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Bringing climate change into ecosystem based management of the sea: Data and methods for the Symphony framework

Symphony - a cumulative assessment tool developed for Swedish Marine Spatial Planning

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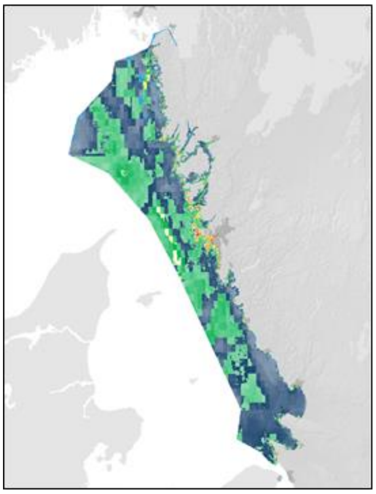
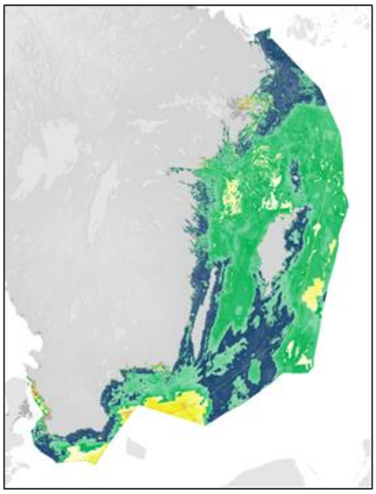
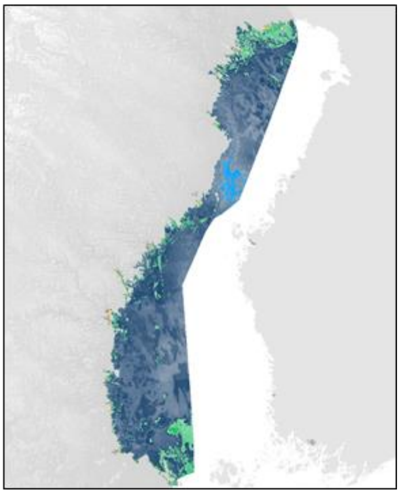

Front:
Spatial distribution of cumulative environmental impact by 2070-2099 based on RCP4.5 emission scenario. Green and yellow fields indicate relatively high impact. Red and black fields indicate maximum impact. Climate change pressures (changes to temperature, salinity, ice cover) increase the cumulative impact by 50-100% compared to current state. These are preliminary results.

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Symphony - a cumulative assessment tool developed for Swedish Marine Spatial Planning

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Summary

This report is a review of available data and information sources for climate proofing the tool Symphony as a part of Work Package 1 (WP1) in the Formas project ClimeMarine - Integration of climate-change impacts into the ecosystem-based management and planning of the Swedish marine environment. The aim of ClimeMarine is to climate proof planning and management of the Swedish marine resources by using and further developing the tool Symphony, the cumulative assessment tool developed for the Swedish Marine Spatial Planning. ClimeMarine is a cooperation project between the Swedish Meteorological and Hydrological Institute (SMHI), Swedish Agency for Marine and Water Management (SwAM), University of Gothenburg (GU), and Geological Survey of Sweden (SGU), all involved in marine science, management, and planning.

In this report, we give a short description of Symphony as well as its underlying assumptions. These assumptions are explicitly selected to make the tool sufficiently simple for transparent interpretations. We also summarize the latest climate and nutrient load projections for the Baltic Sea that are incorporated into Symphony and elucidate the uncertainties in these climate projections. In addition, we investigate the potential to include connectivity and changing habitat distributions into Symphony, which are important aspects for Swedish Marine Spatial Planning and for understanding climate change impacts. Habitat change modelling is a complementary method, which can lead to improvements of the Symphony datasets. We describe possible ways to study habitat vulnerability and the impact from climate change, utilizing the same climate projections as implemented into Symphony. The results will lead to further understanding of climate change impacts on the interactions between human-induced pressures on habitats and ecosystem and analyses how the knowledge can be included in the Marine Spatial Planning.

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1 Introduction

The objective of this report is to review available data and information sources for climate proofing of Symphony and in addition, investigate how to include connectivity and habitat changes into Marine Spatial Planning. The work is a deliverable in the Formas project ClimeMarine - Integration of climate-change impacts into the ecosystem-based management and planning of the Swedish marine environment. The aim of ClimeMarine is to take the first steps towards a climate proof management and planning of the Swedish marine resources. This is conducted by incorporating the latest climate change projection into the tool Symphony. Symphony is a decision support tool, developed by the Swedish Agency for Marine and Water Management (SwAM) and used in Marine Spatial Planning. It estimates the cumulative environmental impact with a spatial perspective, integrating pressures from human activities across selected ecosystem components and accounting for the sensitivity of each ecosystem component to each pressure.

Climate change and eutrophication are considered to have major impacts on the marine environment, and the Baltic Sea is one of most affected coastal seas worldwide (Helcom 2017; Kemp et al. 2009). Climate change induces increased atmospheric temperature and in the Baltic Sea area, the atmospheric temperature is projected to increase more than the global average. Consequently, the seawater temperature is increased and in the Baltic Sea, the projected warming is highest in the surface water during summer (Bacc 2015; Saraiva et al. 2019b). There is also a gradient from north to south with largest warming in the northernmost part, mainly due to the positive ice-albedo feedback mechanism. When snow and ice thaw the open water is increasing and backscattering of longwave radiation is less efficient leading to more solar radiation being absorbed by the seawater (Pithan and Mauritsen 2014; Serreze et al. 2007). Climate change will most likely also affect other parameters, e.g. salinity, stratification, and river discharge. This in turn will change the biogeochemical cycling and the marine environment (Bacc 2015).

The challenges from climate change co-exist with present pressures from human activities, such as eutrophication, shipping, fishing, and use of coastal areas for e.g. harbours, tourism, and recreation. Due to major and rapid environmental changes from global warming and the complex interactions in marine systems, responsible states and authorities need to handle both current pressures and future climate change. Therefore, it is essential to have an effective management of the oceans' natural resources to protect and preserve what in many cases represent irreplaceable nature values. A future climate may also change ocean circulation with implications for the connectivity in the seascape. Changes in dispersal patterns of free-drifting larvae may affect source-sink dynamics of marine organisms, rates of recolonization, and evolution of local adaptations (Jonsson et al. 2018).

Symphony is a model-based decision support tool developed to support ecosystem-based Marine Spatial Planning in Sweden. The basic model comes from work at a global scale (Halpern et al. 2008), but has been adapted to Swedish conditions (Hammar et al. 2018). By calculating the cumulative impact of human activities on the marine environment, planners are informed of the baseline conditions as well as the potential effect of various planning options on the cumulative impact in different areas. This has been used continuously during the Swedish Marine Spatial Planning process (2017-2019) and during the Environmental Impact Assessment of the plan (Carneiro et al. 2019).

ClimeMarine utilizes the latest availible climate and nutrient load projections for the Baltic Sea, developed by the Swedish Meteorological and Hydrological Institute (SMHI). The climate projections are based on the same assumptions used in the 2013 Intergovernmental Panel on Climate Change scenario pathways for projections of climate-driven changes in key environmental parameters (Ipcc 2013). The climate projections are the two Representative Concentration Pathways RCP4.5 and RCP8.5 (Moss et al. 2010), which describe the radiative forcing caused by e.g. greenhouse gas emissions and greenhouse gas concentrations in the atmosphere. Three nutrient load projections are also considered, ranging from a more pessimistic (Worst) to a more optimistic (Baltic Sea Action Plan, BSAP) scenario. The climate and nutrient load projections provide the physical and biogeochemical changes for the Baltic Sea and indicate that climate and nutrient load responses are likely to occur (Saraiva et al. 2019a; 2019b). In addition, uncertainties in the climate projections are presented for the four different downscaled global models, the two RCPs, and the three nutrient load scenarios. These future projections of sea surface and bottom salinity and temperature as well as ice cover have been incorporated as pressure layers into Symphony. The objective of the project is to develop and update the previous climate change data layers in Symphony and align them with the remaining pressures deriving from human activities. ClimeMarine also explores the possibility to implement habitat changes and connectivity into Symphony. By modelling and identifying important sources and sinks for both ecosystem components and pressure-related components, this important aspect can be incorporated.

2 Symphony – a cumulative assessment tool developed for Swedish Marine Spatial Planning

2.1 Symphony

Symphony is a decision support tool that has been developed to aid the Swedish Marine Spatial Planning process. The objective is to show simplified versions of how the environmental impact from human activities varies in different areas, and the effects of different planning. Symphony assesses the cumulative environmental impact spatially. Each area in the Swedish sea (divided into a grid of 250 x 250 m squares or pixels) is given a value describing the extent to which human activities impact a representation of the marine environment in the form of different nature values or ecosystem components. The value is calculated based on the best available data, and is used to compare the areas rather than providing an absolute value. The method builds on three main components: 41 maps of pressures, 32 maps of ecosystem components, and a sensitivity matrix showing how sensitive each ecosystem component is to each pressure (Fig.1). Pressures are the results of human activities that can affect and harm the marine environment. Ecosystem components are habitats, species, or groups of animals or plants that constitute of the marine ecosystem. To calculate the environmental impact in each area (pixel), the values for the three main components are multiplied, i.e. pressures x ecosystem components x sensitivity. The product is the calculated cumulative, or aggregated, environmental impact.

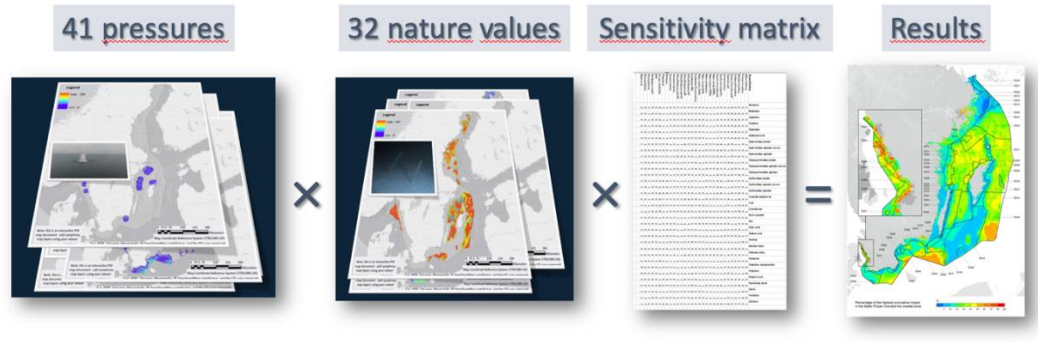

Figure 1. Symphony components; pressures, ecosystem components (nature values), sensitivity matrix and finally the results.

Because the input data contain varying degrees of reliability, the aggregated uncertainty is also estimated. In most cases, the data represent average values from the most recent years or decade. Therefore, the results reflect the present situation and how current pressures affect the existing ecosystem. Single, short-duration pressures are not included, nor are season-specific analyses. Symphony builds on a simple scientific method (Halpern et al. 2008). Even though the results are based on massive data volumes, the calculations are intended to have an easy-to-understand structure. All underlying assumptions and metadata are explained in the Symphony report (Hammar et al. 2018). This transparency encourages review and revision of the method.

2.2 Assumptions in the current version of Symphony

Symphony does not currently consider interactions between different parts of the ecosystem. In this current system, an effect on cod will not have any consequences for its prey, e.g. herring, even though a decrease in cod will be positive for its prey. For the ecosystem components that are habitats, sensitivity to pressures considers the effect on the biotope in its entirety, which implicitly includes interactions between its species and how well the habitat tolerates disturbance. Interactions between ecosystem components could result in a regime shift, with a change in the balance or dynamics of the ecosystem.

Symphony does not currently process historic changes, only the impact on the existing ecosystem. This means that all pressures that have caused historic environmental impacts and regime shifts do not necessarily emerge as equally important in the analyses.

Symphony calculates the total environmental impact without weighting between ecosystem components in order to keep the approach transparent and the limitations easily understood. This means that the impact on rare species and biotopes is overshadowed by the impact on those that are more common. To understand impact on underrepresented species such as deep sea corals, tailored analysis can be made specifically for such ecosystem components.

Single short-term disturbances, such as construction work and accidents are not included among the pressures. This is because individual short-term disturbances cannot easily be described numerically on the same scale as long-term disturbances. Symphony provides an illustration of the long-term environmental impact; the inclusion of impact of single disturbing elements would thus be overrepresented in the results. Environmental impact of construction work and accidents must therefore be processed using methods other than Symphony. Additional pressures that are absent among the current data include marine litter, micro plastics, introduction of invasive species, and emission of environmentally hazardous substances from shipping (only oil spills, noise, and erosion effects from shipping are currently included). Environmental impacts from these pressures have been difficult to describe spatially.

Symphony builds on the assumption that the impact of several pressures results in an equal and additive effect. For example, that the impact from noise can be added to the impact from environmental toxins in the proportions 1+1. This may be incorrect, it could also be possible that exposure to environmental toxins reduces the sensitivity to noise (antagonistic effect, 1×0.5+1) or increases the sensitivity to noise (synergistic effect, 1×1.5+1). Research into non-linear cumulative effects is in its infancy, and has thus not been included. However, many studies have been conducted in recent years and these results indicate that most pressures are additive or antagonistic (Cote et al. 2016).

Finally, positive environmental impacts cannot be processed in the current version of Symphony. If an artificial reef means a positive change in an area, this could also result in an increased environmental impact because the reef creates an additional value as an ecosystem component, which in turn contributes to a higher environmental impact if there are pressures that affect this area. This is correct, but the result can be misleading since the added ecological value is not reported positively in the analyses. Furthermore, breakwaters and foundations are present in Symphony both as an ecosystem component (artificial reef) and pressure (infrastructure in the sea), which means that the environmental impact automatically increase if the sensitivity matrix connects them.

Symphony has two inherent uncertainty maps, which show the area with and without and a complementary one representing data as well as the quality of the data in the area (based on point data, or unverified or verified model). Uncertainty maps for the climate change layers will also be developed.

2.3 Sensitivity matrix

One of the weaker links in Symphony is the subjective opinions in the sensitivity matrix. As the matrix is based primarily on expert opinion, there is a need to restrict the bias as much as possible. This has been estimated by letting the experts' judge to what degree of certainty they have for their responses to the survey. These responses were divided into certain and uncertain answers. There was a slight, but in some cases significant difference. This justified the exclusive use of high certainty responses in the matrix. Few of the experts referred to literature to motivate their assessment however,as such citing was not requested as mandatory. Based on the few reported references to literature it was not considered meaningful to use them in a concise analysis, as they would introduce relevance bias. Instead cross-validation was conducted through comparison with other existing sensitivity matrices, for example the one used by HELCOM for its Baltic Sea Impact and Pressure Indices. The experts are well known in their own fields, and the sensitivity matrix consists of well over 1,000 correlations, which has been deemed impossible to find relevant literature references for. Instead, the Symphony sensitivity matrix has been compared to a Danish sensitivity matrix for the North Sea. Large discrepancies (+/- 30%) have been analysed and adjusted for.

The most controversial topic has been climate change impacts. As the past and current expert data on this has been weak, we improved this by extending the expert pool with species and habitat experts, in addition to the climate change experts. We set up a Delphi-method workshop during early spring 2020, where the respondent experts collectively discuss and decide on a number for each sensitivity matrix interaction.

3 Future scenarios

To study the influence on physical and biogeochemical parameters of climate change and nutrient loading in the Baltic Sea until year 2099, a regional, three-dimensional coupled physical-biogeochemical-ice model, RCO-SCOBI, was used (Section 3.3). In total, 21 simulations were performed to describe 6 combinations of climate change and nutrient load scenarios (Table 1). The change scenarios were RCP4.5 and 8.5 (Section 3.1), and the nutrient load scenarios were the Baltic Sea Action Plan (BSAP), Reference (REF), and Worst case (Worst) scenarios (Section 3.2).

3.1 Climate scenarios

To perform climate projections for a smaller region, downscaling of the coarse-resolution Global Climate Models (GCM) is required. GCM's are global three-dimensional earth system models that include 3-dimensional general circulation models for atmosphere, ocean as well as a parameterisation for the land surface. As basis for the 5th IPCC assessment report, a number of GCMs were used to obtain projections for 4 different Representative Concentration Pathways (RCPs) for the cumulative effect from greenhouse gases. An RCP represents the radiative forcing at the end of the century due to greenhouse gases in the atmosphere. The radiative forcing is a measure for the difference in radiative solar energy that comes in to the Earth and the energy that radiates back out into the space. However, the GCMs are too coarse to produce applicable climate change information on a regional level. Therefore, a regional climate model (RCM) is used for downscaling to a higher resolution. The approach is to first perform model runs with the GCMs forced by RCPs to simulate the response of the global climate system due to increased radiative forcing in the atmosphere. The results from the GCMs are then used to force the RCM, which is a regional coupled physical ocean–atmosphere model. The RCMs have higher resolution than the GCMs and often have more detailed topography and coastlines, and advanced parametrisation schemes for small scale processes. This allows regional-scale effects to be added more adequately to the broad projection of conditions provided by the GCMs. Finally, the atmospheric forcing from the RCM is used to force a coupled physical-biogeochemical ocean model.

Table 1. A summary of Global Climate Models (GCM), Representative Concentration Pathways (RCP), Regional Climate Model (RCM), nutrient load projections, and the coupled ocean-biogeochemical model (Ocean model) used to build an ensemble of integrate future projections for the Baltic Sea.

RCP	GCM	RCM	Nutrient load	Ocean model
4.5	MPI-ESM-LR [a]	RCA4-NEMO	Baltic Sea Action Plan (BSAP)	RCO-SCOBI
8.5	EC-EARTH [b]		Reference (REF)	
	HadGEM2-ES [c]		Worst case (Worst)	
	IPSL-CM5A-MR [d]			

[a] http://www.mpimet.mpg.de/en/science/models/mpi-esm.html
[b] https://www.knmi.nl/kennis-en-datacentrum/achtergrond/ec-earth-goals-developments-and-scientific-perspectives,
[c] http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadgem2,
[d] http://icmc.ipsl.fr/

In this project, four GCMs were selected (Table 1) as these perform reasonably well in the North Sea and Baltic Sea regions for simulation of present-day climate. They correspond to the optimum subset of models to estimate uncertainties for the climate system results of this region (Wilcke and Barring 2016). The RCM used is the Rossby Center Atmosphere Version 4 atmosphere model coupled to the Nucleus for European Modeling of the Ocean model (RCA4-NEMO) (Dieterich et al. 2013; Wang et al. 2015). RCA4-NEMO is a high resolution coupled atmosphere-ocean climate model, with an interactively coupled mass and energy fluxes (Dieterich et al. 2019; Gröger et al. 2019; 2015; Wang et al. 2015). This gives a more realistic representation of the complex atmosphere-land-sea boundary layer compared to the respective standalone models for the ocean and the atmosphere. A coupled RCM is needed to produce afterwards spatially refined climate fields over the Baltic Sea, as the dynamics between sea surface, land surface, and atmosphere is better resolved.

Future climate is strongly dependent on how the Greenhouse Gases (GHG) emissions develop. Two RCPs utilised by the IPCC for its 5th assessment report (AR5) are used to describe radiative forcing (IPCC, 2013). Selected RCPs are 4.5 and 8.5, as they represent an intermediate and an extreme scenario respectively. In the RCP4.5 scenario, the carbon dioxide emission peak around 2060 and the radiative forcing are then stabilised at 4.5 W/m^2 and contains assumptions about moderate climate mitigation actions. It has an expected global atmospheric warming of 1.1-2.6°C (Ipcc 2013, Table SPM.2). RCP8.5 is 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.

3.2 Nutrient scenarios

Three different nutrient load scenarios, from a green road to a worst case, were simulated with river nutrient concentrations related to future development in the Baltic Sea region (Zandersen et al. 2019), consistent with the global Shared Socio-economic Pathways (SSP) developed for climate research. Hydrological discharge data for the supply of river runoff and nutrients to the open sea are based on the results from the hydrological model E-HYPE (Hydrological Predictions for the Environment, http://hypeweb.smhi.se), which is a process based multi-basin model for Europe (Donnelly et al. 2013; 2017; Hundecha et al. 2016). The E-HYPE simulations used the same radiative forcing and are driven by the same GCMs and RCM as the ocean model, the RCO-SCOBI. Below is a short summary of the three nutrient load scenarios (Fig. 2) modified from Saraiva et al. (2019a; 2019b). For further details, see Zandersen et al. (2019).

- **Baltic Sea Action Plan (BSAP)**: This scenario is related to SSP1, the sustainable or green road where the translation to the Baltic Sea is the BSAP proposed by HELCOM (2007; 2013). In this scenario, nutrient loads from rivers in different basins will linearly decrease from 2012 from current values (average 2010–2012), to the maximum allowable input defined in the plan until 2020. The nutrient loads then remain constant until 2100. Furthermore, atmospheric depositions are assumed to follow the BSAP.
- **Reference**: This scenario is related to SSP2, the middle of the road. This scenario assumes no socio-economic changes compared to the historical period (1976–2005). The nutrient load changes are only changing climate induced (runoff and atmospheric conditions). The scenario uses the E-HYPE projections for nutrient loads under two different greenhouse gas emission scenarios (RCP4.5 and RCP8.5) where the land and fertilizer usage, soil properties and sewage water treatment do not change over time. The assumptions of this scenario are based upon past developments (e.g., economic growth, demographic transition).
- **Worst:** This scenario is based on SSP5, the worst scenario with increasing nutrient loads. SSP5 assumes a fossil-fuelled development with accelerated globalisation and rapid development of developing countries. This scenario was built by combining the climate change effects caused by runoff changes (E-HYPE projections on nutrient loads for RCP4.5 and 8.5) with a socio-economic impact factor that summarises the impact of socio-economic development on current nutrient loads. Changed atmospheric depositions following the socio-economic development of this scenario are considered, meaning that nutrient load changes respond to both changing climate and socio-economic effects.

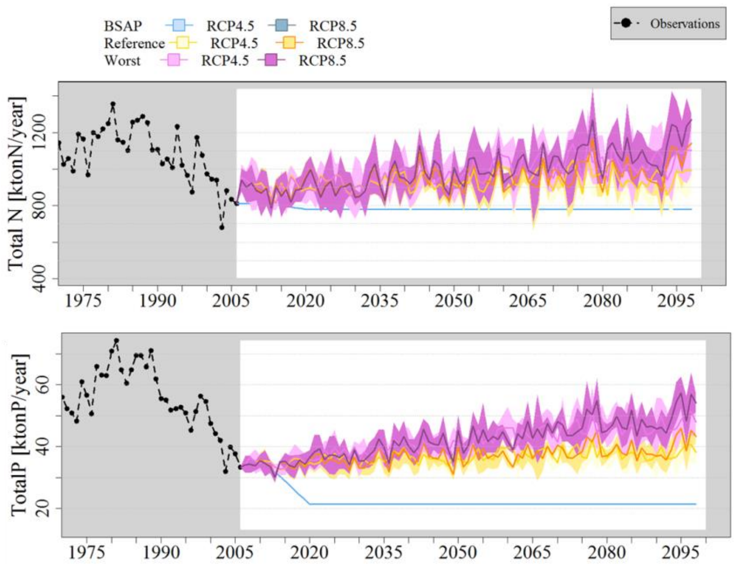

Figure 2. The three nutrient load scenarios calculated for the Baltic Sea. Observed and projected ensemble mean of the total bioavailable nutrient loads of nitrogen (upper) and phosphorus (lower) to the Baltic Sea between 1970 and 2098 (sum of loads from rivers, point sources and atmosphere). The results were calculated as the ensemble average (see section 3.4 for explanation) from four hydrological model simulations during the historical (1976–2005) and future (2069–2098) periods according to the RCP4.5 and RCP8.5 scenarios combined with three nutrient loads scenarios (BSAP, Reference, and Worst Case). The coloured shaded areas are the standard deviations among the ensemble members. Modified from Saraiva et al. (2019b).

3.3 Model overview

To study the influence of climate changes and human activities on biological and chemical processes and the cycling of nutrients in the Baltic Sea, the three-dimensional physical-biogeochemical model RCO-SCOBI was used. The model consists of the physical Rossby Centre Ocean (RCO) model (Meier et al. 2003) coupled with the Swedish Coastal and Ocean Biogeochemical (SCOBI) model (Eilola et al. 2009). The horisontal and vertical resolutions are 3.7 km and 3 m (corresponding to 83 depth levels) respectively, and have an open boundary in the northern Kattegat.

The biogeochemical model SCOBI (Fig. 3) describes the dynamics of:

- Nitrate (NO_3)
- Ammonium (NH_4)
- Phosphate (PO_4)
- 3 phytoplankton groups (diatoms (A1), flagellates and others (A2), and cyanobacteria (A3))
- Zooplankton (ZOO)
- Nitrate and Phosphate Detritus (ND and PD)
- Oxygen (O_2)

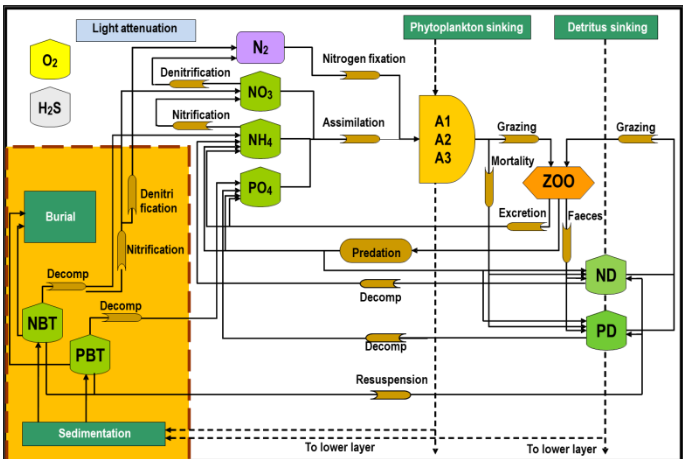

Figure 3. Schematic picture of SCOBI, the Swedish Coastal and Ocean Biogeochemical model. For abbreviation see text.

The sediment contains nutrients in the form of benthic nitrogen (NBT) and benthic phosphorus (PBT). A simplified wave model is used to estimate the resuspension of organic matter (Almroth-Rosell *et al.*, 2011). In addition to these biogeochemical parameters, physical parameters are simulated, e.g. temperature and salinity. RCO-SCOBI has previously been evaluated and applied in numerous long-term climate studies. For further details and for thorough evaluation the reader is referred to Meier et al. (2003; 2011; 2012), Eilola et al.(2011; 2009) and Almroth-Rosell et al. (2011).

3.4 Uncertainties in climate projections

Uncertainties of future climate projections arise mainly from three sources: (i) the scenario uncertainty, i.e. which RCP and nutrient load scenario that is actually closest to what is really going to happen, (ii) the internal variability, i.e. the natural variability that causes differences on various time scales, and (iii) model uncertainty that is caused by lacking, poor or coarsely represented processes in the models. The scenario uncertainty is handled by investigating various possible scenarios that comprise the probable realization. In the present case this is done by a matrix of two RCPs and three nutrient load scenarios. The model uncertainty is estimated at regional scale by performing regional downscaling for as many as possible different global models and not using only one model.. In many cases bias adjustment is also performed to reduce GCM errors before downscaling. However, also regional models have model uncertainties due to missing or inadequately resolved processes. In order to handle internal variability and model uncertainty, an ensemble of model runs is performed for each combination of scenarios in order to cover different possible realizations for each scenario. In ClimeMarine this is done by using an ensemble of GCMs. This results in a multidimensional ensemble matrix that in ClimeMarine is built along three coordinate axes representing; the different available global climate models, eutrophication scenarios, and RCP scenarios.

Ensemble modelling results in a range of possible outcomes rather than a specific number. This may be a problem for people affected by changes due to climate and eutrophication. Handling uncertainties depends strongly on the specific needs of affected persons. For planning agencies, it may for example be important to know the risk of extreme sea levels in the future. For that, one would either have to assume an RCP or associate a probability to each RCP. For decision makers, it may be useful to calculate mean changes over available models in order to extract the benefit of a low emission RCP scenario over a high emission RCP scenario. In contrast, averages over different climate scenarios should be avoided because scenarios are often built upon contradicting assumptions (e.g. GHG emissions cannot rise and decrease at the same time). ClimeMarine agreed to deliver data from all available combined scenarios, in order to assess the cumulative effect of climate change and other drivers of change in the Swedish seas. Guidance is thus needed how this information can be used in a reasonable way, considering the specific activities carried out by affected persons.

In summary, uncertainties accounted for in ClimeMarine comprise those associated with different RCP scenarios, nutrient load scenarios (eutrophication), internal variability, and model uncertainty. This is an important challenge to address during the project, both scientifically and visually through Symphony and the associated ClimeMarine maps. It is important to bear in mind, and to communicate, that Cumulative Impact Assessment methodology and Symphony address management issues at a large scale strategic level. At this level, uncertainties aggregate and any use of the results will have to consider the limitations of the method. Symphony is a decision support tool tailored for usage at this strategic level only, and is unsuited to be used for detailed area analyses.

4 How to include connectivity in Marine Spatial Planning

It is challenging to include connectivity in Marine Spatial Planning because connectivity is a relationship between pairs of locations and not easily visualized into a mapping tool. In this project, connectivity is based on modelled dispersal probability between all locations within the HELCOM area. At this stage we are focusing on species where dispersal is strongly influenced by the water transport, which is modelled with SMHIs oceanographic circulation models combined with biological traits. We work with two main strategies. First, we will produce maps of network metrics based on connectivity matrices, e.g. source strength, which indicates the importance of a site to provide recruits to other areas. This information is also combined with the Species Distribution Models (see 5.5 below) to indicate particularly important areas. Secondly, we are implementing the full connectivity matrix into Symphony to distribute localized pressures (e.g. pollution, dredging, shipping etc) to surrounding areas according to modelled connectivity.

In addition, we include the bold task of producing a database with future connectivity using a biophysical model forced by an ocean circulation model (RCO-SCOBI) with projected velocity fields for the period 2093-2097 and for the emission scenarios RCP4.5 and 8.5.

5 Projected habitat changes as a complimentary method in Marine Spatial Planning

A complementary method to the cumulative impact method in Symphony to assess pressure and risk for ecosystem changes is to model future scenarios for habitats, given the same climate variables as used in the analytical process of Symphony.

By modelling ecosystem changes, it is possible to delineate areas where climate effects are projected to have direct impacts, both positive and negative, to the ecosystem components in Symphony. The results from this modelling are ecosystem component maps under future climate conditions without considering future human pressures. These will be used for several purposes:

- Delineations or bracketing of future climatic limits to valuable areas for ecosystem components and services, i.e. climate envelopes and ecosystem limits on a habitat level.
- Modelling of valuable areas in respect to current and future ecosystem components and services, e.g. as a basis for a more future-proof “green map”, aggregated by ecosystem service or ecosystem value using the MOSAIC framework (Hogfors et al. 2017).
- Delineation of areas with habitat patches resilient to climate change, an aspect that should be considered when planning spatially for the future.
- Identification of especially valuable resilient habitat patches that may form climate refuges in the future: either locations on the climatic fringe of habitats, patches central in the future green infrastructure (through connectivity, germination, movement etc. – see above in the section on connectivity) or habitat patches valuable through their future size and abundance. Climate refuges may form important components of future Marine Protected Areas (MPAs) and be included in future revisions of the Swedish Marine Spatial Planning.

Habitat models can also be used to create location-specific pressure data for use in Symphony. As modelled habitat change 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 Symphony process. A future area of development is thus how the habitat change model can be incorporated into the pressure calculations of the Symphony method. Within this work package, future predicted habitat changes are modelled according to a method described below

5.1 Selecting time horizon, scenario, and data for future habitat distribution modelling

Available data for relevant parameters covers the historical reference period (1961-1990), the midpoint of future projections (2035-2064), and the end point (2070-2099).

From the three available nutrient load scenarios the Reference scenario (Sect 3.2, Fig. 2) is used for biogeochemical parameters. For each parameter, available data gives estimates for monthly averages as well as maxima and minima for the different scenarios (RCP4.5 and 8.5), and for each GCMs. By this, not only the mean change is considered, but the change in extreme conditions as well. For the purpose of testing this methodology, ensemble averages have been chosen for Reference scenario of the RCP4.5 and RCP8.5 scenarios and for the 30-year end-period (centred around 2085). For a moderate estimate of plausible peaks and lows in data, the ensemble maxima and minima within each season has been chosen (e.g. the warmest ensemble summer month). For more extreme values, it would be possible to take the maximum seasonal value from one specific model or the maximum of the model average over a season.

Habitat modelling has been performed for three scenarios; (i) the reference period, using reference data, forming a baseline or predicted distribution today, (ii) RCP4.5 at year 2100 with ensemble mean values, and (iii) RCP8.5 at year 2100 with ensemble mean vales. Ensemble max and min values will be tested later, once the base predicted future habitat maps have been produced. Specifically, maximum and minimum values will be tested in respect to factors possibly strongly adversely affecting benthic communities, such as low oxygen and low salinity during a single season to investigate possible magnitudes and extents of century extremes.

5.2 Climate data for modelling habitat changes

Owing to the mesosaline character of the Baltic Sea, salinity gradients are a major contributor to zonation of benthic communities. Likewise, the mix of cool freshwater runoff in springtime, and cold saline bottom waters and warm coastal waters in the summertime, makes temperature gradients a major structuring factor. Oxygen depletion primarily in the deeper portions of the Baltic and dissolved nutrients in the photic nearshore zone, together with light availability 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 and changes in wind patterns are likely to affect both ocean circulation and wave climate. These parameters, all volatile and influenced by climate change, interact with the more stable marine landscape consisting of the seabed substrate, topography, and the more general regional wave climate and bottom currents to shape the benthic communities. These parameters have been tested and selected based on their explanatory power in the various predictive models used and mentioned below.

We obviously do not know how society will handle nutrient discharge in the future. The selected nutrient load scenario represents no socio-economic changes compared to the historical period (Reference scenario). 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 results are reduced nutrient load and improved water clarity (Meier et al. 2019) and, in this case, the distribution of many species will probably be increased, e.g. with an improved ecology (Friedland et al.

2012), due to a reversal of the long-term eutrophication effects (Andersen et al. 2017). If the Worst scenario is used, it will probably result in opposite results and impoverished habitats for most important habitat-forming species. As we do not know if the nations around the Baltic Sea will successfully implement the Baltic Sea Action Plan, we must assume that it is indeed probable that ongoing mitigation efforts (and current slight improvements nutrient input to the Baltic) will not lead to a worst case scenario, the Reference scenario 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.

5.3 Data preparation and validation needed for working with habitat changes

Both physical and chemical data need to be harmonised before being used in habitat modelling. A challenge is to make the (from a habitat perspective) coarse models from e.g. RCO-SCOBI useful for Symphony. This harmonisation has two aspects: geographical (areal) adjustments/interpolations and temporal generalisation. A positive aspect is that, as water is in constant flux due to waves and currents, a coarser model for water characteristics can be used as an approximation for water characteristics over time. Likewise, benthic biota like perennial algae are rarely permanently altered by momentary fluctuations in the physical or chemical properties of the surrounding water, so habitats are to a large degree shaped by seasonal climates. This means that with a wise choice of temporal generalisations, various climatic indicators useful on Symphony level, can be assembled from the coarser model data available. Precisely how this should be done varies with project preconditions, but a general suggestion and method to create the following datasets follows:

- Total means, maxima and minima of ensemble means (not ensemble extremes or model extremes) for yearly and seasonal data (cold period and warm period).
- Data for bottom layer, surface layer, and water column mean, and the above values and seasons. Surface and bottom layers are extracted from the 3D model data as the first and last data value in each pixel stack.
- These datasets adjusted to the resolution (interpolated, bilinear) and extent of Symphony grid.

As model data is missing in many complex nearshore environments (fjords, archipelagos) data needs to be projected into these areas from adjacent pixels. The method used for this purpose was 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 shallow water in the coastal zone is cooled quicker than surrounding water and also receives cool meltwater in springtime. The oxygen level is lower in the nutrient-rich inner archipelago, 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 archipelagos and sounds trap nutrients from runoff.

5.4 Preparing and adapting supporting physical data

Aside from data already available in Symphony and the data prepared from climate models, the following datasets were assembled and adjusted to the Symphony grid for habitat modelling:

- Water velocity at the seabed (currents and wave velocities), and wave exposure at the surface.
- Metrics calculated from bathymetry (i.e. benthic topographic indexes, slope and rugosity).
- Isostatic uplift, affecting future bathymetry.
- Light availability at the seabed.
- Seabed substrate data (modelled).

The following data, affecting habitat structuring, needed to be adapted to a change of climate by using the datasets mentioned above:

- Bathymetry needs to be adjusted to a change in sea level and isostatic uplift.
- Light availability at the seabed needs to be adjusted by a change of depth and light penetration.

There is no high-resolution model, relevant on a habitat modeling scale, over future waves and currents that cover the entire Baltic Sea area. Both the future magnitude of storm surges and the direction of the wind/fetch are uncertain, which makes this parameter very uncertain and calls for further attention. It is therefore omitted at this stage. This is a limitation since benthic communities both at sheltered and exposed locations are likely to be affected by altered oceanographic conditions due to climate change. This will be investigated further in the light of available data.

5.5 Methods for modelling habitats using climate data

The relationship between benthic communities and physical/chemical parameters are poorly understood and by all accounts very complicated. However, pragmatic approaches to model the distribution of species and the influence upon them exist. Instead of empirical/experimental studies, it is possible to model the probable extent of habitats (climate envelopes, niche models, species distribution and habitat suitability models) by establishing relationships between physical/chemical variables and species occurrence/abundance using statistics, modelling techniques, and machine learning.

Once such relationships are established, future extents of habitats can be modelled by applying future physical/chemical variables to the modelled relationships. 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.

Within this work package, different models have been tested and were selected for the most robust one, yielding high measures of confidence (e.g. true skill statistics (TSS) or Receiver Operating Characteristic (ROC)). The analytical framework was the R programming language, in which a variety of modelling methods were tested including 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).

Results comprises predicted habitats of selected benthic species, as well as a quantification and localisation of changes (loss and gain of habitat), accompanied with measures of model performance. From these habitat maps, maps of high ecological values with respect to potential for key species was created, as well as maps of predicted habitat change and habitat refuges, showing future modelled presence weighted by resilience (habitat patch size and abundance) and connectivity according to a method determined within the Pan Baltic Scope project (http://www.panbalticscope.eu/).

5.6 A note on uncertainties

On a general level, projections are made for two climate scenarios. It is wholly uncertain which projection is most probable. The most decisive uncertainty is perhaps not how climate parameters depend on emission levels of climate gases but rather societal, economic and political developments and, consequently, the path which society takes, and which emission scenario which is most probable. While the RCP4.5 roughly corresponds to a global temperature increase of 2°C or an ambitions societal effort to tackle climate change, the RCP8.5 (or 4°C) represent the more probable *laissez faire* scenario, ”business as usual”. Therefore, modelling results for both scenarios are kept. Aside from the selected scenario, it is possible to model habitats using various average and extreme values, which has been mentioned above. The purpose of current project is to present a moderate variant of each scenario, with the ensemble averages previously discussed.

5.6.1 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 possible to get distribution approval from the Swedish Defense Forces. At this level, each pixel represents an average of microenvironments 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 modelling captures 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%, both user and producer accuracy. Technical performance is included in the deliverables and an example is given in Table 2 (Allouche et al. 2006; Guisan et al. 2017). This means 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*. The methods used are: evaluation of the model using the Cohen's Kappa statistic (Kappa); average of model means weighted by True Skill Statistics (TSS); and evaluation of the model using the Area Under the ROC (Receiver Operating Characteristic curve). Cutoff is optimal decision threshold, the associated cut-off used for transform fitted vector into binary outcome. Sensitivity can be described as the ratio of positive sites (presence) correctly predicted over the number of positive sites in the sample. Specificity is the ratio of negatives sites (absence) correctly predicted over the number of negative sites in the sample.

Method	Cutoff	Sensitivity	Specificity
KAPPA	356.0	97.486	83.585
TSS	699.0	89.868	95.921
ROC	696.5	89.944	97.08

5.6.2 Environmental variables

The actual primary results of the modelling process are models of the dependence of habitat on the environmental variables. Especially in the coastal zone, predictors such as temperature and salinity lack resolution, being resampled from 1 or 2 nm 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 subregions for more detailed studies, but that would require improvements in hydrodynamic models, models over nutrient flows and salinity gradients etc.

There might exist environmental variables relevant to species distribution but which are not included in the models. Likewise, there are most probably dependencies between species and habitats that could be investigated using joint species distribution models, something which is not dealt with at this stage.

As previously mentioned, the nutrient load scenarios available are the Baltic Sea Action Plan (BSAP), Reference (REF), and Worst case (Worst) scenarios (Table 1, Section 3.2), of which REF was used to drive oxygen level but BSAP and Worst will be used in future work. Nutrient load as such was not included directly into the habitat models for two reasons. First, the parameters are more relevant in the BSAP or worst case scenarios, where they are predicted to lead to noticeable changes in habitat preconditions (Friedland et al. 2012). Secondly, nutrient load is particularly volatile, and any modelling including such predictors need 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 chlorophyll a and nutrient concentrations (NH_4, PO_4, NO_3) can be used both to try to find relevant biota samples correlating with nutrient loads. 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.

5.7 Using the results from the habitat models

Modelled projections of future habitats indicate areas resilient to climate change, and thus point to areas of concern and of conservation value. The results also have potential to improve the Symphony sensitivity matrix by analyzing the modelled changes of ecosystem components together with climate-induced pressures. 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, and also by directly relating modelled ecosystem changes with climate induced changes of physical/chemical parameters at specific locations.

In summary, the modelled habitat changes can lead to further refinements of the Symphony methodology in respect to the sensitivity matrix, cumulative impact, ecosystem values, and subsequently influence the national Marine Spatial.

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