Macroalgae Production Manual

Production, Challenges & Pathways

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Summary

This report aims at highlighting the potential of macroalgae production in The Baltic Sea region. Three different production tracks; macroalgae cultivation, wild harvest of macroalgae and beachcast collection, were examined through a survey among the project partners within the “GRASS initiative”, together with a literature study.

Seven potential production macroalgae species were identified for cultivation in the region. Cultivation is already ongoing in the Western Baltic Sea region on the Swedish west coast where cultivations of *Saccharina latissima*, *Laminaria digitata* and *Ulva sp.* are established. Land-based and small-scale coastal cultivations exist in the Baltic Sea region but with limited production because of low salinity, which inhibits high production of true marine species such as *Saccharina latissima*. *Furcellaria lumbricalis* is the only macroalgae species used in the region for wild harvest. In Estonia, an unattached form of the species is harvested each year in a limited amount. Four beach-cast projects were reported within GRASS (Latvia (2), Russia and Sweden), but small-scale projects of beach-cast collection occur in several parts of the region.

Production challenges identified by the project partners include demanding environmental conditions, legislation obstacles, lack of knowhow and high labour costs. To overcome these challenges, we suggest that more focus and effort is put on research and development of production systems in the Baltic Sea. The precautionary principle must be the leading star in harvesting of *Furcellaria lumbricalis*, and sustainability aspects must also be considered for beachcast harvest in the region. To accommodate growth of sustainable macroalgae production systems for cultivation, harvesting and collection, we need knowledge transfer and build capacity to support the development of technology, legislation and policies in this area.

Introduction

Macroalgae are regarded as a promising alternative feedstock for biofuels, pharmaceuticals, cosmetics and functional food (Duarte et al. 2017, Hasselström et al. 2020). Global macroalgae production is on a steady rise since several decades, but only 1.4% of the global algae biomass production takes place in Europe today. Most of the European produced algae biomass originates from harvesting wild stocks, although several macroalgae aquaculture sites have been initiated during the last decade (Camia et. al 2018). However, the progress in the Baltic Sea Region remains slow (Gröndahl and Blidberg, 2012) which could partly be explained by the specific conditions of the Baltic Sea, but also by other challenges yet to be detected or further explored, such as systemic ones related to production.

Partners of the project GRASS - Growing Algae Sustainably in the Baltic Sea - collaboratively share experiences and challenges of macroalgae production, and explore potential pathways towards a growing system for sustainable macroalgae production in the Baltic Sea Region. As part of GRASS; the results are communicated in this manual. It aims to build capacity on macroalgae production among public authorities, and other relevant stakeholders across the Baltic Sea Region. Moreover, this manual discusses pathways towards a sustainable macroalgae production system in the Baltic Sea Region.

Approach

The manual is based on empirical data from projects and initiatives within the regions of GRASS project partners, and complemented by scientific literature. GRASS project partners' responses to a questionnaire provided the empirical data, and the literature search was performed during the process of compiling the information provided in the questionnaires. The questionnaire consisted of open ended questions and can be found in Appendix I.

Sea Characteristics & Site Conditions

Developing efficient production methods for macroalgae cultivation, harvesting and collection begins with identifying characteristics and conditions of the Baltic Sea which are significant to increase macroalgae aquaculture in the Baltic Sea Region. Available literature in the area has been used to address this and a recent publication on macroalgae resources and aquaculture potential in the Baltic Sea, by Weinberger et al. (2020) serves as a central source of information for identifying relevant characteristics and conditions. Site specific conditions of the current macroalgae projects from all types of tracks (cultivation, harvesting and collection) from GRASS project partners are presented and co-related to the literature on the subject.

The most specific characteristic of the Baltic Sea is its brackish water; a condition which all cultivation sites share. The particular salinity gradient is the reason for low diversity in algal species, as well as decreased growth potential of macroalgae (Schultz-Zehden and Matczak, 2012, Weinberger et al, 2020). Several other stressors are also affecting the growth and survival of abundant species such as ice-scraping in cold winters and anthropogenic eutrophication. This could be one reason for the relatively weak tradition of using natural seaweed resources in the area, except for beachcast used as fertilisers by local farmers (Weinberger et al, 2020).

The species pool of macroalgae species in The Baltic Sea in the Swedish east-coast (Baltic Sea) has four times less macroalgae species compared to the Swedish west coast at corresponding latitude in Kattegat, North Sea (Weinberger et al., 2020). The most important species for biomass-production in Europe is lacking or is on its margins of distribution in the Baltic Sea (e.g. *Ascophyllum nodosum*, *Chondrus crispus*, *Himanthalia elongata*, *Laminaria hyperborea*, *Laminaria digitata*, *Palmaria palmata*, *Porphyra umbilicalis* and *Saccharina latissima*). Only *Fucus sp*. and *Ulva sp*. are naturally occurring with a wider distribution in the Baltic Sea (Camia et al. 2018).

On the other hand, the high nutrient levels of the Baltic Sea are noticeable for increasing algae growth. However, the excessive nutrient load has led to eutrophication of the sea which affects the conditions for macroalgae cultivation, harvesting and collection, for instance by altering species composition. Other significant and critical conditions to be considered and balanced for successful macroalgae cultivation and harvesting are level of exposure (sheltered/exposed), water depth (shallow/deep), sea bottom type and competing/collaborative activities at sea. All the above-mentioned characteristics and conditions are relevant to address for the three tracks of macroalgae activity.

Environmental conditions for optimal growth and yield is essential for sea based cultivation of macroalgae. The main species for cultivation in the Baltic Sea Region today is *Saccharina latissima*; although generally capable of fast growth the low salinity gradient in the Baltic Sea becomes a limiting factor for cultivation. Thus, the limit for cultivation of *Saccharina latissima* is in the Kiel Bight. Most macroalgae species require salinity levels of around 30 psu for optimal growth and it is currently considered unmotivated to cultivate at locations with annual mean sea surface salinities of less than 16 psu (Weinberger, 2020), although there are exceptions and a few species of macroalgae also have a wide distribution in the brackish water of the Baltic Sea. In search of sites for cultivation, the salinity has to be carefully considered to match the choice of species.

Moreover, the level of exposure has to be carefully balanced in choosing cultivation sites. High exposure equals high wave action which is satisfying in terms of contributing to a continuous water exchange and thereby securing a steady nutrient supply to the cultivated species, in contrast to sheltered locations. However, exposure to mechanical stress from high wave impact can reduce the quality of the produce by ripping the biomass. And while the risk of fouling (i.e. organisms settling on the crop) potentially decreases in exposed conditions (compared to sheltered places), the challenges of establishing cultivation sites (by constructing mooring systems) and accessing exposed sites (for maintenance and continuous tending) are more prominent. The risk of ice coverage during the winter season should also be considered when selecting a site, as it could shorten the growing season. Conditions such as distance to shore, geographical shelter, and mean water temperatures and ice coverage could indicate the level of exposure of a site in consideration. Experiences from the Swedish west coast shows that the largest specimens of *Saccharina latissima are* found in semi-exposed sites and the more exposed sites produces smaller specimens then the sheltered areas.

Similarly, water depth and sea bottom type are essential to factor in; the combination of shallow waters and soft bottoms can cause suspended sediments to settle on the macroalgae, while reducing the amount of light reaching the algae and thereby inhibiting its growth. Moreover, a mixture of shallow waters and hard bottoms may cause shading of wild macroalgae by the cultivation system whose life cycle is a natural source of nutrient supply, on which the cultivations depend. Nutrient deficiency could also be a problem in very deep waters as nutrients from the bottom (remineralized from decomposing organic matter) only will reach the surface in areas of natural surge. Deep waters and soft bottoms also pose challenges to establishing mooring systems for cultivation; being costlier in shallow waters and complicated to anchor on soft bottoms. The general guideline is to go by a water depth of 2-50 meters and hard bottoms (Weinberger, 2020). The sites that are now developed on the Swedish west coast have a water depth of about 12-27 meters and the bottom is mostly sand and gravel without any natural populations of kelp.

Establishing production sites can also render competitive or collaborative conditions with other activities at sea. Attempts and ideas to convert potentially competitive activities to collaborative ones are currently being explored by incorporating macroalgae cultivations in established fish and shellfish aquaculture by using waste nutrients of the latter two for growing macroalgae. In Norway the combination of fish-, mussel and seaweed farming have been tested but not on the Swedish west coast or in other areas of the Baltic Sea. Meanwhile, ideas of sharing offshore structures with wind farms to construct mooring systems for macroalgae cultivation are being developed (Buck and Grote 2019) in some areas and have been tested in Danish waters.

Main Species for Production

Red, brown, and green macroalgae all have complex and diverse life cycles, often including both sexual and asexual reproduction. The importance of understanding life cycles of the focal species of macroalgal cultivations could not be exaggerated. Most cultivation technologies include a hatchery phase (indoor facilities needed) where gametes form sporophytes that are seeded into a substrate (line, rope or else). The seeded substrates will in turn be planted into an infrastructure in the open sea for further growth. We will not in detail describe all types of life cycles and or potential cultivation technologies in this text. In fact there are today few mature cultivation systems for the species abundant in the Baltic Sea area, but below we list and describe the most interesting macroalgae species for cultivation in the area.

Brown algae

Chorda filum

The species is abundant in both saline and brackish water and the distribution in the Baltic Sea reaches the southern parts of the Gulf of Bothnia. No experimental studies on *Chorda filum* have been reported from the Baltic sea region but a study from the White Sea suggest that *Chorda filum* is a potential species for cultivations, since it is a fast-growing annual species that could be used as food, medical goods or as an alginate resource (Shklyarevich & Shoshina 2012). The species has its optimum growth during the summer month and needs relatively sheltered conditions since heavy wave conditions may damage the tissue and break the thalomes from the substrata. Integrated cultivations in combination with *Mytilus edulis, Laminaria digitata* or *Saccharina latissima* are suggested for *Chorda filum* (Shklyarevich & Shoshina 2012). Simple and well described reproductive cycle and a fast growth rate, and high tolerance to low salinity are some of the features that make *Chorda filum* an interesting species for cultivation experiments in the Baltic Sea Region.

Fucus vesiculosus

Fucus vesiculosus, bladderwrack is one of the dominant species of the coastal ecosystems in the Baltic Sea. The canopy forming species is classified as a keystone species with importance for ecosystem structure, function, species richness in the whole Baltic Sea Region (Kautsky, Qvarfordt, & Schagerström, 2019). The species is also commercially interesting as an ingredient in organic cosmetics and as food supplement (Meichssner et al., 2020). There have been attempts to cultivate *Fucus vesiculosus* in small-scale projects within the region for example in Sweden (Haglund & Pedersén, 1988), Denmark (Ferdouse et al. 2018 and in Germany (Meichssner et al., 2020). Haglund & Pedersén (1988) studied spray cultivation of macroalgae species on the island Furillen outside Gotland using a spray cultivation system with circulating brackish water. Among various species in their study, *Fucus vesiculosus* was classified as the more robust species suited for this kind of cultivation system adopted for small scale production. In the Kiel fjord, Germany the first coastal cultivation of *Fucus vesiculosus* and *Fucus serratus* for commercial purposes was initiated on a small scale during 2015 (Meichssner et al., 2020). The two species are cultivated using cage or netsystems with unattached thalli. The first trial of cultivation was heavily affected by biofouling and recent experiments are trying to reduce biofouling through periods of desiccation which has shown positive results (Meichssner et al., 2020). This experimental study could be seen as a promising step for initiating similar pilot cultivation systems at other locations around the Baltic Sea area. One of the main problems with bladder wrack in addition to the difficulties to cultivate the species, is that it is a relatively slow growing seaweed. In the Baltic Sea e.g., on the Island of Sarema (Ösel) there are populations of free floating *Fucus vesiculosus* that may be easier to cultivate.

Laminaria digitata

Laminaria digitata is one of two species within the *Lamerales* (the other one is sugar kelp *Saccharina latissima*, see below) that are cultivated in Europe. The cultivation in Europe is still in its infancy and on a relatively small scale in relation to the production of the related Asian species *Saccharina japonica* (Kerrison et al. 2017). *Laminaria digitata* show similar requirements of physicochemical conditions as sugar kelp but are more sensitive to higher temperatures but tolerate a higher flexibility of salinity levels. Production techniques for the two *Lamerales*-species are similar, starting with spore seeding on twines in a hatchery which are transplanted on ropes placed in open water structures (shown in Fig.1). The reported biomass production from long-line cultivations is lower for *Laminaria digitata* (8.0 kg wet material m−1 y−1) compared to 28.4 kg m−1 y−1 for *Saccharina latissima* (Kerrison et al 2015). The is a higher market value of *Laminaria* which also makes it interesting for cultivation. More information about physicochemical demands, nutrient limitation, density effects etcetera, will also increase the potentials of efficiently cultivate *Laminaria digitata.*

Saccharina latissima

The main species for cultivation at sea in the western Baltic Sea Region is *Saccharina latissima (Sugar kelp)*. Salinity level in the Baltic Sea is generally too low for growing *Saccharina latissima*, but a land-based experimental cultivation exists in Germany, at the lowest possible salinity level for it to grow (15 PSU). However, production levels cannot reach optimal levels due to the low salinity levels restricting the growth potential. In the western part of the Baltic Sea Region we find some areas with salinity levels are optimal for growing *Saccharina latissima*, being higher than 25 PSU. Cultivation of *Saccharina latissima* is applied both at sea and in land-based systems. The techniques at sea are primarily based on long-line techniques (see Figure 1 for detailed description) at sea. The techniques for cultivation are in some cases combined with infrastructure to accommodate for the processing of the products, such as drying facilities. The development of techniques and infrastructure for macroalgae cultivation engages a range of actors, including universities, public authorities and agencies, and the private sector. Most projects on cultivation of macroalgae at sea are based in Sweden.

Figure 1. Schematic layout of long line production systems. Reprinted from “Explorative environmental life cycle assessment for system design of seaweed cultivation and drying” by van Oirschot, R., Thomas, J.-B. E., Gröndahl, F., Fortuin, K. P. J., Brandenburg, W., & Potting, J A. Algal Research, 27, 43-54. Copyright (2017) by Elsevier.

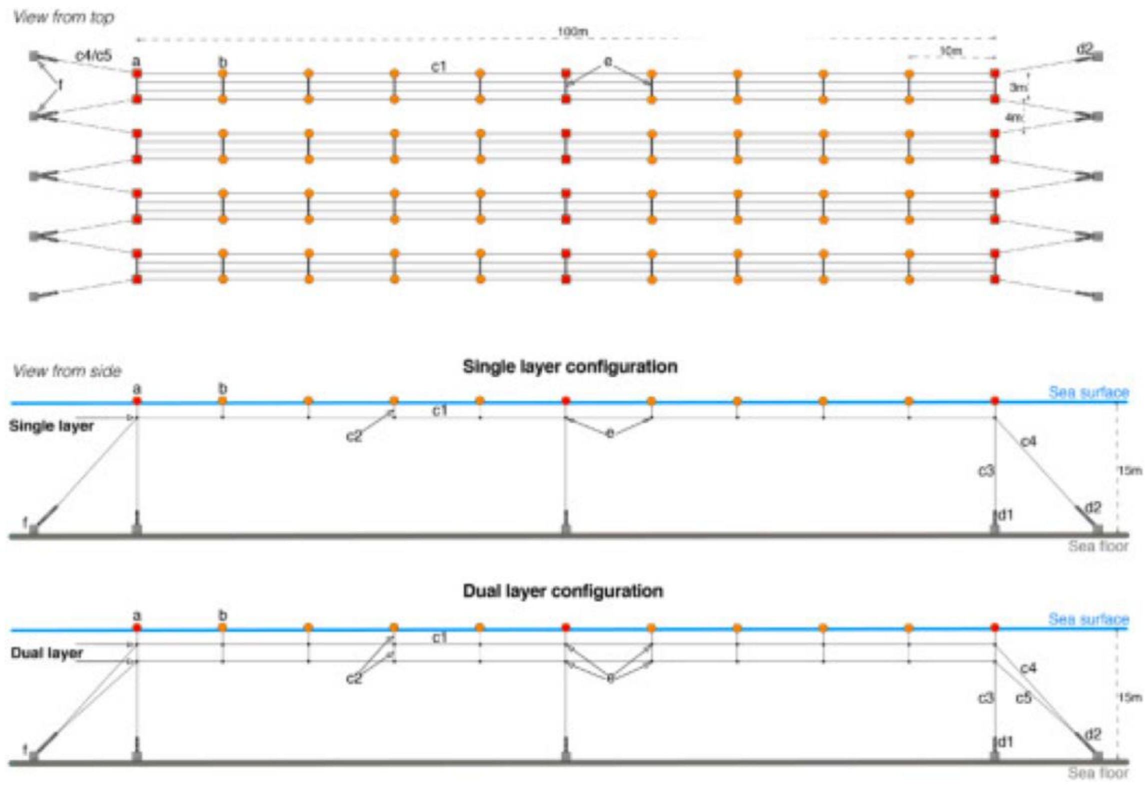

Fig. 1 Showing long-line production system infrastructure including both single and double line systems. The system includes marker buoys, smaller buoys, longline rope, steel chains, strip strengtheners and concrete anchors. (Figure from van Oirschot et al., 2017, https://doi.org/10.1016/j.algal.2017.07.025), Creative Commons Attribution-NonCommercial-No Derivatives License (CC BY NC ND).

Red Algae

Furcellaria lumbricalis

Furcellaria lumbricalis is the only species from the Baltic Sea that is harvested for commercial purposes in the Baltic Sea Region. The species has been harvested since the 1940ies in the Baltic Sea. The harvested biomass is used for extraction of furcellaran for usage in food and cosmetic industries as stabilizing, thickening and gelling agents (Weinberger, Paalme, & Wikström, 2020). There are two forms of *Furcellaria lumbricalis,* one attached and one unattached (loose-lying), where the latter is more interesting for harvesting. This form of *Furcellaria lumbricalis* is only common in Estonian coastal waters today where about 100000-150000 tonnes of wet weight of the species is produced every year. About 2000 tonnes are harvested and another 4000 tonnes is collected from *Furcellaria lumbricalis* beachcast wrecked on beaches. The population size of unattached *Furcellaria* is followed closely by Estonian researchers and harvest needs to be kept at a low level to sustain a viable population in the area (Weinberger et al., 2020). Other environmental pressures as eutrophication and ocean acidification (Kersen, Paalme, Pajusalu, & Martin, 2017; Pajusalu et al., 2020) might decrease the population of *Furcellaria lumbricalis* which imply that harvest of wild stocks might need further restrictions in the future from a conservation point of view. Thus, developing an aquaculture system for *Furcellaria lumbricalis* is of high priority. Experiments have so far showed that the spore settling of the species requires specific substrate and wave conditions (Kersen et al., 2017). The understanding of reproduction biology and settling on various substrates is one important piece of knowledge for developing open sea cultivations of *Furcellaria lumbricalis* in the Baltic sea.

Palmaria palmata

Palmaria palmata (Dulse) is yet another red algae species abundant in the Western Baltic Sea Region and the species is already in high demand on the world's food markets, and as feed, biofuel or for bioactive compounds (Grote, 2019). The species is today harvested from wild populations in several areas around Europe to meet this demand. When considering harvest of wild populations of macroalgae there is always a trade-off between harvesting biomass and the risk of negative effects on ecosystem structure, function and diversity. This is the reason behind advancements in cultivation techniques for the species. *Palmaria palmata* could be cultivated in land based systems leading to production of high quality biomass but at a high cost and high demand of labour, energy and material. There is a potential to develop large-scale open sea cultivations of Dulse in Europe but more knowledge about cultivation techniques, disease control and strain selection is needed before a commercialization of the production system could be developed (Grote, 2019). In Denmark studies of *Palmaria palmata*-cultivations have shown how to improve the efficacy of the hatchery phase (Schmedes & Nielsen, 2020a) and how to avoid biofouling by changing salinity levels (Schmedes & Nielsen, 2020b). Cultivation experiments in indoor cultivation systems have been tested in Sweden but the results are not promising. For the moment North Sea countries like Scotland and Ireland could provide the market with wild harvested *Palmaria palmata.*

Green algae

Ulva spp. (*Ulva lactuca, Ulva intestinalis*)

Ulva species are often dominant species in the specific macroalgae blooms called green tides. Macroalgae blooms are often leading to negative effects for the local environment and recreational values of populated coastal areas worldwide. *Ulva spp.* could be used for human consumption (Li, Kangas, & Terlizzi, 2014), bioenergy (Bruhn et al., 2011) or for bioremediation to reduce nutrients in highly eutrophicated waters (Kruk-Dowgiałło & Dubrawski, 1998). There have been some attempts to cultivate both *Ulva lactuca* and *Ulva intestinalis* within the Baltic Sea Region in pilot or experimental projects (Kovaltchouk 1996 ; Kruk-Dowgiałło & Dubrawski,. 1998; Haglund & Pedersén, 1988; Weinberger et al., 2020).

The genus is though not taxonomically well supported and recent studies based on molecular data suggest that earlier species identification based on morphology may not be correct and that species morphology show large variations within species depending on environmental setting and geographical location (Steinhagen, Karez, & Weinberger, 2020). This is an important issue to solve if cultivation systems of *Ulva* species should be developed in the area. Techniques of more intensive cultivation of *Ulva* species have been developed elsewhere. For example, in the eastern Mediterranean Sea where systems of aerated and non-aerated off-shore cage systems for cultivations have been tested (Chemodanov et al., 2019). During the last year (2020)*Ulva* cultivations on ropes in the sea have been developed by the Swedish seaweed company Nordic Seafarm in cooperation with scientists from University of Gothenburg (UGOT).

Projects & Initiatives

Cultivation of macroalgae

The GRASS partners have identified ongoing projects of macroalgae production in respective countries. Results of present cultivations in open sea are presented in Table 1 shows that *Saccharina latissima* is cultivated in three sites along the Swedish West Coast and in one site in the Bay of Kiel, Germany. In December 2020 the Swedish seaweed company Nordic Seafarm received permits of about 30 hectares of sea to cultivate seaweeds during the coming years making them one of Scandinavia's largest seaweed producers. In the Kiel Bight area they are also experimenting with cultivations of *Fucus vesiculosus*.

The environmental conditions of the cultivation sites reported by the GRASS project partners show varying sea bottom types from sandy to hard bottom sediments and the cultivations are situated both at sheltered and more exposed sites. The salinity level is around 25 PSU for the three Swedish sites whereas the Bay of Kiel only has a salinity of about 12-15 PSU which is a limiting factor for production of *Sacharina latissima* in this area and elsewhere in the Baltic Sea.

Table 1. Specific conditions for macroalgae cultivation projects and initiatives in the Baltic Sea Region.

MACROALGAE CULTIVATION PROJECTS							
Region/project	Species	Infrastructure, Technology	Sea bottom/ Sediment type	Degree of shelter	Salinity [PSU]	Distance to shore [m]	Temp. [°C]
Germany, Kieler Meeresfarm GmbH, Kiel-Pries	*Saccharina latissima, Fucus vesiculosus*	Seaweed cultivation in the sea - long lines, chessboard pattern, 1-2 m deep	Sandy, muddy floor	Sheltered	12-15	50	2-20
Sweden, Koster Archipelago	*Saccharina latissima*	*Long line production systems*	Mixed	Sheltered	> 25	3 000	8.5–11.5
Sweden, Gummarsfjord	*Saccharina latissima*	*Long line production systems*	Hard bottom	Semi-exposed	> 26	5000	8.5–11.6
Bohus Sea Culture	*Saccharina latissima*	*Long lines and an experimental rig production system*	Hard bottom	Exposed	> 26	3 000	8.5–11.6

Harvesting of wild seaweed

Furcellaria lumbricalis is the only species used for wild harvesting of macroalgae in the Baltic Sea. *Furcellaria lumbricalis* grow in attached and unattached forms; the attached type is widely distributed on hard sea bottoms and can be found at salinities down to 3.6 PSU. (Weinberger et al, 2020). The unattached form of *Furcellaria lumbricalis* is the form of the species that is harvested today. This form was common in the waters of Kattegat until harvesting intensified during the 1950s to 1970s and heavily reduced the stocks. Similarly, stocks of unattached Favorable weather conditions can wash up large amounts of *Furcellaria lumbricalis* on shores which facilitates handpicking of the algae. The other harvesting method is conducted by means of bottom trawling, in e.g., Norway and Iceland. Unfortunately, with unfavourable environmental effects. Technical development and experimentation for more sustainable production is under way, such as cages or fences placed at the sea bottom to catch and harvest *Furcellaria lumbricalis*. Extractions of the harvested biomass are primarily converted into two products: the gelling agent (furcellaran) and red color (r-phycoerythrin). (Weinberger et al, 2020).

Only one GRASS partner includes harvesting of wild macroalgae species in their reporting, Estonia. The Estonian harvesting sites are situated in relatively sheltered areas with sand or clay sediments. Salinity levels vary between 6.0-7.0 PSU and harvest is conducted up to 5000 meters from the shore, and the depths in the Estonian harvest sites are between 5 to 9 meters. Temperatures stay above freezing, and ice coverage is not an issue for harvesting *Furcellaria lumbricalis*.

Table 2. Site specific conditions for the ongoing project of wild macroalgae harvesting in the Baltic Sea Region.

WILD HARVESTING PROJECTS							
Region	Species	Sea bottom/ Sediment type	Degree of shelter	Salinity [PSU]	Distance to shore [m]	Depth [m]	Temp. [°C]
Estonia, Kassari Bay	Furcellaria lumbricialis	Sand and clay	Relatively sheltered	6.0–7.0	5000	5-9	8.5–11.6

Collection of beachcast

Beachcast consists of a mix of macroalgae and seagrass species, which is commonly used as fertiliser without prior treatment other than composting in passive piles. Collection of beachcast is done using machinery for plowing, scooping and removing piles after the completed composting process Gröndahl & Blidberg (2012), Nathaniel et al. (unpublished).

The procedure is practiced at a systemic scale in Russia, Sweden and Latvia. There are several drivers for beachcast collections and initiatives may come from various actors like individual farmers or land-owners, local NGOs and local or regional authorities Nathaniel et al. (unpublished). Thus, the techniques and approaches used in beachcast collection and management varies among localities.

The composition of macroalgae species in beachcast varies according to regions, seasons, and species, but the excessive nutrient load in the Baltic Sea has made opportunistic species the most prevailing (Weinberger et al, 2020). The eutrophication effect has also favoured eelgrass; a species shown to contain higher levels of Cadmium than others (Weinberger et al, 2020; Franzén et al., 2019). Although all species of macroalgae are known to accumulate heavy metals, which correlates to the low salinity of the Baltic Sea making species biologically available to assimilate metals (Weinberger et al, 2020).

Four beachcast collection projects have been reported within GRASS. Two projects in Latvia, one in Sweden and one in Russia. For the Latvian projects *Furcellaria lumbricalis* is the dominating species of the collected biomass. As for the Swedish reported collection, the biomass commonly consists of a mix of *Furcellaria lumbricalis*, *Fucus vesiculosus*, Filamentous red algae and *Zostera marina*. For the Russian project, *Cladophora glomerata* is the targeted species for collection.

The four reported projects should be viewed as examples of systematic beachcast collection in the Region, although numerous small-scale initiatives of bechcast collection exist. Germany alone has over 20 small-scale beachcast projects (Weinberger et al., 2020). Overall, collection of beachcast is conducted from accessible beaches where the bottom sediments vary, with the single and shared purpose of using beachcast as fertiliser. However, regarding the organisational structure and involved actors, the projects differentiate. In the case of Latvia, beachcast collection is a communal service (e.g. “Tranzits L” and Ventspils labiekartosanas kombinats) executed by private contractors, whereas in Sweden and Russia beachcast collection is treated as an environmental measure, supported by government institutions regulating such matters (e.g. Swedish Agency for Marine and Water Management and Department of Improvement and Ecology of the Resort District of St. Petersburg, respectively) in combination with external/private contractors executing the collection. A summary of the represented beachcast collection projects are presented in Table 3.

Table 3. Overview of beachcast collection projects

BEACHCAST COLLECTION PROJECTS				
Region	Species	Sea bottom/ Sediment type	Products/ Purpose	Organisations/Actors involved

Latvia, Liepaja	Furcellaria dominating sp.	Mixed sediments	Fertiliser	Ltd. “Tranzits L” – communal services, or other companies providing communal services, based on contracts
Latvia, Ventspils	Furcellaria dominating sp.	Mixed sediments	Fertiliser	Municipal Ltd. "Ventspils labiekartosanas kombinats"- communal services
Sweden, Gotland	Furcellaria,Fucus ves., Filamentous red algae, Zostera	Mixed sediments	Fertiliser	LOVA subsidizing system managed by Swedish Agency for Marine and Water Management and Gotland County Administration: Local NGOs and municipalities can apply for funding and contract local entrepreneurs and farmers
Russia, St Petersburg	Cladophora glomerata	Mixed sediments	Soil amendment in flower beds and tree plantations	Department of Improvement and Ecology of the Resort District of St. Petersburg

Sea bottom type is critical as it needs to support the weight of machinery, while not doing damage to the machinery or the environment (Weinberger et al, 2020). Sand bottoms are preferred in the production process. The type of sediment is also important in terms of the end product as fertiliser; stones and too much sand is undesirable to farmers (Nathaniel et al., unpublished).

The fact that beaches are being used for recreational purposes could be both a competing and collaborative activity; sometimes making beaches unavailable for harvesting during summer season, meanwhile fulfilling beach visitors desire for clean beaches. Another challenging situation occurs with regards to nature conservation where untouched bands of beachcast provide habitats for some wildlife other studies show unclear or even contrasting results (Zelinsky et al. 2019).

Present Production Challenges

GRASS project partners have identified and gathered macroalgae production challenges, categorised in three areas: *infrastructure* (from hatchery to harvest), *legislative* and *organisational* (Table 4).

Common ***infrastructure*** challenges for all regions conducting cultivation projects include the need to increase weather resistant infrastructure at sea, improved efficiency of existing equipment and development of new technology, and a lack of facilities for such experimental projects. Cultivation techniques for focal production species need to be developed, from hatchery to production infrastructure and value chains.

Legislative challenges due to lack of applicable jurisdiction for macroalgae production is emphasized for all tracks of macroalgae production; cultivation, harvesting and collection. In practice, several projects declare that this equates to long and complicated permit processes for acquiring licences for macroalgae production, which in turn inhibits the growth of a macroalgae industry. Hence, streamlining permit processes could be crucial to creating a vital macroalgae industry, requiring political support.

In terms of ***organisational*** challenges, knowledge gaps are the overarching theme. For macroalgae cultivation, there is a lack of expertise in technological development. As for harvesting, knowledge of operations in other industrial areas is lacking. Such knowledge is of interest for collaborative purposes, such as with fishery, in order to create industrial symbiosis between established industries and an emerging macroalgae industry. The biggest challenge for beachcast collection is a lack of knowledge regarding marine ecosystem effects from harvesting as well as terrestrial effects on agricultural ecosystems from its use as fertiliser.

Table 4. Challenges for macroalgae production identified by GRASS project partners, presented by country region. The challenges are categorised in three areas: infrastructure from hatchery to harvest, legislative and organisational.

CHALLENGES OF MACROALGAE PRODUCTION				
REGION	**Project**	**Infrastructure** *From hatchery to harvest*	**Legislative**	**Organisational**

Poland	Cultivation at sea, species undecided	Ice coverage requiring submerged infrastructure	No specific legal regulations, but a long and complicated permit process. Two species are protected requiring special permits to grow in areas where they occur wild.	Lack of knowledge regarding cultivation and harvest, limited scientific knowledge about reproduction and growth of potentially cultivable species.
Finland	Planned cultivation at sea, species undecided	Need of technological development in all phases	New permitting activity, pilot cases needed to assess legislation	Lack of knowledge and expertise in farming, high labour costs
Latvia	Cultivation at sea, species undecided	No existing infrastructure. Extreme wind and wave conditions as well as ice coverage are predicted to affect	Legislation is one of the biggest challenges. No special license/permit system but based on individual proposals. License process can last 400 days	No experience yet. Lessons learned from mussel farming will be applied
	Extraction of *Furcellaria lumbricalis* from beachcast	Improved machinery for fast harvest and drying of large volumes	No reported challenges. Specific rules for beach cast apply	No reported challenges
Estonia	Extraction of *Furcellaria lumbricalis* from beachcast & Trawling of *Furcellaria lumbricalis*	Pumping techniques are investigated for more environmentally friendly methods	Seaweed-, mussel- and fish farming is by the law almost the same operation like built up wind park, the normal planning and investing on this is almost impossible	Lack of industry specific knowledge and transfer; the idea to engage local fishermen during off-season is challenging to accomplish
	Extraction of free-floating *Furcellaria lumbricalis* from sea	Cages and fences on the seabed. Light, strong and effective construction needed	Complicated and restrictive permit process	Lack of knowledge. Possible involvement of local fisherman during offseason

Germany	Cultivation of *Saccharina latissima*, land based tanks	Poor salinity conditions	Restriction on operations in coastal and maritime regions. Long permission process (up to 2 years)	High staff costs
	Ulva spec. *Gracilaria* & *Mastocarpus* species, in photobio-reactors indoors	—	—	Low production compared to workload
Sweden	*Saccharina latissima*, long-lines at sea	Offshore exposed infrastructure is a challenge. Nearshore sheltered sites are reliable, productive and cost effective. A main bottleneck to expanding the Swedish production is to dry biomass quickly and effectively at large scale.	Lack of clear pathway for obtaining correct permissions. Lack of political support to help streamline processes. Acquiring licenses has been problematic, draft for new legislation is ongoing.	No identified challenges.
	Beachcast collection	Technology to harvest with minimal sand removal	Ambiguous rules and regulations	Knowledge gap regarding the environmental effects from beachcast collection; marine and land based
Russia	*Ulva spp.*, *Cladophora glomerata*, *Pilayella littoralis*	Lack of appropriate buildings.	Permission process is a problem, but successful examples exist.	Lack of trained personnel

Sustainable Paths Forward

Potential pathways towards establishing a sustainable macroalgae industry in the Baltic Sea calls for addressing and overcoming several production oriented challenges. An interdisciplinary approach combining environmental, technological and social/economic aspects of the challenges is crucial. It can be illustrated by a potential chain effect of events starting with building up knowledge of environmental effects from macroalgae production (cultivation, harvesting and collection). Such knowledge could serve as sustainability guidance for policy makers; and thus, simplify permit processes for macroalgae production. A more straightforward permit process could, in turn, secure or expand economic subsidies and increase investments in technological development, and other critical challenges. Discovering connections between different production challenges - including environmental, social, economic and technical aspects - could provide momentum for the development of macroalgae production in the Baltic Sea Region.

The following tangible steps are recommended:

- For the Western Baltic Sea Region we recommend further development and streamlining of the relatively mature production technology for cultivation of *Saccharina latissima, Laminaria digitata and Ulva sp.* which are the only commercially off-shore cultivated species in the area today.

- There is an urgent need for more research and knowledge building about life-cycle, cultivation techniques, and product value chains for alternative species for open sea cultivations in the region, such as *Furcellaria lumbricalis*, *Fucus vesiculosus*. *Ulva sp.*, *Chondra filum, etc.*. This is specifically important for the Baltic Sea (Eastern Baltic Sea Region) since species with mature cultivation techniques and infrastructure found in other areas are lacking in the Baltic Sea. “New” production systems must therefore be developed before establishment is possible in the region.

- Land-based systems are available or under development already today for several species in the region such as *Fucus vesiculosus, Ulva sp.*, *Saccharina latissima*. But infrastructure, technology and cost efficiency need to be improved for these systems to be commercially interesting. Land-based systems are advantageous by being less region-specific and by producing macroalgae biomass of high quality.

- Wild harvest of *Furcellaria lumbricalis* needs systemic analysis of environmental effects to assure that sustainable methods are applied. Research on cultivation techniques for *Furcellaria* aquaculture should also be promoted.

- The management systems for beachcast in the Baltic Sea Region are formed locally but the challenges are similar. In order to achieve sustainable paths forward, emphasis should be on identifying sustainable levels of collection with regards to the effects on marine ecosystems, terrestrial effects from beachcast removal (e.g. erosion), as well as environmental effects from the use of beachcast as fertiliser as agricultural use currently is the most common application.

- Gather and share knowledge to build capacity to support the development of legislation and policies which accommodate growth of sustainable macroalgae production systems - for cultivation, harvesting and collection.

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Appendix I.

The questionnaire formulated and used for data collection in the GRASS project.

Review efficient production methods of macroalgae throughout the Baltic Sea

Country:

1. List experimental algae farms, algae production initiatives and/or wild algae/beach cast harvest in your country; past, current and anticipated. Please use the table below.

Farm name & site	Species & harvest volume	Product(s)	Type of infrastructure (long line/nets/etc.)	Organizations involved

2. Describe the cultivation site/s (e.g. exposed or not, distance from shore, rocky/sandy/muddy floor, yearly temperature ranges, PSU (salinity) and related this to the production potential.

3. What are the production related challenges from your country?

   a. Hatchery challenges

   b. Infrastructure (lines/nets etc.) challenges

   c. Legislative challenges

   d. Organizational (knowledge, work power, gender issues) challenges

4. Based on the experience from your country what are the most suitable farming and harvesting equipment and why?