GoA 2.1. Assessing the PanBaltic potential of macroalgae cultivation and of harvesting wild stocks

Jonne Kotta, Holger Jänes, Tiina Paalme, Anneliis Peterson, Ilmar Kotta, Robert Aps, Robert Szava-Kovats, Ants Kaasik, Mihhail Fetissov

Estonian Marine Institute, University of Tartu

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Content

1. Summary

Sustainable cultivation and harvest of macroalgae plays a key role in meeting the goals of blue growth initiatives in the coming years as maritime activities are expected to increase. To secure space for macroalgae cultivation, spatial planners need to know which environmental variables drive plant production as well as where productive areas are located. First, we pooled together all available data on environmental proxies and algal production to quantify relationships between macroalgal production and the environment as well as to predict macroalgae production at the Baltic Sea scale. Second, we built a similar model for macroalgal beach-cast and predicted the potential beach-cast production at the Baltic Sea scale. The resulting maps are useful for maritime spatial planning because they enable to detect the most suitable areas for macroalgae farming and/or beach-cast harvesting. From the range of suitable sites, it is then possible to detect areas that allow long term cultivation actions while considering trade-offs and avoid conflict with existing industries (e.g. fisheries, shipping routes etc). Information is accessible for everyone through the user-friendly ODSS online platform at http://www.sea.ee/bbg-odss/Map/MapMain. This guides public authorities interested in setting up / investing in / funding a farm in their region to private actors who want to get involved in the macroalgae business.

2. Introduction

Throughout the world, high demand on natural resources necessitates the development of alternative means to produce commodities such as food, feed, fuel, cosmetics, and pharmaceuticals. “Blue growth” is a proposed long-term strategy by the FAO to support productive growth and sustainable use of aquatic resources (FAO, 2018) Focus is on building resilient coastal communities, restore the productive potential of fisheries, develop aquaculture, support food security, alleviate poverty and sustainably manage living aquatic resources. A stronger reliance on factual data concerning environmental changes, as well as socio-economic benefits, will increase the uptake and application of Blue growth concepts in developed and developing economies.

In Europe, Blue growth policies have been mainly driven by demands to implement new innovative ocean activities (e.g., biotechnology and renewable energy) and revitalize existing economies (e.g., fisheries and tourism) (Pinto et al., 2015). This is because maritime activities are expected to increase in the future and marine spatial planning strategies such as the Blue growth offer balance management, consideration of trade-offs and mitigate negative environmental threats (Knight et al., 2019).

Aquaculture is the fastest-growing food-producing sector and currently represents nearly 50% of global fish, crustacean and mollusc production (FAO, 2018); and macroalgae cultivation is a promising upcoming industry within the aquaculture sector that aligns with the long-term vision of Blue growth. Macroalgal cultivation process removes naturally occurring nutrients in the environment, purifies water and alleviates potential of eutrophication in coastal regions without competing for arable land or freshwater resources. Most recently, macroalgae cultivation, research initiatives and businesses developments have focussed on increasing cultivation capacity and refining of seaweed biomass (Kraan, 2013; Peteiro et al., 2016). This is because marketable macroalgal products have wide applicability from human food products to animal feed, fuel, cosmetics, and pharmaceuticals (Leandro et al., 2020). Global seaweed aquaculture production more than tripled from 1995 to 2012 to the order of 23.8 million tons per year and is mostly concentrated in Asia, with 81% of global production coming from China and Indonesia alone (FAO 2014). Despite the recent growth in cultivation in Asia, macroalgal production is still in its infancy and there is a lack of in-depth knowledge on the potential socio-economic benefits of macroalgae production. This is because aquaculture practices applied in South-east Asia often neglect to consider negative environmental impacts of farming and hence fail to fully account for sustainable socio-economic targets.

European seaweed production comes almost entirely from the harvesting of natural stocks and has decreased by approximately a third from 2000 to 2012, to around 230,000 tons per annum, primarily due to concerns over environmental impacts (Thomas et al., 2019). The history of seaweed aquaculture in Europe relies on kelps *Saccharina latissima, Undaria pinnatifida* and *Alaria esculenta* but also *Ulva* spp. are cultivated. Norway, France and Ireland are the biggest seaweed producers (Table 1, FAO, 2019) , however in the Baltic Sea, specifically in the central and eastern parts, the potential for seaweed aquaculture has remained underdeveloped. Macroalgae can be used to add minerals and vitamins to food as well as for baking bread (e.g. Welsh laverbread). However, a notable share of the European macroalgae production goes to other than direct food or feed uses, but there are currently no reliable estimations of the material flows and destinations of the produced macroalgae biomass. Small companies are producing seaweed food products in Denmark, Sweden, Germany and Estonia to make wine, beer, cocktails, pesto and sandwich spread, flour, pasta and snacks. Gourmet restaurants have added seaweeds into their menus, however, the wider use of the Baltic Sea macroalgae as food is still rare. The development of large-scale seaweed aquaculture in Europe has the potential to play an important role in meeting future resource needs but must do so in a manner that does not undermine the use and value of existing marine resources.

Harvesting of naturally occurring beach-cast and turning it into a marketable product (food, cosmetics etc.) offers an alternative avenue to macroalgal production while aligning with Blue Growth concepts. Beach-cast does have ecological functions such as providing food and habitat for sandy beach fauna, nutrients for dune vegetation, and protection for coastal dunes. Nevertheless, beach-cast is often considered a nuisance to humans due to the production of unpleasant odours when cast matter decomposes on the shoreline. This decomposition process also coincides with the production of carbon emissions. It has been estimated that the annual CO_2-C flux from seagrass wrack globally is between 1.31 and 19.04 Tg C yr^{-1}, which is equivalent to annual emissions of 0.5–9 million people depending on their geographic region (Liu et al., 2019). Thus, harvesting and removal of beach-cast while turning it into a marketable product offers a possibility to develop coastal carbon budgets as climate change and coastal development are accelerating.

For improved management of maritime activities including seaweed aquaculture, we need to recognize the relative importance of coastal areas for seaweed production at scales relevant to resource management. Seaweed aquaculture and growth potential of cultivated species is underpinned by various ecological processes such as temperature, salinity, nutrient content in the water and solar radiance that are all scale-dependent. Before this work, most of the work on macroalgal production potential has been mainly case-specific and at much smaller scales (Thomas et al., 2019; Hasselström et al., 2020). Instead, we need spatially explicit information covering a wider geographic range, as the growth rate of cultivated macroalgae can vary markedly in time and space. Application of different spatial analysis techniques to study the relationships between the key environmental variables and macroalgal production potential will lead to a better understanding of landscape suitability for macroalgal cultivation.

In this report, we identify, assemble and synthesize existing environmental and growth data in the Baltic Sea. This is because the Baltic has a long and well-documented history of scientific activity, high data density and multiple on-going cross-border collaborations for effective management of marine resources. Focussing on the iconic *Fucus vesiculosus* and *Ulva intestinalis* we aim to **(a)** quantify species-specific production potential and **(b)** identify coastal areas and environmental conditions suitable for macroalgae cultivation as well as **(c)** model accumulation of beach-cast and identify areas for beach-cast harvest. Gathered data was catalogued and harmonized into a user-friendly GIS tool covering the whole Baltic Sea area. Underlying data layers combine experimental and environmental data with predictive spatial modelling tools. The main output of this report provides a basis for assessing where to designate areas for macroalgae farming, cultivation and harvesting in the environmental point of view. We hope our results raise confidence in the public sector towards balanced and environmentally friendly marine macroalgae farming and harvesting in the Baltic Sea region as well as support decision-makers with the best tools for strategy development, resource allocation and spatial planning.

3. Methods

In this study, we compiled all available experimental evidence on macroalgal harvesting and beach-cast in the Baltic Sea region into a harmonized georeferenced database (n ≈ 10000) and this database was used to model the potential growth and beach-cast yields across the key environmental gradients.

Model inputs for the physical and biogeochemical conditions in the Baltic Sea were obtained from the products BALTICSEA_ANALYSIS_FORECAST_PHY_003_006 and BALTICSEA_ANALYSIS_FORECAST_BIO_003_007 at the Copernicus open access data portal (http://marine.copernicus.eu/services-portfolio/access-to-products/). These physical products covering the whole Baltic Sea area contain data with hourly resolution and 25 vertical levels. The biogeochemical data are served with 6-hour resolution and 25 vertical levels. For both products, the horizontal grid step is regular in latitude and longitude and is approximately 1 nautical mile. The physical product is based on simulations with the HBM ocean model code (HIROMB-BOOS-Model). The biogeochemical product is based on simulations with the BALMFC-ERGOM version of the biogeochemical model ERGOM, originally developed at IOW, Germany. The BALMFC-ERGOM version has been further developed at Danish Meteorological Institute (DMI) and Bundesamt für Seeschifffahrt und Hydrographie (BSH). The BALMFC-ERGOM model is run online coupled with the HBM ocean model code. In the analyses presented here, monthly and annual averages of environmental variables were used.

The locations of hard bottom areas were obtained from the EMODnet portal (http://www.emodnet.eu/) and unpublished sediment data were collated from Finnish Environment Institute, Geological Survey of Sweden, and the Bundesamt für Seeschifffahrt und Hydrographie. Wave exposure data were produced by Aquabiota, using the Simplified Wave Model method (SWM; Wijkmark and Isæus 2010). The SWM method calculates the wave exposure for mean wind conditions using a nested-grids technique to take into account long-distance wind effects on the local wave exposure regime. This method results in a pattern where the fetch values are smoothed out to the sides, and around islands in a similar way that refraction and diffraction make waves deflect around islands. Then a depthattenuation correction was applied to the SWM in order to estimate depth-attenuated wave exposure (Bekkby et al. 2008).

Boosted Regression Trees (BRT; R 3.2.2. for Windows; Elith et al., 2008) was used to quantify relationships between environmental variables, macroalgal production potential and beach-casts. Then the established relationships were used to predict either macroalgal production or beach-cast accumulation at the Baltic Sea scale. In contrast to traditional regression techniques, BRT avoids starting with a data model and rather uses an algorithm to learn the relationship between the response and its predictors (Elith et al., 2008). BRT was first used to test if and how different environmental factors (predictors) contribute to the variability of measured dependent variables (training data). Then, BRT was used to predict macroalgal production or beach-cast accumulation at the Baltic Sea scale based on the predictive model created from the first step (model application). In fitting a BRT, the learning rate and the tree complexity must be specified. The optimum model was selected based on model performance, with learning rates, number of trees, and interaction depth set at 0.001, 3000, and 5, respectively. Model performance was evaluated using the cross-validation statistics calculated during model fitting (Hastie et al., 2009). Standard errors for the predictions and pointwise standard errors for the partial dependence curves, produced by R package "pdp" (Greenwell 2017), were estimated using bootstrap (100 replications).

4. Results

4.1. Fucus vesiculosus production potential

Macroalgal production potential was combined with environmental variables and analysed with Boosted Regression Trees (BRT) modelling. BRT output shows that the three most important variables with a combined relative contribution explaining around 73% of model variability were average solar radiance (33%), nitrate (21%) and phosphate concentration (19%) (Fig. 1). Temperature and salinity contributed 11% and 10% to the model variability, respectively. Exposure and water velocity had both a marginal 3% effect on models explanatory output. Partial dependence plots which represent the relationship between the variables and the fitted function from the BRT are displayed on Fig. 1. Partial dependence plots give an indication of how macroalgal production potential changes when the predictor variable values increase. In general, higher solar radiance and nitrate levels increased *F. vesiculosus* production, however, saturation point was observed when either radiance or nitrate levels were too high. Overly high phosphate values, on the other hand, lowered *F. vesiculosus* production. This is rather from the indirect effects of phosphate related to higher phytoplankton or epiphyte production that in turn reduces the amount of light reaching *F. vesiculosus.*

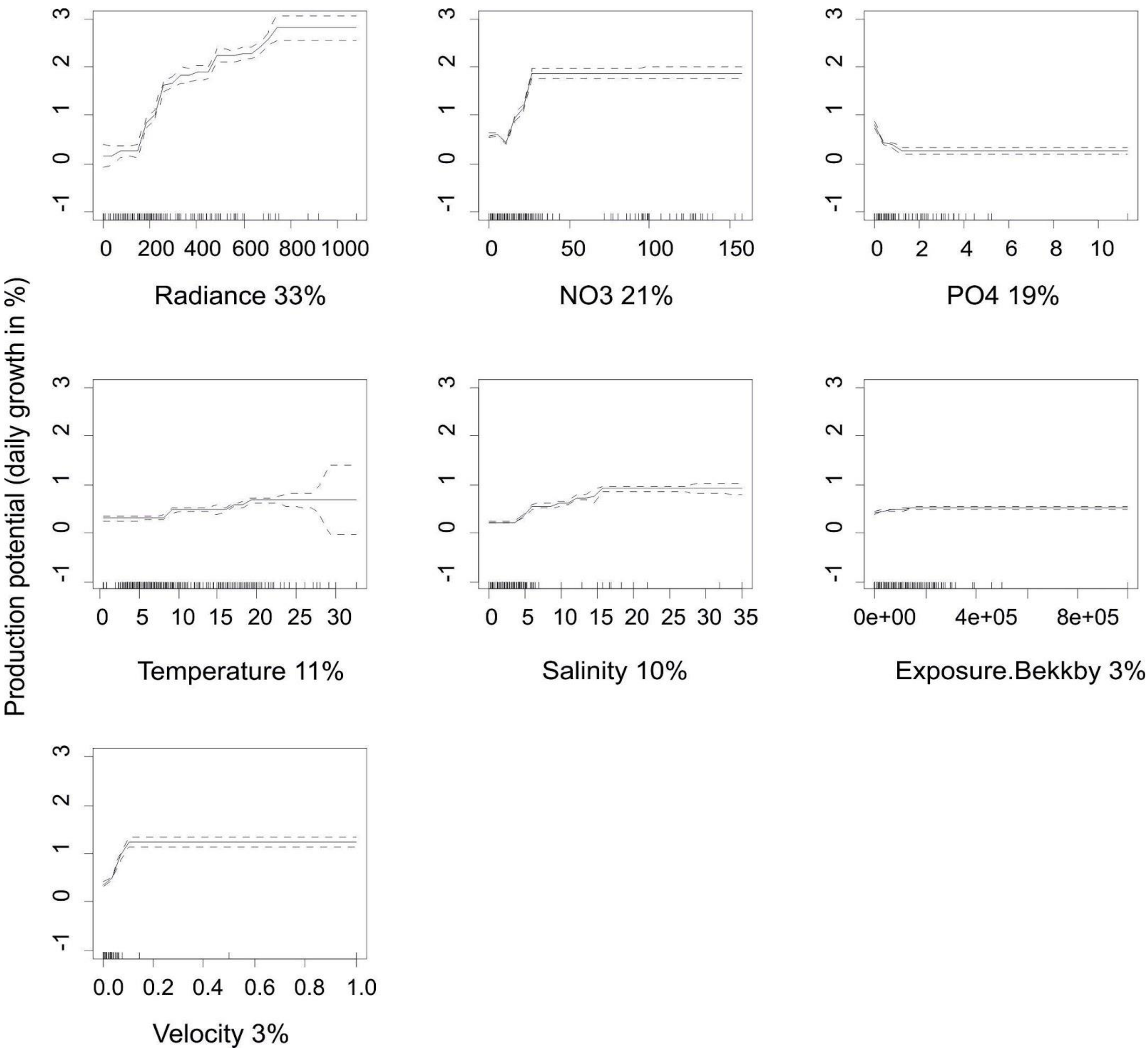


Figure 1. Relative contribution of independent variables to BRT model variability about production potential of *F. vesiculosus*. Dotted lines around the response curve of each independent variable represent standard error.

Clear hotspots of *F. vesiculosus* production emerged around Danish Straits, however, notably high production values were observed throughout the southern Baltic and along Polish, Lithuanian and Estonian coasts (Fig. 2). At these hotspots, production potential indicated as high as 3% daily biomass growth rate. Production potential of *F. vesiculosus* gradually decreased to 0 throughout the Baltic when moving northwards (e.g. in Bothnian Bay and eastern part of the Gulf of Finland) as these areas have salinity below a threshold value of *F. vesiculosus*. The largest spatial extent in the Baltic was characterised by medium production potential, averaging around 1.5% daily biomass increment.

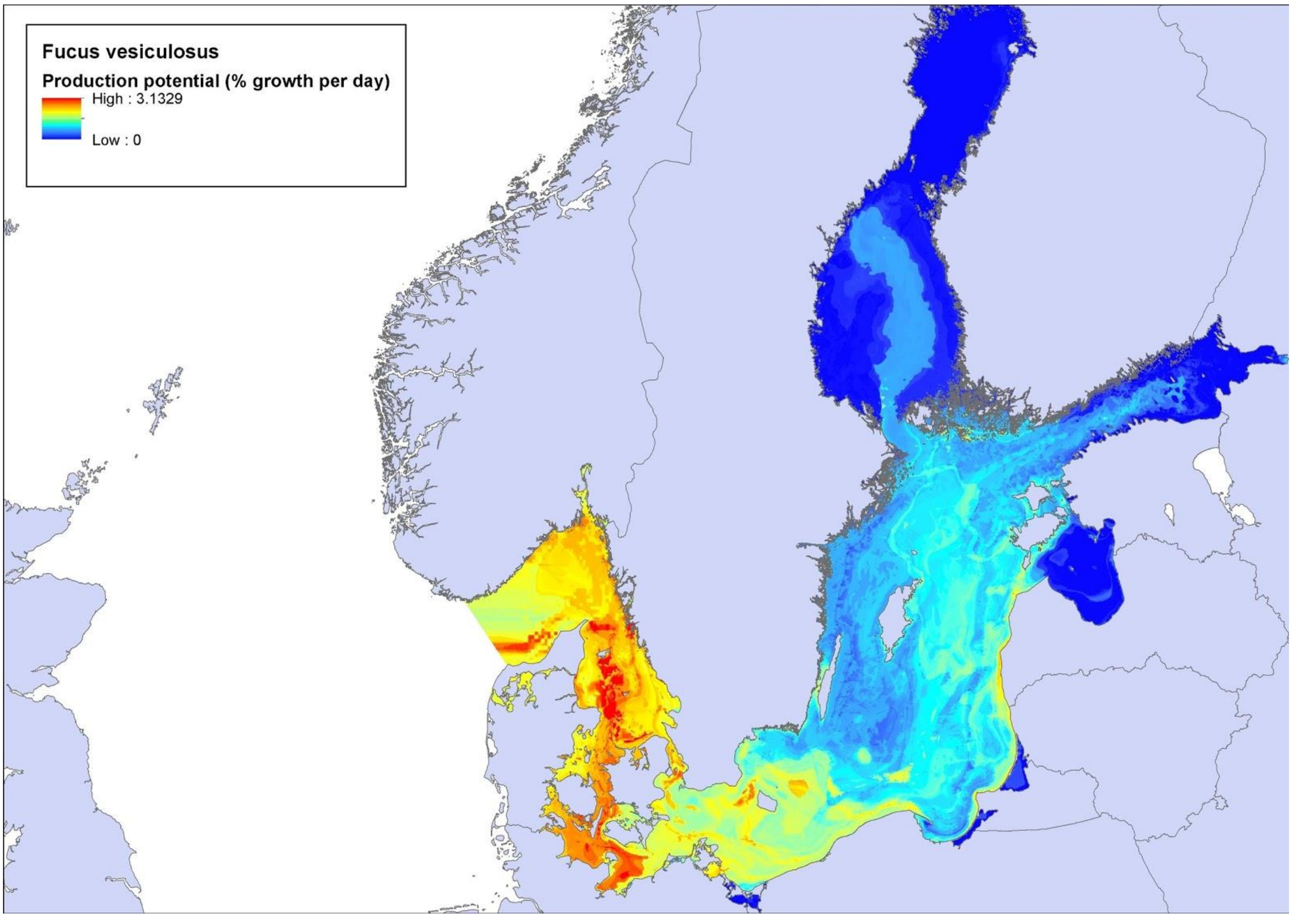


Figure 2. *Fucus vesiculosus* production potential across the Baltic Sea.

4.2. *Ulva intestinalis* production potential

BRT output shows that the three most important variables with a combined relative contribution explaining 93% of model variability were average solar radiance (42%), nitrate

(26%) and temperature (25%) (Fig. 3). Salinity and water velocity explained a modest 5% and 2% respectively. Partial dependence plots which represent the relationship between variables and the fitted function from the BRT are displayed on Fig. 3. Partial dependence plots give an indication of how macroalgal production potential changes when the predictor variable values increase. In general, higher solar radiance, phosphate and temperature levels increased *U. intestinalis* production, however, production saturated when radiance, phosphate or temperature levels were too high. Ulva prefers warm, light-filled and nutrient-rich (specifically phosphate) coastal regions.

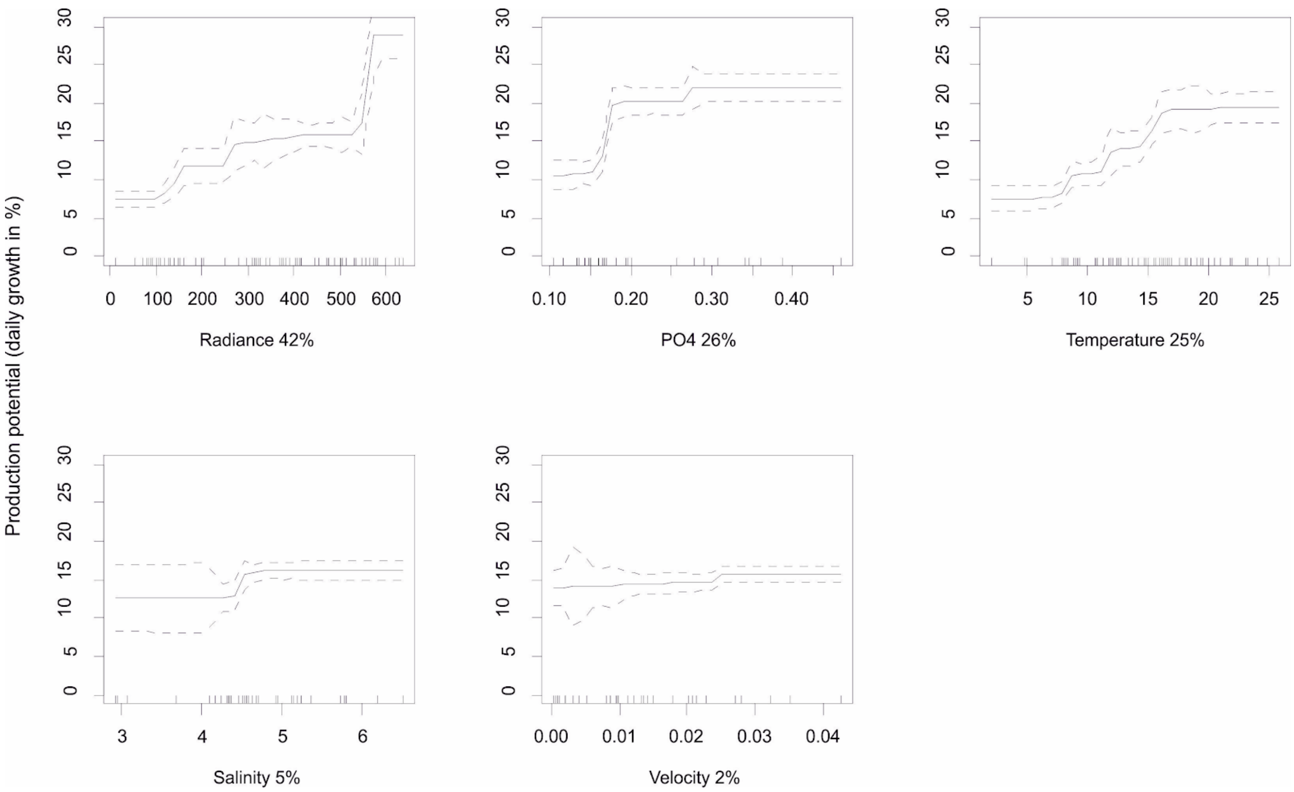


Figure 3. Relative contribution of independent variables to BRT model variability about production potential of *U. intestinalis*. Dotted lines around the response curve of each independent variable represent standard error.

Due to its ephemeral nature, *U. intestinalis* had a higher production potential (daily growth rate in %) compared to *F. vesiculosus* and had a wider spatial distribution of production hotspots; encompassing all Danish Straits, coasts of southern Sweden, Germany, Poland, Lithuania, Latvia and Estonia (Fig. 4). At these hotspots, daily growth in biomass was as high as 13.5%. The overall spatial distribution of the low production zone was only limited to the very northern parts of the Baltic Sea (e.g. Bothnian Bay) where daily biomass increase was around 1%. The largest spatial extent of the Baltic Sea was characterized by medium production potential zone, in this instance averaging around 7% daily biomass increment compared to 1.5% of *F. vesiculosus*.

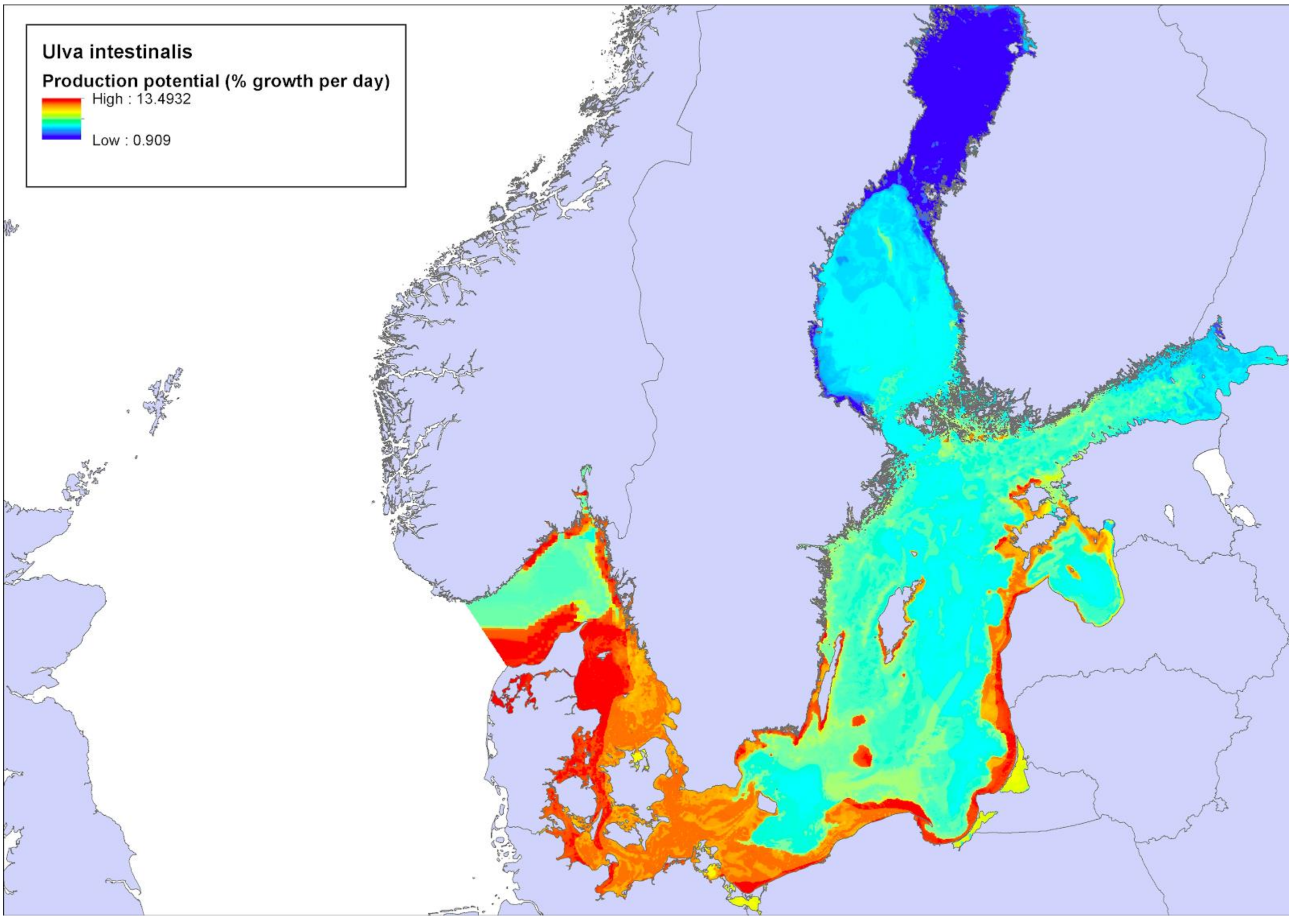


Figure 4. *Ulva intestinalis* production potential across the Baltic Sea.

4.3. Macroalgal beach-cast

Beach-cast production peaked at late autumn and was affected by multiple environmental variables. BRT output shows that the three most important variables with a combined relative contribution explaining 48% of model variability were temperature (19%), distance to 10m isobath (17%) and wave direction (12%). The explanatory power of the remaining 6 variables ranged from 11%-6%: month, salinity, irradiance, coastal slope, wave height and availability of hard bottoms (i.e. potential algal growth areas) in the adjacent sea areas. Higher amount of beach cast is expected in the late autumn months and the early winter along with the end of production season and the onset of heavier storms. High beach-cast production is predicted at shores that have narrow photic zone (i.e. distance to the 10 m isobath less than 1 km) and are exposed to favourable wave direction. Moreover, higher solar radiance and water salinity is associated with elevated beach casts (Fig. 5).

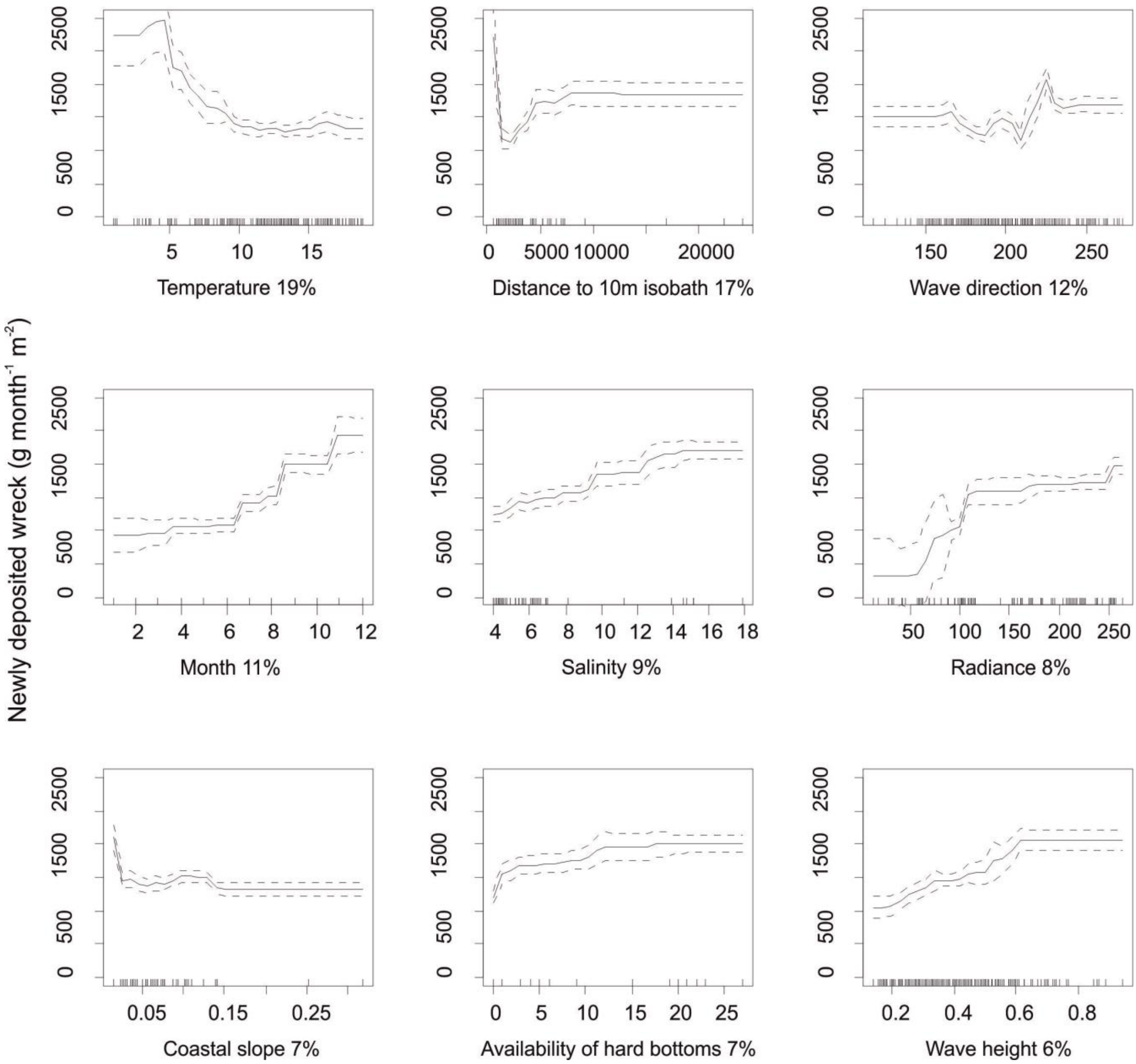


Figure 5. Relative contribution of independent variables to BRT model variability about macroalgal beach-cast. Dotted lines around the response curve of each independent variable represent standard error.

Clear hotspots of beach-cast production emerged throughout the whole Baltic Sea area (including Kattegat) (Fig. 6). The highest production values (up to 4000 g per m^2 per month) were observed on the west and east coast of Sweden, all along the southern coast of Finland, west coast of Estonia and in Gdansk Bay (Fig. 6). However, some production hotspots were sporadically found even on the east coast of Finland, reaching northernmost parts of the Bothnian Bay as well as on the shores of St. Petersburg (Fig. 6). The remaining parts of the Baltic sea were characterised by lower beach-cast production potential (approximately 0 - 1,000 g per m^2 per month).

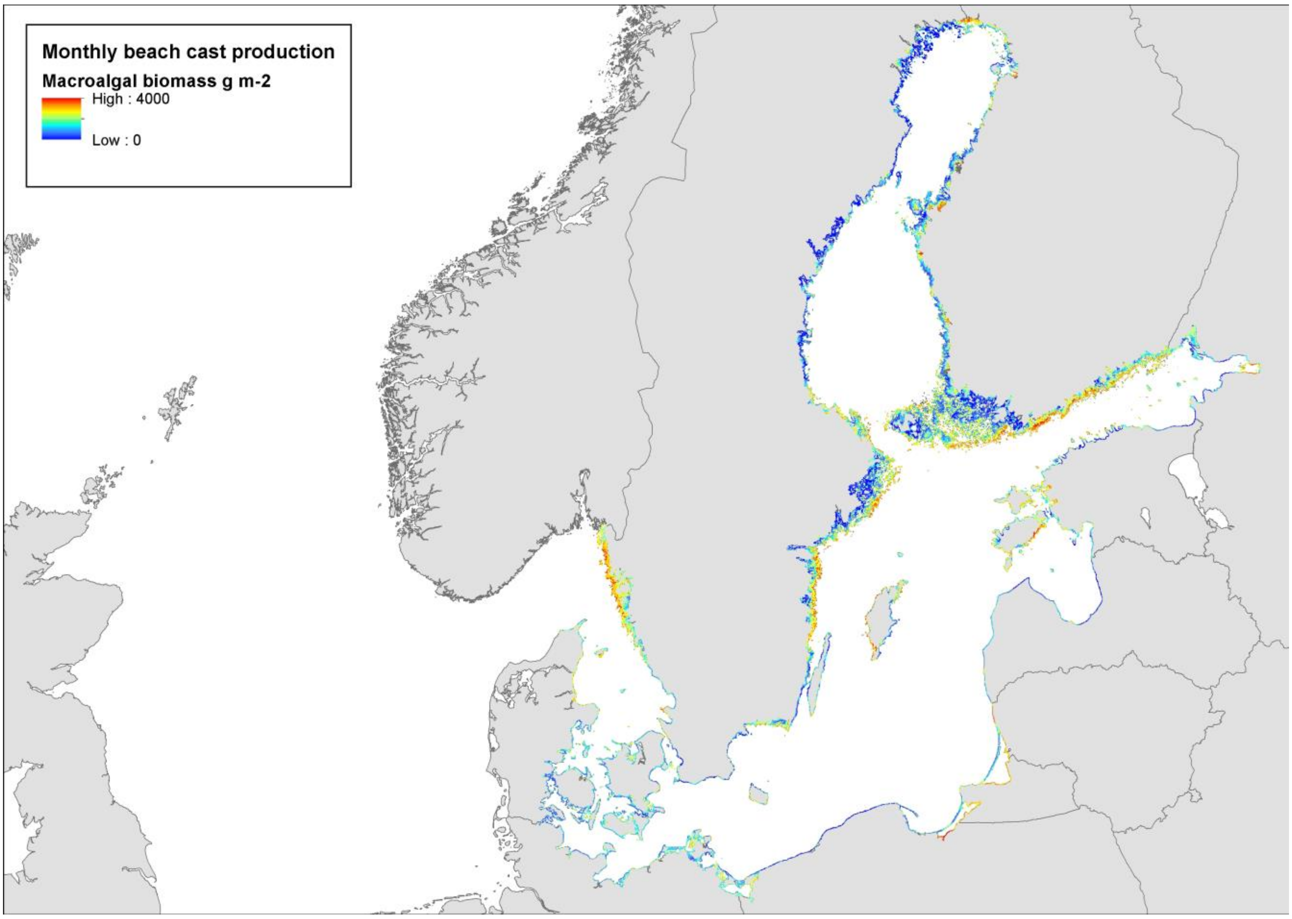


Figure 6. Monthly beach-cast production potential across the Baltic Sea in late autumn.

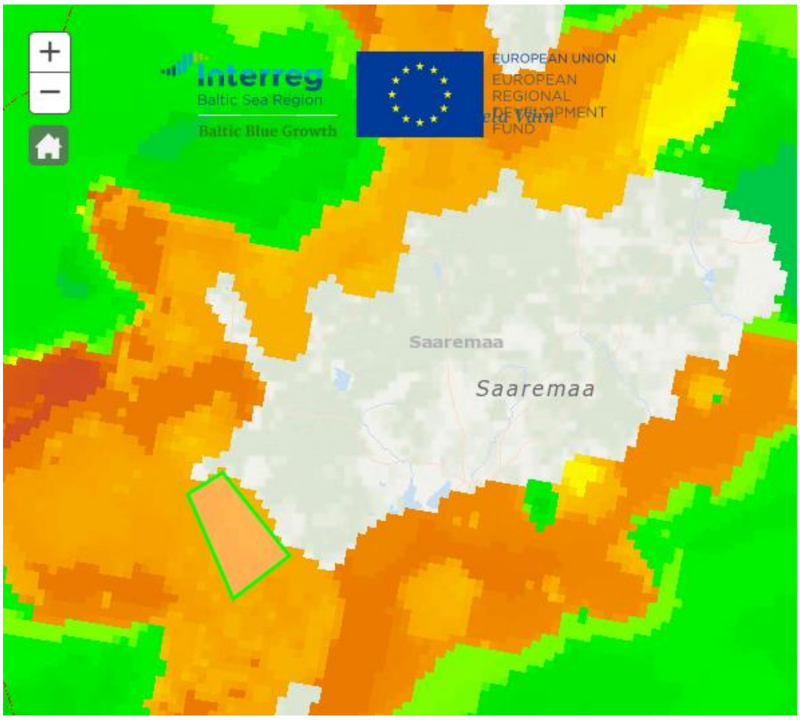
5. Discussion

Macroalgal production potential modelling showed that the studied species have strong cultivation potential in many subregions of the Baltic Sea. Both *U. intestinalis* and *F. vesiculosus* have production hotspots around the Danish straits which gradually decreased to mid-levels in the central Baltic with virtually no production potential in the northernmost areas such as the Bothnian Bay. Solar radiance, nutrients and water temperature were the most important variables affecting macroalgal growth. In case radiance or salinity were not limiting, then better cultivation sites were areas with higher nitrate and phosphate content such as the northern part of Gulf of Riga. *F. vesiculosus* preferred modest nitrate content and temperatures whereas *U. intestinalis* preferred warm phosphate-rich areas.

Spatial distribution of beach-cast production hotspots showed different patterns compared to *F. vesiculosus* and *U. intestinalis*. Danish straits and southernmost parts of the Baltic had marginal importance for beach-cast production (except Gdansk Bay) whereas they were production hotspots for *F. vesiculosus* and *U. intestinalis*. Higher production of beach-cast was aggregated in archipelagos and inner bays around the mid-Baltic region with broader spatial extent productive areas when compared to either *F. vesiculosus* or *U. intestinalis*. Beach-cast production was at its highest in late autumn, with cooler temperatures and on shorlines well angled for beach-cast deposition by waves.

Here we used data-driven analyses through harmonized data handling and spatial modelling techniques to identify suitable macroalgal cultivation areas and beach-cast accumulation hotspots. The resulting modeling products were published in the Operational Decision Support System (ODSS) to support maritime spatial planning processes in the Baltic Sea.

The main output of this report provides stakeholders with the basis to identify suitable areas for macroalgae cultivation and harvesting. All environmental data from the macroalgal cultivation sites as well as the results of spatial modelling of production potential is accessible for everyone through the user-friendly ODSS online platform at http://www.sea.ee/bbg-odss/Map/MapMain. On the main page of the geoportal under “switch layers tab” the user can, for example, select and view the map of *Fucus* production potential across the Baltic Sea. The user can then click on “plan your farm” tab and draw a polygon of theoretical farm area and acquire various important statistics (e.g. algal growth rate, water temperature and salinity) relatable to the polygon area (see Fig. 7 for illustration). Through its analytical capabilities to synthesize and disseminate up-to-date information and knowledge to different end-users, the ODSS is designed to facilitate and improve the quality of decision-making of maritime spatial planners, scientists, policy actors and investors.



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Name	Average	Area (km2)	Percent (%)	Count	Classes
AIS Shipping Density (2016)	0	73.73	83.62	1	
N Removal by mussels (Mytilus, g/m rope @ 2 years)	7.3	50.09	56.81	3	
P Removal by mussels (Mytilus, g/m rope @ 2 years)	0.67	50.09	56.81	3	
Mussel growth (kg/m rope @ 2 years)	1.13	83.39	94.59	7	
Sediments				2	Sand,Hard bottom complex
Summer chlorophyll (mg m-3)	3.29			39	
Salinity (psu)				1	5 - 7.5 psu
Simplified wave model (m2 s-2)	218046.21			71	
Temperature (°C)	18.02			4	
Baltic Sea Ice		60.87	69.04	1	
Fucus growth (daily growth rate in %)	0.97	88.1	99.92	105	
Ulva growth (daily growth rate in %)	10.61	88.13	99.96	83	

Figure 7. Zoomed in macroalgal production potential map of Saaremaa (Northeastern Baltic) with polygon specific summary statistics of growth rates and associated environmental variables.

ODDS guides public authorities interested in setting up / investing in / funding a farm in their region to private actors who want to get involved in the macroalgae business or assess trade-offs between macroalgae cultivation and other maritime uses of the sea. This is because public authorities play a key role in closing the legislative gap and unlocking the potential of macroalgae production in the region. However, they lack the capacity to look into the environmental and socio-economic aspects of macroalgae production in the Baltic Sea unless presented in a data-driven and harmonized way. This poses a great challenge for the development of the regional macroalgae industry. GRASS builds capacity to deal with current legislation barriers and gaps and to improve governance among public authorities to support the macroalgae sector in the Baltic Sea region.

6. Conclusion

The modelling of macroalgal and beach cast production potential has shown that macroalgae can be successfully farmed and harvested in much of the Baltic Sea when cultivation methods are adapted to the local conditions. With this activity we aim to close the environmental gap for macroalgae production. The ODSS tool that will help us to fulfil this goal by linking maps of the suitable sites for macroalgal cultivation and beach cast harvest with important environmental variables, state of the Baltic Sea and different human uses. The outputs will mainly be used by regional and national public authorities such as environmental and planning agencies. Other target groups are practitioners, research institutes and NGOs in the field of sustainable blue growth.

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