Report on ecological impacts of macroalgae cultivation in the Baltic Sea region

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Contents

Glossary

Allelopathy	Release of chemicals during decomposition
Benthic	Related to or within the bottom of the water body
Integrated multi-trophic aquaculture (IMTA)	Aquaculture of different trophic levels (e.g. mussels, macroalgae and fish) on a single site
Pelagic	Related to or within the water column
Photosynthesis	The process of converting light, carbon dioxide and water into organic matter
Primary production	The process of assimilation and fixation of inorganic carbon and other inorganic nutrients into organic matter by autotrophs

Introduction

In the recent years, the European marine waters have become a testing ground for macroalgae cultivation methods employed mainly in Asia, where most of the world's macroalgae are grown and harvested (van Oirschot et al., 2017). Macroalgae offer a means to increase food security, jobs and income while decreasing the nutrient load to eutrophic coastal areas and mitigating the eutrophication effects (Campbell et.al., 2019). For these reasons, macroalgae cultivation and harvesting is seen as a potentially socially, economically, and environmentally sustainable maritime activity, the development of which would support the EU blue growth strategy and blue bioeconomy initiatives.

The environmental conditions necessary for growing macroalgae vary among species. However, the key variables determining their growth are levels of sunlight, nutrients, salinity, and temperature. Due to the difference in these factors in the Baltic Sea the availability of wild grown, beach cast macroalgae and the possibility to cultivate currently commercially viable species varies[1][2]. Because of the environmental constraints, there are currently only a few types of macroalgae being cultivated and harvested in the Baltic[1] and only a hand full of methods being applied[2].

This report is a summary of the environmental risks and, most importantly, the benefits of macroalgae cultivation in the Baltic Sea. It is well known that macroalgae need nutrients for growth and assimilate them from the surrounding environment. This is an important quality of macroalgae that could help overtime decrease the levels of phosphorus and nitrate in the Baltic marine environment. This report outlines in detail the ways in which nutrient removal could benefit the Baltic Sea ecosystem.

The report concludes that macroalgae serve as carbon and nutrient sinks and their cultivation and harvest could mitigate the local effects of eutrophication and improve water quality which would regulate the occurrence of harmful algal blooms (Campbell et al., 2019; Duarte et al., 2017). Further, that suspended macroalgae cultivation using longline systems at a small or medium scale is unlikely to have any significant negative impacts on marine ecosystems, if cultivation does not spatially overlap with sensitive or protected habitats. Large-scale cultivation or harvesting activities should take place with more caution. Large longline installations may introduce stressors over large areas for prolonged periods of time – shading extensive areas of the seabed and affecting communities of organisms underneath the installation and within the water column.

[1] Further on environmental suitability for different species of algae: Assessing the PanBaltic potential of macroalgae cultivation and of harvesting wild stocks

[2] Further on production methods and challenges: GRASS Macroalgae Production Manual, Efficient production methods for macroalgae cultivation and harvesting, Production, Challenges & Pathways

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The information presented here is gathered from scientific studies assessing the impacts of macroalgae cultivation and harvest in the Baltic Sea, as well as the knowledge accumulated by GRASS project partners throughout the duration of the project.

Ecological importance of macroalgae in the Baltic Sea

Besides providing raw material for human use and a source of nutritious and culturally significant food, macroalgae supply various other ecosystems services and perform numerous ecosystem functions.

In the marine environment, macroalgae can be found in 3 different states – attached, loose-lying and beach cast. Attached macroalgae are primary producers and a food source for other marine species, therefore an important part of the food chain (Schultz-Zehden and Matczak 2012). They also provide habitat and shelter, as well as nursery grounds for juvenile invertebrates and fish. One of the most important functions performed by macroalgae, in the Baltic Sea context, is assimilation and accumulation of nutrients, which mitigate the effects of eutrophication (Schultz-Zehden and Matczak 2012). Further, as part of the photosynthetic processes, macroalgae assimilate dissolved carbon in the form of CO_2, making them contributors to oceanic carbon sinks (Duarte et al., 2017).

Beach cast algae are also an essential part of the food chain - they provide a source of food for birds, and microorganisms in the sand and sediment. Further, beach wrack is vital for the nesting of seabirds (Schultz-Zehden and Matczak 2012).

Cultivated species and methods in the Baltic Sea

A range of brown, red and green macroalgae are found in the Baltic Sea only a few of which are currently cultivated and harvested (See Table 1, and further on production methods and challenges, and a wider description of species in: *GRASS Macroalgae Production Manual, Efficient production methods for macroalgae cultivation and harvesting, Production, Challenges & Pathways*). To prevent the introduction and spread of alien species, only species native to the Baltic are permitted for cultivation under the EU Regulations ((EU) No 1143/2014).

Table 1. Main species for cultivation of macroalgae in the Baltic Sea.

Fucus spp

Fucus vesiculosus, (photo by Ieva Barda)

In the Baltic Sea *Fucus* is a brown macroalgae widespread on hard substratum and often dominates the shallow macroalgal communities (Torn et al., 2006). In the northern Baltic Sea, it is the most common and essential canopy-forming macroalgae. It is an integral part of the marine ecosystem and a food source for many invertebrate herbivores and provides shelter (Rinne and Salovius-Laurén 2020).

The cultivation techniques in the field for *Fucus* are still under development. In 2015, an experimental cultivation site of *Fucus vesiculosus* and *Fucus serratus* was established at the Kiel fjord in the Western Baltic Sea, which are among the first trials to cultivate *Fucus* species for commercial purposes (Meichssner et al., 2020).

Saccharina latissima

(photo by SUBMARINER Network)

Sugar kelp *S. latissima* is wildly distributed in temperate areas in the Northern hemisphere. It is relatively fast-growing and a crucial as habitat engineering macroalgae for various marine species. Their distribution is limited to the south-western Baltic Sea due to higher salinity demand (Nielsen et al., 2016; Weinberg et al., 2019)

Saccharina latissima is currently the only species of macroalgae cultivated in the Baltic in the milder, saltier waters of the western Baltic using longline systems (anchored long-lines suspended by buoys approximately 1–2 m below the surface)[3] (Campbell et.al., 2019; van Oirschot et al., 2017; Weinberger et al., 2019; Visch et al., 2020).
Furcellaria lumbricalis

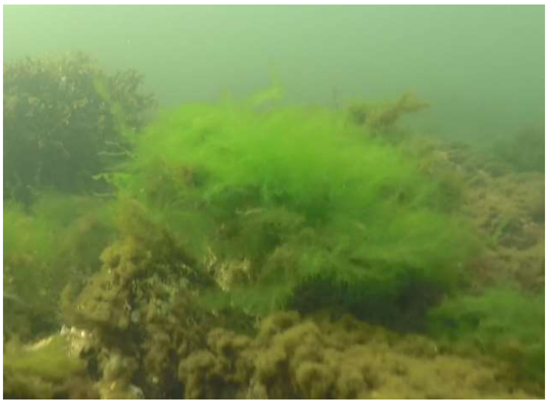
Furcellaria lumbricalis (photo by Juris Aigars)

The attached *F. lumbricalis* is widely distributed on hard substrata in the Baltic Sea (Bucas et al., 2007), while unattached (loose-lying) thallus forms currently inhabits only semi-exposed habitats with soft bottoms of the West Estonian Archipelago Sea area (Martin et al. 2013). The loose-lying *F. lumbricalis* are the only macroalgae in the Baltic Sea harvested from the wild for commercial use (Weinberg et al., 2019).

Several pilot projects regarding field cultivation techniques for both unattached and attached forms of *F. lumbricalis* has been initiated to develop in Estonia (Kersen et al., 2019; Est-Agar, 2019).

[3] Further on macroalgae cultivation methods and challenges in: Efficient production methods for macroalgae cultivation and harvesting Production, Challenges & Pathways

Ulva spp



Ulva spp (photo by Ingrida Purina)

Various species of *Ulva* genera (opportunistic green algae) typically develop as a result of eutrophication. In the Baltic Sea, *Ulva* is wildly distributed in the littoral zones and often dominate coastal biomass in the form of floating mats made up of unattached *Ulva* filaments (Bäck et al. 2000).

There have been some experimental cultivation trials in the field in the Baltic Sea, such as *Ulva spp*. in the Gulf of Gdansk on nets (Brzeska-Roszczyk et al., 2017), in the Finland on polyethylene nets and ropes in the northern part of Baltic Sea (Suutari et al., 2017) and on the ropes in the Hjarnø Kattegat (Christiansen, 2018).

The ecological impacts of macroalgae cultivation

1.1 Nutrient assimilation and retention

It is well known that the release of nutrients (nitrogen and phosphorus) into the Baltic Sea has resulted in an over-nourished marine environment. This has led to increased levels of phytoplankton (microalgae), increased occurrence of harmful algal blooms, reduced light conditions in the water, oxygen depletion at the seafloor, and other changes in the ecosystem (HELCOM 2018). Studies suggest macroalgae can be used to control eutrophication and algal blooms due to their nutrient assimilation capabilities (Jiang et al., 2020).

Marine phytoplankton (microalgae) is a group of organisms responsible for around half of the global primary production, and the diversity among species determines the functioning of plankton communities and pelagic ecosystems (Otero et al., 2020). Like macroalgae, phytoplankton need nutrients for growth and remove them from their surroundings. However, due to a range of different reasons, including over nourishment of the marine environment, some types of bloom-forming phytoplankton are much more frequently occurring and their short life span of only a few days means they are very ineffective and end-up contributing to as one of the sources of eutrophication (Ojaveer et al., 2010).

The increased abundance of macroalgae increases competition for dissolved nutrients, which reduces nutrient availability for phytoplankton increasing phytoplankton diversity and reducing the occurrence of harmful algal blooms (Jiang et al., 2020). Some have also suggested that macroalgae can also inhibit phytoplankton growth by releasing chemicals during decomposition (allelopathy) and shading, leading to a decrease in phytoplankton biomass, further reducing the occurrence of harmful algal blooms (Campbell et al., 2019). However, study results have so far been inconsistent (Jiang et al., 2020) as the interaction between macroalgae and phytoplankton is complex and depends on resource availability and the scale of cultivation site (Campbell et al., 2019).

Evidence such as this suggests that macroalgae cultivation presents an opportunity to reduce the amount of nutrients in the marine environment and over time decrease the effects of eutrophication. As macroalgae grow, they accumulate large amounts of nutrients within their tissue removing them from the surrounding environment serving as a temporary nutrient sink. Nutrients are stored within the algae tissue for months or even years. If the algae are harvested, the nutrients are removed from the marine environment completely. It has been estimated that 20 t/ha dry weight of macroalgae can extract around 480 tons of nitrogen per year in the large-scale kelp farm (20 km^2) (Campbell et al., 2019).

Due to these qualities, it has also been suggested, macroalgae cultivation and harvest could be used to reduce the negative impacts of fish aquaculture (Bouwman et al., 2011) and make it economically and environmentally more sustainable through the practice of Integrated multi-trophic aquaculture (IMTA) (Science for Environment Policy 2015).

IMTA largely refers to the farming of fishes alongside either macroalgae or shellfish. The waste nutrients from the fish would be consumed by the macroalgae or shellfish, thus partly mitigating the environmental impacts of finfish culture (Science for Environment Policy 2015). However, it does not preclude mussels and seaweed aquaculture as co-cultivation for the potential bioremediation ability for reducing nutrient load in marine waters, including the Baltic Sea. Moreover, macroalgae and mussels often co-exist in marine ecosystems and display multiple interactions. Mesocosm experiments of the green macroalgae *Ulva lactuca* and *M. edulis* to see whether co-cultivation with mussels increases *Ulva* production has been conducted in the Oosterschelde, Netherlands (Tonk & Jansen, 2019). Studies from Kiel Fjord of co-cultivation of seaweed (*Saccharina latissimi*) and mussels (*Mytilus edulis*) revealed a specific growth-enhancing effect of mussels on the seaweed at the early nursery stages during the hatchery and the grow-out period at sea. The positive effect of mussels on increased productivity at the grow-out stage of cultivation resulted in higher macroalgae biomass and carbon content (Rößner et al., 2014).

Within the GRASS project, a geospatial tool for estimating the nutrient removal potential of macroalgal cultivation and harvesting from sea water has been developed. The tool is accessible for everyone through the Operational Decision Support System (ODSS) online platform at http://www.sea.ee/bbg-odss/Map/MapMain, which also hosts the implemented results of project *Baltic Blue Growth*. On the main page of the geoportal under "switch layers tab" the user can select and view the map of Areal nutrient removal estimate by alga *Fucus* or *Ulva* (P & N Removal, t/km^2) across the Baltic Sea. The user can then click on "plan your farm" tab, draw a polygon representing their mussel and macroalgae farm and acquire various insightful statistics including algal growth rate and areal nitrogen or phosphorus removal by macroalgae within the polygon area. The estimates illustrate the effects of macroalgae cultivation on nutrient concentrations in the marine environment and aim to guide future cultivators in site selection and public authorities responsible for the aquaculture licensing and permitting process.

1.2 Hazardous substance assimilation and retention

As they grow, macroalgae absorb a range of different hazardous substances including heavy metal ions, such as zinc and cadmium, as well as iodine, and pesticides from their surroundings and store them within their cell walls (Rönnberg et al. 1990; Greger et al.,2006; Rubio et al., 2017). Macroalgae are known to be "hyperaccumulators" of heavy metals and other hazardous substances and are used to analyse and estimate marine pollution (Ishii et al., 2003).

The rate of substance accumulation differs across species, and depends on the type of hazardous substance, time of the year and plant part and location (Ryan et al., 2012; Foster 1979). Although some metal ions are essential micronutrients, high levels of metals in the water can prevent algae growth (Rönnberg et al. 1990). Further, if heavy metals accumulate within algae tissue, algae can become toxic to organism higher up the food chain, including humans. Recent findings suggest that brown and red algae can accumulate very high concentration of heavy metals in their tissue relative to the surrounding water (Ryan et al., 2012). According to the same study, *Fucus vesiculosus* has a particular ability to absorb Lead, Cadmium, Chromium, Manganese and Nickel, and the green algae *Ulva sp* has also been found to accumulate Chromium.

Studies have also shown that salinity plays an important role in heavy metal uptake as a decrease in salinity increases the availability of the metals (Greger et al., 2007). For instance, *Fucus vesiculosus* in the northern Baltic (around 7 ‰ salinity) have been found to have 10-times-higher cadmium concentration than the same species macroalgae in the North Sea (around 30 ‰) (Greger et al., 2007).

Once algae are harvested, heavy metals, just like nutrients, are removed from the marine environment. In cases where the water is polluted with heavy metals, removal of algae leaves the marine environment a safer place for living organisms. Some have suggested, that macroalgae could be used to capture remove and recover heavy metals from wastewaters (Niazi et al., 2016) to control levels of hazardous substances in water environments.

Meanwhile, high metal concentrations can compromise macroalgal use possibilities once they are harvested (Phillips 1990). Testing is common and has shown that macroalgae safe for human use can be harvested in some regions of the Baltic.

1.3 Light conditions

The quality and intensity of light underwater are altered by the water column itself and by the vegetation in it (Campbell et al., 2019). When cultivated using longline systems, macroalgae are suspended at the top of the water column, where the levels of light are exactly right for the species to perform photosynthesis.

The positioning of macroalgae alters the surrounding light conditions by physically shading the area (Phillips 1990). Cultivation installations may block the light for living organisms underneath the installation, such as benthic macroalgae influence and increasing competition for light and nutrients among pelagic species causing change to planktonic communities and primary productivity (Campbell et al., 2019).

Cultivation over productive benthic habitats characterised by macroalgae or seagrasses in the shallow waters should be avoided when possible as they are sensitive to shading effects (Campbell et al., 2019). In the Baltic, such habitats are under protection, making spatial overlap with cultivation installations highly unlikely. Further, the waters where productive benthic habitats are found are often too shallow and stony for the installation of cultivation infrastructure. Therefore, the effects of shading are improbable at any scale of cultivation (Campbell et al., 2019).

Fortunately, the impacts on pelagic species are likely to be limited as the movement of water in the water column required for the efficient nutrient and gas exchange for the cultivated species ensured by the design of the installation will ensure that phytoplankton communities move through the installation quickly (Campbell et al., 2019). Therefore, significant effects of shading on the pelagic communities are unlikely at small-medium scales for individual cultivation sites, but increase in likelihood as the installation size increase and the number of installations grow (Campbell et al., 2019).

1.4 Physical alteration

1.4.1 The introduction of macroalgae

All macroalgae are attractive to a diverse range of organisms. Some of the most ecologically valuable habitats types in the Baltic are characterised by macroalgae. In the Baltic, these habitats are mostly associated with a rocky or stony seabed and relatively shallow waters. The longline systems currently used in the southern Baltic for macroalgae cultivation hold the algae in suspension at the top of the water column in deeper waters, making them quite different from wild macroalgae habitats (Campbell et al., 2019).

Cultivation introduces macroalgae into the otherwise structure-less space (Visch et al., 2020; Stévant et al., 2017). This attracts swimming or drifting organisms and increases biological complexity in the water column (Campbell et al., 2019) increasing biodiversity for the time being. Studies of kelp farms in Norway have found a high abundance of juvenile fish around cultivation sites (Stévant et al., 2017). Meanwhile, fish grazing has not been found to affect macroalgae biomass to a significant degree, and suspended macroalgae are unlikely to be accessible to benthic organisms feeding on algae, in the summer planktonic larval stages can settle and develop into grazing juveniles. This can cause macroalgae biomass loss and affect the timing of the harvest (Wood et al., 2017).

Although macroalgae cultivation has been seen to overall benefit the pelagic environment, suspended macroalgae have been found to result in high material deposits on the seafloor, the decomposition of which may cause oxygen depletion and affect benthic organisms (Sévant et al., 2017).

When picking the location for a cultivation site, it is not only important to understand the connectivity between the cultivation site and other habitats to prevent loss of biomass, but also to make sure that the introduction of macroalgae or their increased presence does not support the spread of non-native species – provide them with a place of refuge and a source of food (Campbell et al., 2019).

The Baltic Sea seals feed on crustaceans and fish, thus are also likely to find cultivation sites attractive. This is important to keep in mind when selecting the location for cultivation, as some seals in the Baltic are classed as vulnerable, therefore there is a statutory responsibility to ensure that they, and any other vulnerable or protected species, are not harmed during offshore activities (Campbell et al., 2019).

1.4.2 The introduction of hard substrate

Suspended macroalgae cultivation using longline systems requires anchoring to the seabed. This introduces an artificial substrate (Visch et al., 2020), which can either replace or act as an extension to the existing habitat depending on the initial seabed type. Evidence is limited, but studies of other offshore structures, such as offshore wind farms, suggest that benthic species are likely to colonise the anchors (Wood et al., 2017).

For instance, at the pilot farm at Kiel Fjord macroalgae cultivation of attracted crabs, snails, starfish and fish – species not typically found on a sandy seabed with few stones. With time, the smaller creatures were followed by larger predators such as plaice, butterfish and gobies, thus valuable contributing to biodiversity. Further, large numbers of mussels settled on the harvested algae fields[4]. However, because the footprint of the anchors is relatively small, they will have little effect on the seabed communities, regardless of the seabed substrate type.

1.4.3 Structures within the water column

Suspended macroalgae provide a three-dimensional habitat within the water column increasing species richness (Visch et al., 2020), but it can also create an obstacle for migrating marine species. Observations elsewhere in the world have shown that aquaculture installations can interfere with mammal or other large marine species migration routes leading to 'barrier effects' if sites are not selected with migration and feeding habits in mind (Campbell et al., 2019).

Water exchange and movement are essential for the growth of macroalgae and the productivity of a macroalgae farm. Moving water ensures the exchange of dissolved nutrients and gases, removes sediments and waste, and can reduce the chances of grazers and biofouling marine organisms settling on the algae (Wood et al., 2017). However, suspended cultivation systems also affect the local passage of water currents and waves, and sediment movement (Campbell et al., 2019). Kelp farms and suspended mussel aquaculture have been found to change water velocity and dampen waves around the installation, reduce water flow within the interior of large-scale cultivation sites (Campbell et al., 2019). They have also been found to create an undercurrent beneath the farm also impacting the rate at which suspended, organic and inorganic matter moves through the water column and eventually settle on the sediment (Wood et al., 2017). Direct observations are scarce, but studies of kelp forests and cultivation sites suggest that the changes in water flow effect vertical and horizontal transport of particles. The ecological significance of these changes in not yet very clear, but there are likely to have a local effect on plankton and benthic communities (Eckman et al., 1989).

The precise impacts of longline cultivation systems on the water and particle movement will vary from site to site. Therefore a thorough investigation of the following prior and during cultivation has been recommended to take place: water velocity inside and outside the farm; sediment transport pathways; sedimentation rates within and outside farm (upstream and downstream); and identification of potential sediment deposition locations (Wood et al., 2017, p. 33).

1.5 The spread of non-native species, disease and parasites

Non-native species (NIS) are organisms introduced to ecosystems outside of their native range through human activity. Not all NIS become invasive, but those that do predominantly disrupt the local ecosystem, causing loss of biodiversity, ecosystem functioning and cause economic damage (Campbell et al., 2019). Meanwhile NIS are known to devastate ecosystem, there are cases where non-native species have had no effect on the overall functioning in the ecosystem, and in some

[4] https://www.dbu.de/123artikel24819_.html

cases, they have enriched the ecosystem biodiversity (Katsanevakis et al., 2014). However, once introduced, invasive NIS are close to impossible to eradicate (Ojaveer et al., 2015).

It is said that aquaculture has been responsible for around 121 of 223 of non-native macroalgae introductions across the globe (Campbell et al., 2019). Based on the Aquanis data base, 14 NIS macroalgae species have been found in the Baltic Sea so far, and all of them have been reported from the western part of Baltic Sea (in Germany - 7, Denmark - 11 and Sweden - 2)[5]. To prevent the introduction and spread of NIS in European waters, strategies and regulations have been put in place (e.g., the Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species). According to these regulations, only native species found within the marine environment can be cultivated commercially. Further, to reduce the potential risk of NIS introduction, the movement of biofouling associated with maintenance vessels needs to be monitored and managed (Campbell et al., 2019).

Disease and parasites are a major threat to agriculture and aquaculture. Unlike on land, pesticides and fertilizers cannot be used to control the spread of parasites or disease in the water environment, so if infected, the yield will drop dramatically. Moreover, the nature of the marine environment makes the spread of parasites and disease extremely easy, so this would also put the wild macroalgae population at risk (Campbell et al., 2019; Wood et al., 2017). Macroalgae cultivation experience in some of the top producing countries of red algae and kelp cultivation in Norway shows one of the major limitations to productive cultivation are disease and outbreaks of epiphytic algal pests (Campbell et al., 2020; Stévant et al., 2017). Some of the main reasons for disease outbreaks are over–crowding and monoculture, which leads to a lack of water exchange, light, and nutrients (Werner et al., 2004). To prevent the introduction and spread of disease and pests work must be done on a national and international scale to promote biosecurity (Campbell et al., 2020) and precautions at the project level.

1.6 Noise pollution

Cultivation and harvest activities are likely to increase of vessel traffic and presence of machinery, both of which are sources of anthropogenic sound potentially – noise pollution. The effects of local noise pollution above background levels are not well understood, however, anthropogenic sound has been found to cause behavioural responses in various marine species, as well as stress and in some cases changes in hearing sensitivity (Williams et al., 2015). The impacts vary depending on the type of sound – its frequency and duration, and the animal's proximity to the sound source.

Studies show that harbour porpoise, harbour seal, ringed seal and grey seal are sensitive to sound in a wide frequency range. Further, that it likely that underwater noise affects the Baltic Sea cod,

[5] http://www.corpi.ku.lt/databases/index.php/aquanis/

herring, burbot and potentially sprat, causing acoustic barriers and disrupting important behaviours and causing changes to migration patterns during spawning season (HELCOM 2019).

Literature sources

Bäck S, Lehvo A, Blomster J (2000) Mass occurrence of unattached *Enteromorpha intestinalis* on the Finnish Baltic Sea coast. Ann Bot Fennici 37:155–161

Bouwman, A.F., Pawłowski, M., Liu, C., Beusen, A.H.W., Shumway S.E., Glibert, P.M., Overbeek, C.C. 2011. Global Hindcasts and Future Projections of Coastal Nitrogen and Phosphorus Loads Due to Shellfish and Seaweed Aquaculture. Reviews in Fisheries Science. 19:4. doi.org/10.1080/10641262.2011.603849

Brzeska-Roszczyk, A., Barańska, A., Kruk-Dowgiałło, L., 2017. A review of the selected methods of macroalgae cultivation in marine waters. Bulletin of the Maritime Institute in Gdańsk. 2017; 32(1): 129-136. DOI: 10.5604/01.3001.0010.6980

Campbell, M.L. and Hewitt, C.L. 2008. Introduced marine species risk assessment – aquaculture. In M.G. Bondad-Reantaso, J.R. Arthur and R.P. Subasinghe (eds). Understanding and applying risk analysis in aquaculture. FAO Fisheries and Aquaculture Technical Paper. No. 519. Rome, FAO. pp. 121–133.

Campbell I., Macleod A., Sahlmann C., Neves L., Funderud J., Øverland M., Hughes AD., Stanley M. 2019. The Environmental Risks Associated with the Development of Seaweed Farming in Europe - Prioritizing Key Knowledge Gaps. *Frontiers in Marine Science*. 6:107. doi.org/10.3389/fmars.2019.00107

Christiansen, E.R., 2018. The Potential of Ulva for Bioremediation and for Food and Feed. Master's Thesis M.Sc.Eng. Biotechnology.

Duarte, C.M., Wu, J., Xi, X, Bruhn, A., Krause-Jensen, D.2017.Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? Frontiers in Marine Science.4. 10.3389/fmars.2017.00100

Eckman, J.E., Duggins, D.O., Sewel A.T.1989. Ecology of understory kelp environments. I. Effects of kelps on flow and particle transport near the bottom. Exp. Mar. Biol. Ecology. 129. 173-187.

Science for Environment Policy. 2015. Sustainable Aquaculture. Future Brief 11. Brief produced for the European Commission DG Environment by the Science Communication Unit, UWE, Bristol. Available at: http://ec.europa.eu/science-environment-policy

Est-Agar. 2019. Presentation: Est-agar Blue growth start-up in Estonia, Seaweed, and mussel innovation. https://www.submariner-network.eu/images/06_Estagar_seaweed_24.04.2019.pdf

Foster P. 1979. Concentrations and concentration factors of heavy metals in brown algae. Environmental Pollution. 10. Applied Science Publishers Ltd: England

Greger, M., Malm, T., Kautsky, L.2007. Heavy metal transfer from composted macroalgae to crops. European Journal of Agronomy. 26:3. 257-265. doi.org/10.1016/j.eja.2006.10.003

HELCOM. 2018. HELCOM Thematic assessment of eutrophication 2011-2016. Baltic Sea Environment Proceedings No. 156. http://www.helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials/

HELCOM 2019. Noise sensitivity of animals in the Baltic Sea. Baltic Sea Environment Proceedings N° 1. https://www.helcom.fi/wp-content/uploads/2019/08/BSEP167.pdf

Ishii, T., Hirano, S., Watabe T. 2003. Hyperaccumulation of radioactive isotopes by marine algae. Proceedings of the international symposium: Transfer of radionuclides in biosphere. Prediction and assessment. (JAERI-Conf--2003-010). Amano, Hikaru, & Uchida, Shigeo (Eds.): Japan

Jiang, Z., Liu, J., Li, S., Chen, Y., Du, P., Zhu, Y., Liao, Y., Chen, Q., Shou, L., Yan, X., Zeng,J., Chen, J. 2020. Kelp cultivation effectively improves water quality and regulates phytoplankton community in a turbid, highly eutrophic bay. Science of The Total Environment.707. doi.org/10.1016/j.scitotenv.2019.135561.

Kersen, P., Paalme, T., Pajusalu L., Martin G., 2019. Biotechnological applications of the red alga *Furcellaria lumbricalis* and its cultivation potential in the Baltic Sea. Botanica Marina 2017; 60 (2): 207–218. DOI 10.1515/bot-2016-0062

Meichssner, R., Stegmann N., Cosin, A. S., Sachs, D., Bressan, M., Marx, H., Krost, P., Schulz, R., 2020. Control of fouling in the aquaculture of *Fucus vesiculosus* and *Fucus serratus* by regular desiccation. Journal of Applied Phycology, 32:4145–4158

Marine Scotland. 2017. Seaweed Cultivation Policy Statement, https://www.gov.scot/publications/seaweed-cultivation-policy-statement-2017

Nielsen, M. M., Paulino, C., Neiva, J., Krause-Jensen, D., Bruhn, A., & Serrão, E. A. (2016). Genetic diversity of *Saccharina latissima* (Phaeophyceae) along a salinity gradient in the North Sea-Baltic Sea transition zone. Journal of Phycology, 52(4), 523–531. doi:10.1111/jpy.12428

Niazi, N.K., Murtaza, B., Bibi, I., Shahid, M., White, J.C., Nawaz,M.F., Bashir, S., Shakoor, M.B., Choppala, G., Murtaza, G., Wang H. 2016. Removal and Recovery of Metals by Biosorbents and Biochars Derived From Biowastes. Environmental Materials and Waste. Academic Press, 149-177. doi.org/10.1016/B978-0-12-803837-6.00007-X.

Katsanevakis S., Wallentinus I., Zenetos A., Leppäkoski E., Çinar M. E., Oztürk B., Grabowski M., Golani D., Cardoso A.C. 2014. Impacts of invasive alien marine species on ecosystem services and biodiversity: a pan-European review, Aquatic Invasions. 9:4, 391–423. 10.3391/ai.2014.9.4.01

Ojaveer H., Galil B.S., Lehtiniemi M., Christoffersen M., Clink S., Florin A., Gruszka P., Puntila R., and Behrens J.W. 2015. Twenty-five years of invasion: management of the round goby Neogobius melanostomus in the Baltic Sea, Management of Biological Invasions. 6:4, 329–339. 10.3391/mbi.2015.6.4.02

Ojaveer, H., Jaanus, A., MacKenzie, B.R., Martin, G., Olenin, S., Radziejewska, T., Telesh, I., Zettler,M.L., Zaiko, A. 2010. Status of Biodiversity in the Baltic Sea. PLOS ONE. doi.org/10.1371/journal.pone.0012467

Otero, J., Álvarez-Salgado, X. A., Antonio, B. 2020. Phytoplankton Diversity Effect on Ecosystem Functioning in a Coastal Upwelling System. Frontiers in Marine Science. doi.org/10.3389/fmars.2020.592255

Phillips, M.J. 1990. Environmental aspects of seaweed culture. FAO. www.fao.org/3/AB728E/AB728E05.htm

van Oirschot R., Thomas, J. B. E., Gröndahl F., Fortuin K.P.J., Brandenburg W., Potting J. 2017. Explorative environmental life cycle assessment for system design of seaweed cultivation and drying. Algal Research. 27. 43–54. doi.org/10.1016/j.algal.2017.07.025

Schultz-Zehden, A. & Matczak, M. (eds.). 2012. SUBMARiNER Compendium. An Assessment of Innovative and Sustainable Uses of Baltic Marine Resources. Gdańsk

Stévant, P., Rebours, C. & Chapman, A. 2017. Seaweed aquaculture in Norway: recent industrial developments and future perspectives. Aquacult Int. 25. 1373–1390. doi.org/10.1007/s10499-017-0120-7

Rinne, H., Salovius-Laurén, S. 2020. The status of brown macroalgae *Fucus* spp. and its relation to environmental variation in the Finnish marine area, northern Baltic Sea. Ambio 49, 118–129. doi.org/10.1007/s13280-019-01175-0

Rubio, C., Napoleone, G., Luis-González, G., Gutiérrez, A.J., González-Weller, D., Hardisson, A., Revert, C. 2017. Metals in edible seaweed. Chemosphere. 173. 572-579. doi.org/10.1016/j.chemosphere.2017.01.064.

Ryan, S, McLoughlin P, O'Donovan O. 2012. A comprehensive study of metal distribution in three main classes of seaweed. Environmental Pollution. 167. 171-177. doi.org/10.1016/j.envpol.2012.04.006

Rönnberg, O., Adjers, K., Ruokolahti, C., Bondestam, M.1990. *Fucus vesiculosus* as an Indicator of Heavy Metal Availability in a Fish Farm Recipient in the Northern Baltic Sea. Marine Pollution Bulletin. 21: 8. 388 392. doi.org/10.1016/0025-326X(90)90648-R

Rößner, Y., Krost, P. & Schulz, C. 2014. Increasing seaweed crop yields through organic fertilisation at the nursery stage. J. Appl. Phycol. 26:753-62. DOI 10.1007/s10811-014-0269-7

Suutari, M., Leskinen, E., Spilling, K., Kostamo, K., Seppälä, J., 2017. Nutrient removal by biomass accumulation on artificial substrata in the northern Baltic Sea. J Appl Phycol 29:1707–1720. DOI 10.1007/s10811-016-1023-0

Tonk, L., Jansen H.M., 2019. Co-cultivation of the seaweed *Ulva sp*. and *Mytilus edulis*. Wageningen University & Research report C011/19. 34 p.

Torn, K., Krause-Jensen, D., Martin, G. 2006. Present and past depth distribution of bladder wrack (*Fucus vesiculosus*) in the Baltic Sea. Aquatic Botany 84:53–62

Visch, W., Kononets, M., Hall, P.O.J., Nylund, G.M., Pavia, H. 2020. Environmental impact of kelp (*Saccharina latissima*) aquaculture. Marine Pollution Bulletin. 155. doi.org/10.1016/j.marpolbul.2020.110962

Weinberger, F., Paalme, T., Wikström, S.A., 2019. Review: Seaweed resources of the Baltic Sea, Kattegat and German and Danish North Sea coasts, Botanica Marina. doi.org/10.1515/bot-2019-0019

Werner, A., Clarke, D., Kraan, S. 2004. Strategic Review of the Feasibility of Seaweed Aquaculture in Ireland. Marine Institute. www.marine.ie/marinertdi

Williams R., Wright, A.J., Ashe, E., Blight, L.K., Bruintjes, R., Canessa, R., Clark, C.W., Cullis-Suzuki, S., Dakin, D.T., Erbe, C., Hammond, P.S., Merchant, N.D., O'Hara,P.D., Purser, J., Radford A.N., Simpson, S.D., Thomas, L., Wale, M.A. 2015. Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management. Ocean & Coastal Management. 115. 17-24. doi.org/10.1016/j.ocecoaman.2015.05.021

Wood, D., Capuzzo, E., Kirby, D., Mooney-McAuley, K., Kerrison, P. 2017. UK macroalgae aquaculture: What are the key environmental and licensing considerations? Marine Policy. 83. 29–39. dx.doi.org/10.1016/j.marpol.2017.05.021