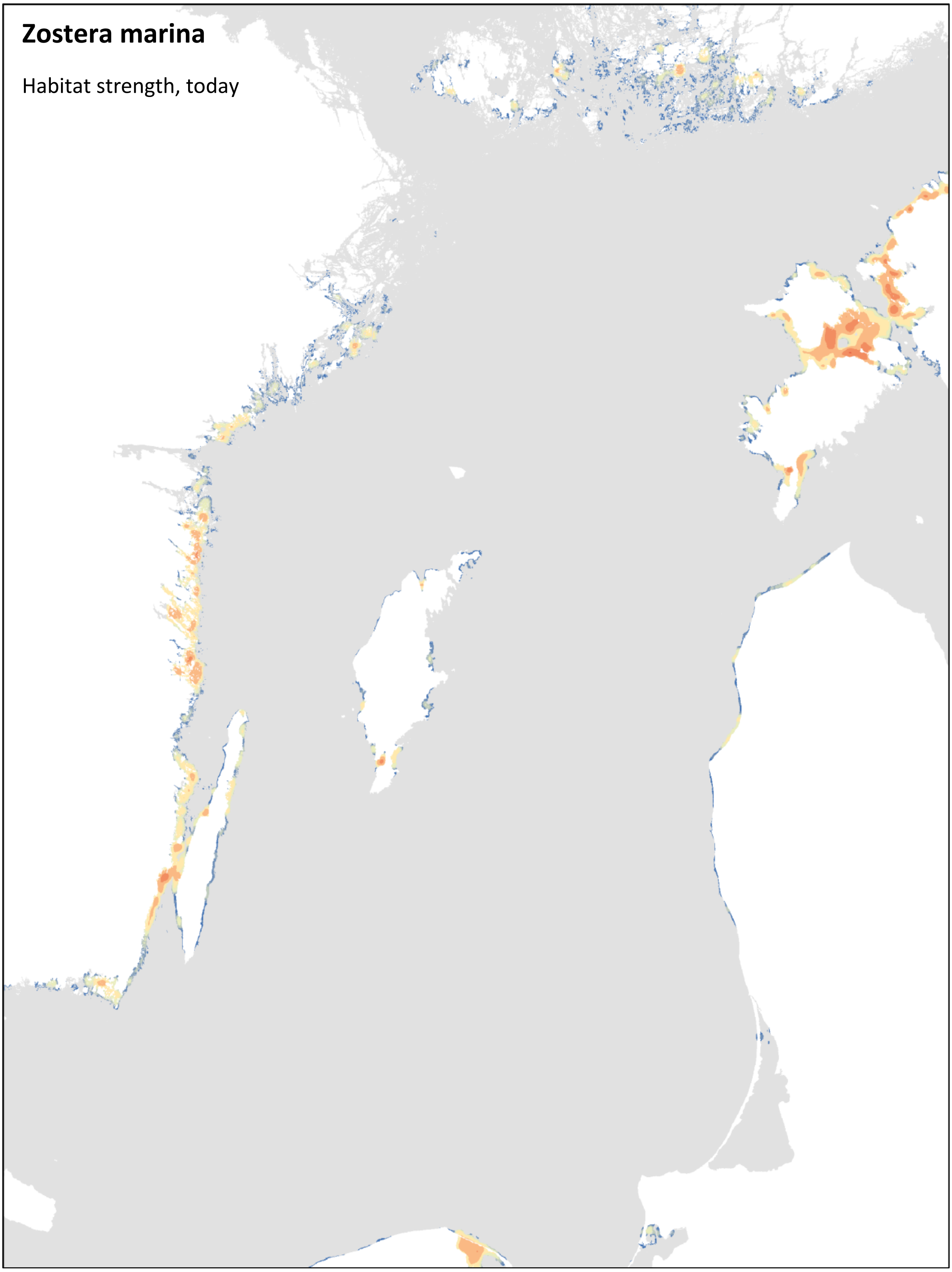


Figure 56. Modelled strength or resilience of *Zostera* communities in terms of habitat suitability weighted by the patch as sink for dispersal from the habitat network through connectivity. Red areas denote patches with high suitability and a positive contribution from the network.

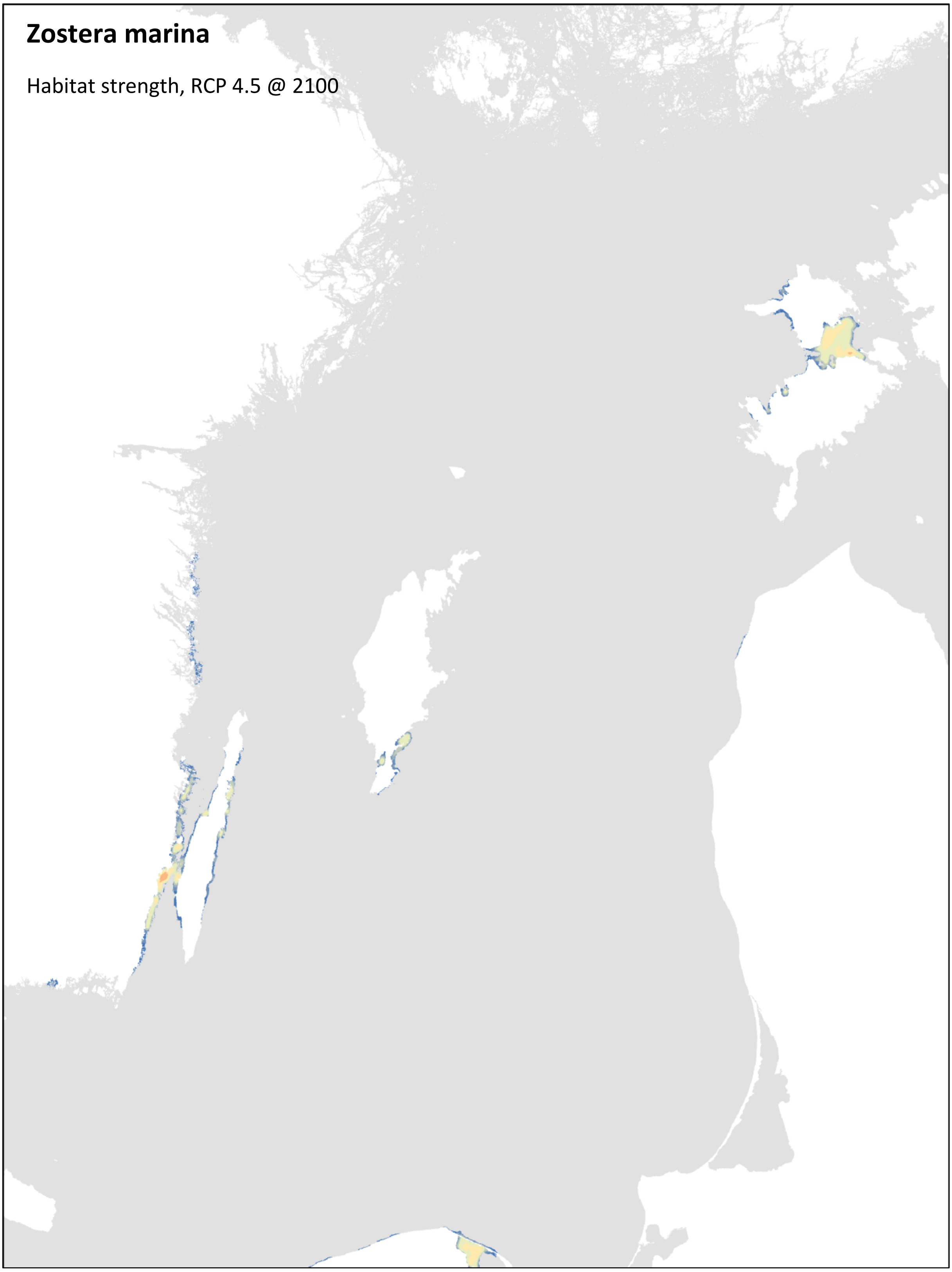


Figure 57. Modelled strength or resilience of *Zostera* communities in terms of habitat suitability weighted by the patch as sink for dispersal from the habitat network through connectivity. Predicted situation given RCP 4.5, at year 2100. Only few areas with (moderately) high suitability and a positive contribution from the network can be found, orange in the map. These are plausible important future climate refugia.

Figure 58. Modelled strength or resilience of *Zostera* communities in terms of habitat suitability weighted by the patch as sink for dispersal from the habitat network through connectivity. Predicted situation given RCP 8.5, at year 2100. No patches with high suitability and a positive contribution from the network can be found.

Climate refugia in the Baltic Sea

Habitat-forming species are key in providing ecosystem services, green infrastructure and a blue economy. This report presents modelled spatial distributions for key species based on two IPCC climate change scenarios.

Our models indicate there is a risk that many species will have a radically different distribution in the year 2100:

- Species limited by salinity will be radically reduced and may even disappear in the northern and central Baltic Sea, as well as the Bothnian Sea, and some will relocate to new areas
- Distribution of freshwater species will remain similar or with slight changes
- Particularly hard bottoms but also sandy bottoms will lose ecosystem functions
- Certain areas stand out as especially important as cores, refugia or "last stands" for species

These predictions indicate that climate change is a significant threat to ecosystem functions and to the basis of the blue economy within the next 80 years. Immediate actions to mitigate climate change and to restore damaged habitats to salvage ecosystem functions seem highly warranted.

Pan Baltic Scope is a collaboration between 12 planning authorities and organisations from around the Baltic Sea. We work towards bringing better maritime spatial plans in the Baltic Sea Region.

Swedish Agency for Marine and Water Management
Bundesamt für Seeschifffahrt und Hydrographie
Ministry of Environmental Protection and Regional Development of the Republic of Latvia
Danish Maritime Authority
VASAB
Republic of Estonia Ministry of Finance
Satakuntaliitto The Regional Council of Satakunta
SYKE
Nordregio
Ålands landskapsregering

Pan Baltic Scope
Co-funded by the European Maritime and Fisheries Fund of the European Union

Get our results:
www.panbalticscope.eu