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Predicting the Impact of Climate Change on the Distribution of the Key Habitat-Forming Species in the Ne Baltic Sea

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ABSTRACT

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Macrophytes provide food, shelter and habitat for a multitude of other species and are therefore considered as important habitat-forming species. Loss or decrease of habitat-forming species severely affects biodiversity and functioning of coastal marine ecosystems. In the brackish Baltic Sea, such special, structuring species are large perennial macroalgae *Fucus vesiculosus* and *Furcellaria lumbricalis* on hard seabed and eelgrass *Zostera marina* and charophytes (*Chara* spp.) on soft substrates. The Baltic Sea is expected to face severe changes in environmental conditions due to climate change by the end of the 21st century, e.g. decrease in salinity and increase in temperature, wind speed, and storminess. It is essential to forecast changes in the distribution of valuable species in order to provide data for marine environmental protection and management decisions. Boosted regression trees modelling method was used to produce current species distribution models and predict the potential changes based on future climate scenario. Data from over 10 000 benthic sampling sites were used as an input for distribution models. Following the influence of the water depth, the next major drivers of species distribution were substrate type for *Fucus*, temperature for the charophytes and *Furcellaria*, and salinity for *Zostera*. Based on the model predictions, the climate change may cause a significant reduction of the distributional range of *Zostera* and *Furcellaria*. Slight decline of *Fucus* was also detected. Unlike the other habitat-forming species, charophytes are potential winners by probably increasing their distribution in the future. However, charophytes are not able to replace the niche of the other key habitat-forming species due to different substrate, wave exposure and salinity preferences.

ADDITIONAL INDEX WORDS: *Macrophytes, species distribution modelling, abiotic environmental factors.*

INTRODUCTION

Ongoing climate change has been demonstrated to have remarkable effects on the distribution of benthic macrovegetation (Takolander, Cabeza, and Leskinen, 2017). Climate change is expected to have the strongest effect in enclosed northern areas like the Baltic Sea (Dippner, Fründt, and Hammer 2019). The Baltic Sea is a brackish water sea featuring considerable north-south direction salinity gradient, spatio-temporal variations in thermohaline stratification and pronounced seasonality (Soomere *et al*., 2008). The Baltic Sea hosts a mixture of submerged aquatic vegetation of marine, brackish and freshwater origin, living often close to their physiological limits (Snoeijs, 1999). Therefore, even small changes in the abiotic environment can dramatically affect species distribution (Jonsson *et al*., 2018).

Loss or decrease of habitat-forming species severely affects the ecological stability and functioning of marine ecosystems (Lemieux and Cusson, 2014). In the Baltic Sea, the habitat-forming species are perennial brown macroalga *Fucus vesiculosus* L. and red alga *Furcellaria lumbricalis* (Hudson) Lamouroux on hard substrates (Jonsson *et al.*, 2018; Takolander, Cabeza, and Leskinen, 2017) and eelgrass *Zostera marina* L. and charophytes (*Chara* spp.) on soft substrates (Boström et al., 2014; Schubert and Blindow, 2003). Additionally to the attached form, the unique loose-lying community, dominated by permanently unattached form of *Furcellaria,* exists in soft bottom areas in western Estonia. This community forms thick carpet on the seafloor and enhance the diversity of macroinvertebrates by offering a secondary substrate for several true hard-bottom species (Kersen *et al.*, 2009).

The aims of this study were to (1) predict the current and future distribution of key habitat-forming species in the north-eastern Baltic Sea; (2) elucidate which species potentially benefit, or on the contrary, are adversely impacted by climate change; and (3) assess the contribution of environmental variables in predicting the distribution for the species.

METHODS

The study was conducted in Estonian coastal waters in the NE Baltic Sea. The study area includes three major sub-basins of the sea (Baltic Proper, Gulf of Finland and Gulf of Riga) and a small West Estonian Archipelago Sea, which is surrounded by islands and the Estonian mainland. All the sub-basins exhibit considerable

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gradients in depth, wave exposure and salinity. Salinity exceeds 7 in the westernmost study area while it falls to almost 0 in the inner parts of bays with riverine inflow.

Biological Data

Data from 11,474 benthic sampling sites from years 2005–2015 were used as an input for a mathematical model to predict the occurrence of the studied species. The presence–absence data of the species was used based on a visual species determination by a scuba diver at a sampling site or in a laboratory based on underwater video recordings or biomass data collected by grab samplers (soft bottom) or by scuba divers with a metal frame (hard bottom). Geographical coordinates were determined in each sampling site using a handheld GPS device. The collection and analysis of biomass samples followed the HELCOM guidelines.

Four habitat forming species or taxa were included in this study. *Fucus*, *Furcellaria* and *Zostera* are marine species, that can tolerate brackish conditions (minimum salinity limits 1.5–5, depending on species). Charophytes are of freshwater origin. A total of 3619 sites included at least one species of the key habitat-forming taxa.

Environmental Data

The abiotic environmental variables in this study included water depth, wave exposure, salinity, sediment type and temperature, which were all available as raster layers in a geographical information system (ESRI ArcGIS). Depth data originated from the Estonian Maritime Administration. A simplified wave model was used to characterize the wave exposure. The simplified wave model incorporates shoreline topography, fetch and wind data, together with empirically derived algorithms to mimic diffraction (Isæus, 2004). The sediment type was expressed as value between 0 and 1, and it showed the summed proportion of soft substrate types (mud, clay, sand, gravel) in seabed substrate. Temperature and salinity data layers for the current state as well as for future climates originated from the ECHAM5/RCAO general circulation model (GCM) output, which were available from the study by Meier *et al.* (2012). The coupled physical–biogeochemical model used regionalized data from the ECHAM5 (Roeckner *et al*., 2006) and included the 3D ocean circulation model (the Rossby Centre Atmosphere Ocean model, RCAO), acquired from the Swedish Meteorological and Hydrological Institute (Meier, Döscher, and Faxen, 2003). As the ocean circulation model was three-dimensional, we only used data from the bottom water layer.

Future Climate Scenario

In order to consider future climate change, seasonal means for winter (December to February) and summer (June to August) water salinity and temperature were used for the period 2070–2099. The future scenario considered the A1B emission scenario which was based on an assessment of the future developments (e.g. in demographic change, economy and technology) and emissions of CO_2 and other greenhouse gases (Nakićenović *et al*., 2000). Based on this climate scenario, the mean salinity will decrease from 5.5 to 3.7 (largest change of 3.3 unit) in the study area while the mean temperature is projected to increase from 16.6 to 18.3 °C (maximum increase of 7.7 °C) in summer and from 1.4 to 4.5 °C (maximum increase of 3.9°C) in winter, depending on area.

A uniform 10% increase in annual mean wind speed was used, which applies on a 6 m s^{-1} long-term mean windspeed on Estonian coastal sea locations. Due to the counteraction processes (global sea-level increase) and glacio-isostatic uplift, the sea-level changes were considered negligible and were not considered in future modelling. Also, the same sediment data were used in the present and future scenario models as it was presumed that these variables will not change significantly. See more detailed explanations in Torn *et al*. (2019).

Modeling

The predicted distributions of habitat-forming species were modeled using the boosted regression trees (BRT) method. BRT is an ensemble method that combines regression trees and boosting (Elith, Leathwick, and Hastie, 2008). For species distribution predictions, BRT models with tree complexity of 5 were built, the learning rates of models were set to 0.005 and the bag fraction was set at 0.5 which is the recommended default value (Elith, Leathwick, and Hastie, 2008). The input data was randomly partitioned into calibration (85% of data) and validation (15% of data) datasets. Mean absolute error (MAE) and correlation analysis (Pearson r) were used to evaluate prediction accuracy of the species distribution models using the validation dataset. Model predictions were calculated for both, present and future climate scenarios. For future predictions, the values of temperature, salinity and wave exposure based on the future scenarios were entered into the models. Model predictions were calculated to each point in the prediction dataset covering the study area with 100 m rectangular equispaced grid. The output of a model was the prediction of the probability of occurrence of a given species in each grid cell. The probability of occurrence was translated to presences and absences using sensitivity–specificity difference minimizer (Jiménez-Valverde and Lobo, 2007). The point-wise predictions were converted to rasters. The modeling and conversion to rasters was done in the statistical software R 3.3.1 (R Core Team, 2016). The R package gbm (Ridgeway, 2007) was used for BRT modeling.

RESULTS

Depth was the most influential environmental variable in predicting the spatial distribution of species (Figure 1). Other variables had notably lower importance and the order of importance was species specific. The next major drivers were substrate type for *Fucus*, temperature for the charophytes and *Furcellaria*, and salinity for eelgrass *Zostera*.

The distribution extent of all marine species was similar, and they may occur all over the coastline except eastern part of Gulf of Finland and few bays where the low salinity and/or lack of hard substrate limits the distribution (Figure 3). The largest suitable habitat was predicted for *Furcellaria* (~3800 km^2), followed by *Fucus* and charophytes (both ~1100 km^2).

Based on the modeling results, the climate change will cause a significant reduction of the distribution area of *Zostera* and *Furcellaria* (Figure 2). *Zostera* was predicted to almost disappear from the study area while *Furcellaria* is predicted to vanish from West Estonian Archipelago Sea. Slight decline of the brown alga *Fucus* was also detected. Unlike the other species, the distribution area of charophytes will probably increase in the future.

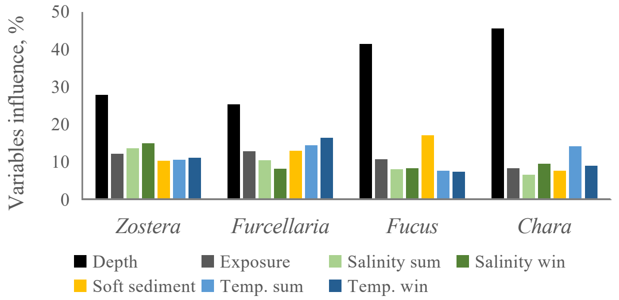

Figure 1. Influence of environmental variables in predicting species distribution in BRT models. Higher values indicate higher importance.

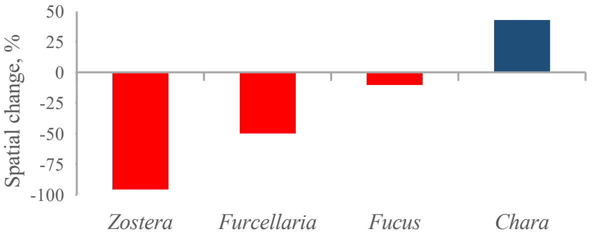

Figure 2. Change of spatial distribution of habitat-forming species.

DISCUSSION

The most important environmental variable describing the species distribution was water depth. The importance of other variables was significantly lower compared to depth. However, as indicated by the modeling results, the future shifts in temperature, salinity and wave exposure may cause marked changes in distribution of valuable habitat-forming species. Based on future predictions, *Zostera* and *Furcellaria* are highly endangered by environmental change while charophytes may benefit from it.

In the study area, water depth mainly influences the distribution of phytobenthic species through underwater light availability. *Furcellaria* had the largest current distribution whereas this species has the widest depth range compared to other studied species. Due to the steeper coastal slope, the occurrence of all habitat-forming species in the Gulf of Finland was notably narrower compared to the distribution area in the western Estonia.

At the moment, the majority of the photic seabed area has salinity over 4 in the Estonian sea area, but this area is expected to decrease over 40% in 100 years perspective. This change will cause distribution shift of marine species along the coastline towards more saline western areas in the Gulf of Finland. The same trend applies also for the western Estonia. Presented model predicted that in future, the whole West Estonian Archipelago Sea will be unsuitable for *Furcellaria*. That indicates a possible extinction of the unique loose-lying red algal community in the Baltic Sea because the loose-lying *Furcellaria* communities have practically disappeared in their former distribution area in Polish and Danish coasts due to eutrophication and excessive harvest during the last century (Kersen *et al.*, 2009). Due to the limits of salinity tolerance of *Zostera*, the future shift in salinity (mainly below 4) in the study area may cause a dramatic loss in the occurrence of the species. Based on our predictions, the distributional contraction of *Fucus* was 10% in Estonian coastal water, while along the whole Baltic coast the reduction of 30% is predicted (Jonsson *et al.*, 2018). The large-scale decline of those habitat-forming species is caused by the general decline of salinity in northern Baltic Sea (Meier *et al.*, 2012). Charophytes mainly occupy the shallow areas with lower salinities (Herkül, Torn, and Möller, 2018). Several charophyte species can withstand somewhat higher wave exposure and therefore are favored by the predicted change in relatively sheltered areas. Similarly to charophytes, other species with freshwater origin will probably expand their distribution under the future climate conditions (Torn *et al.*, 2019).

Rising temperature can benefit some species in the northern Europe through elongation of growth season. At the same time, rising water temperature leads to reduced oxygen concentrations, promote the dispersal of invasive species, and shortens the period of ice cover (Meier *et al.*, 2012). Reduced ice cover affects the benthic vegetation through reduced water transparency and elevated wave effect (Ejankowski and Lenard, 2016). Moreover, synergistic negative effect of raised temperature and low salinity is expected (Takolander, Leskinen, and Cabeza, 2017).

The replacement of habitat-forming species (e.g. northerly distributed kelp species to southerly distributed kelp species) due to climate change has been shown (Teagle and Smale, 2018). However, due to the species-poor environment there are no evident candidates to substitute the habitat-forming macrophytes in the northern Baltic Sea. Therefore, a dramatic decline of *Zostera* and *Furcellaria* will likely to be accompanied by severe loss of biodiversity. The largest decrease of species richness of macrovegetation caused by climate change was predicted to take place in West Estonian Archipelago Sea (Peterson, Herkül, and Torn, 2018). Similarly to that previous result, the major changes in distribution of habitat-forming species were predicted to take place in western Estonia also based on the results of the current study. The effect of climate change on benthic communities is strongest in shallow areas with low salinity where the effect of temperature and salinity change may be exceptionally severe. Species living near their salinity tolerance limit, like *Fucus*, *Furcellaria*, *Zostera* in the NE Baltic Sea, face especially high risk of decline or extinction due to climate change (Takolander, Cabeza, and Leskinen, 2017). It must be kept in mind that this study was purely correlative and biological interactions were not taken into account when modelling the future distributions of the species.

CONCLUSIONS

Based on the model predictions, the climate change may cause a significant reduction of the distribution of valuable habitat-forming species like *Zostera* and *Furcellaria*. Contrastingly, charophytes are potential winners by probably increasing their distribution in the future. However, charophytes are not able to replace the niche of the other key habitat-forming species due to different substrate, wave exposure and salinity preferences.

Although the climate change emission scenarios involve many uncertainties, the current study can still give some valuable insights of the direction of future changes and thus it enables to plan monitoring strategies and conservation measures for hotspot areas.

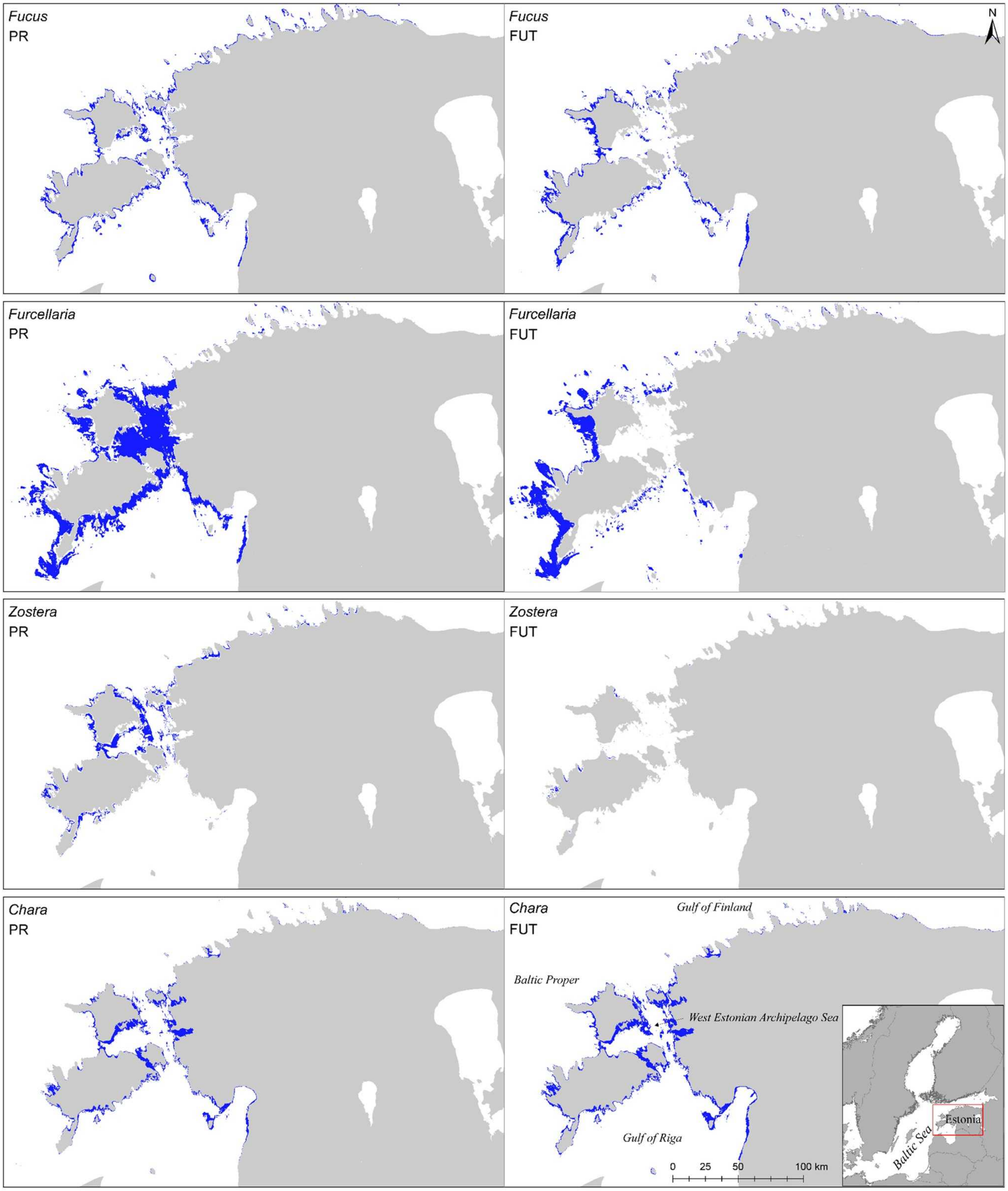

Figure 3. Distribution of species (blue color) as predicted by the BRT models for present (PR) and future climate scenarios (FUT) in Estonian coastal waters, NE Baltic Sea.

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