Socio-economic dimension of the development of the production and the use of macroalgae in the Baltic Sea Region

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Summary

We can only talk about the socio-economic impact of the local seaweed industry on the Baltic Sea Region on the basis of the **assumptions made regarding the scale** of future seaweed cultivation. There is no such assumption in any official policy documents for the Baltic Sea Region. Therefore, we estimate the socio-economic impact in this factsheet based on an ambitious, proprietary strategic vision (described on page 3).

We show that the use of 3,480 ha of Baltic Sea waters for the cultivation of fast-growing seaweed such as *Ulva intenstinalis* can have significant positive environmental effects, such as **significant nutrient reduction** in the eutrophied waters of the Baltic Sea and **significant accumulation of CO_2**. At the same time, some negative impacts on the environment (seabed, landscape) are much smaller than the obtained benefits (see page 2).

The development of the consumption of seaweed, regardless of whether it is based on local production or – as at present – imported raw materials, has a positive effect on the health of the society. The **versatile positive health benefits of seaweed** have been scientifically proven. This is especially important in the face of the growing demand for vegan products (see page 4).

The development of the seaweed sector and at least partial replacement of imported raw materials with local production translates into the **multiplication of the added value in the Region per unit of seaweed products used**. At the same time, the project demonstrated that **biorefining is the most comprehensive and future-proof option for processing seaweed raw materials** (see page 5).

The development of local production of seaweed is an **opportunity to use the human potential**, especially the competences of fishermen leaving the Baltic fishery, as a result of the reduction in fishing opportunities every year (see page 6).

There are a number of strong research centers dealing with seaweed in the Baltic Sea Region. However, there are few initiatives focused on practical implementation so far. Therefore the implementation of any ambitious plan should be preceded first by conducting **experiments on a semi-industrial scale** in the Baltic Proper, as the available literature data regarding the productivity of macroalgae such as *Ulva intestinalis* come from different years and show large divergences.

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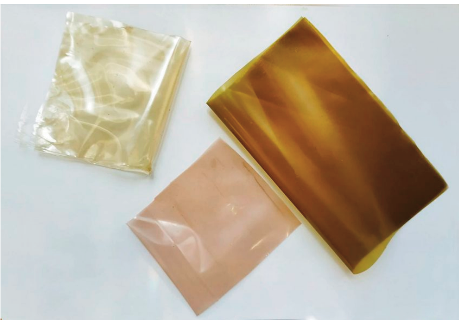
For the environment

The macroalgae cultivation sites have **a huge potential to remove the excess of nitrogen and phosphorus** from surrounding water and therefore to **combat eutrophication**. Macroalgae accumulate and store large amounts of nutrients within their tissue, thus if they are harvested, the nutrients are completely removed from the environment.

Macroalgae aquaculture **can also mitigate CO_2 emissions** in various ways. First of all, seaweeds are ranked among the most efficient photosynthetic organisms on earth. The potential for removing of atmospheric CO_2 by world's macroalgae aquaculture, using data on global production from 2014, has been estimated at 2,48 mln tonnes of CO_2 per year. Secondly, the CO_2 emissions involved in production of macroalgae-based food and feed is much lower than in case of comparable amount of land-based agriculture products. Moreover, macroalgae are promising biofuel feedstock. The production of biofuels of seaweed origin is in many aspects more environmentally sustainable than production of biofuels derived from land crops. Unfortunately, the production of macroalgae-based biofuels, especially at commercial scale, is economically, energetically and technically challenging, thus requires more research.



fot. E. Jamróz

Biopolymers, developed by a team from the University of Agriculture in Krakow, under the supervision of prof. Ewelina Jamróz. New products replace plastic films and are fully biodegradable. It based on furcelleranc (FUR) obtained from the macroalgae Furcellaria lumbricalis caught in Estonian waters.

Macroalgae may **also contribute to the reduction of plastic pollution**, as they can be used to produce bioplastics - biodegradable alternative to plastic materials derived from the renewable biological sources. Although the technology to produce such material from macroalgae is still under the research phase, the findings indicating that macroalgae-based bioplastics are durable and resilient are very promising.

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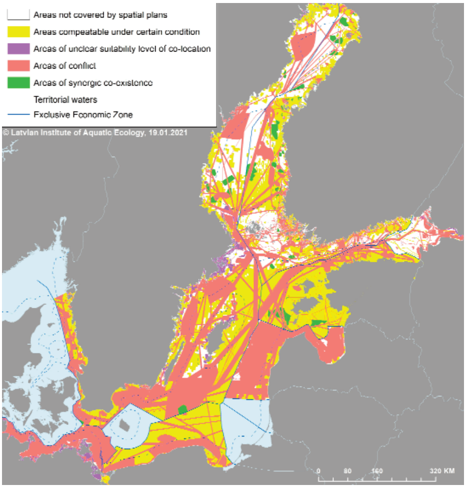
The production of biofuels of seaweed origin is in many aspects more environmentally sustainable than production of biofuels derived from land crops.

On the other hand, the cultivation using long-line system requires anchoring, which introduces artificial substrate to the seabed and potentially might affect the communities of benthic organisms. Large farms may also reduce the light availability in the water column, what might also affect the organisms. However, **the benefits from macroalgae farming seem to far outweigh the potential negative impact on the environment**.

See also:
Armoskaite, A., Barda, I., Fedorovska, A., Purina, I., Sprukta, S., Strake, S. 2021. *Report on ecological impacts of macroalgae cultivation in the Baltic Sea region.* GRASS Report 2.3. Available online: https://www.submariner-network.eu/grass

Strategic vision – macroalgae in the fight against eutrophication of the Baltic Sea and climate change

The socio-economic impact depends on the scale of future production. Our strategic vision is to use for seaweed cultivation by 2050: min. **10% of areas of high productivity and synergistic coexistence** with other activities and min. **1% of high productivity areas where seaweed farming is conditionally acceptable**. Assuming that this sector was initially based only on the cultivation of *Ulva intestinalis* (easier to grow, with high productivity), this gives **an area of 3,480 ha**. With optimistic literature assumptions, up to **302,760 tons (fresh weight) of production** can be obtained in this area.



With these assumptions in our strategic vision, the cultivation of seaweed can reduce the nutrients in the waters of the Baltic Sea on a significant scale annually: **up to 87,000 kg P** and **up to 1,093,000 kg N**. At the same time, at the production level, **6,055,000 kg CO_2 would be accumulated**.

The implementation of this strategic vision requires the involvement of various stakeholders, including: administration, investors (including those engaged in synergistic maritime activities – e.g. wind farm operators), science and innovative and implementation companies that will develop appropriate technologies. The basic impulse for the implementation of this vision, however, must be the openness of the administration **to finance water and environmental services provided by macroalgal farms**.

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The wind farms have been identified as an activity showing high synergy for the cultivation of seaweed.

Data sources: Modeled data of *Fucus vesiculosus* and *Ulva intestinalis* production potential - Estonian Marine Institute, University of Tartu		areas of synergic co-existence (km2)		areas permitted under certain conditions (km2)		areas where spatial planning has not defined area functions (km2)		areas not covered by spatial plans (km2)		areas of conflict (km2)	
		territorial waters	EEZ	territorial waters	EEZ	territorial waters	EEZ	territorial waters	EEZ	territorial waters	EEZ
Fucus> 1.5%	Germany			26		875		107	1	7133	2380
	Estonia			38						5	
	Finland			15				71		12	
	Latvia			151				50		646	
	Poland			375	1041					1949	675
	Sweden - except the West Coast		21	452	481	11		12		794	754
	Sweden - the West Coast	14		2241	470	41		106	4	3357	1644
	Russian Federation (St. Petersburg region)										
Ulva> 7%	Germany			41	33	1561		249	21	9038	4456
	Estonia	334	22	8204	41			1		1412	358
	Finland	19		905	4			2708	13	2163	51
	Latvia			936	317			335	18	3868	714
	Poland			2253	4995					6119	2840
	Sweden - except the West Coast		544	4450	655	1259		1198	5	6977	2713
	Sweden - the West Coast	14		2293	437	41		110	4	3384	1611
	Russian Federation (St. Petersburg region)			1				8		14	

Map and table of areas where seaweed farming: has high production potential and is recognised as synergic co-existence or permitted under certain conditions. Developed under the GRASS project by the Latvian Institute of Aquatic Ecology.

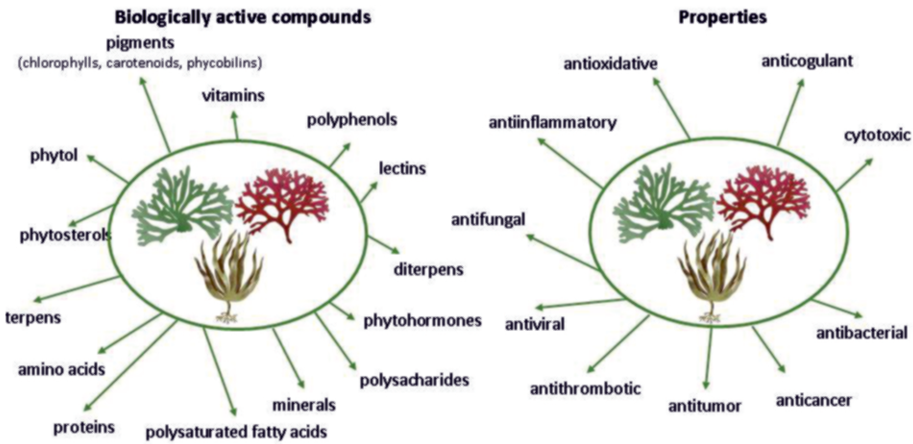
For a healthier society – pro-health benefits of macroalgae

Macroalgae are **an excellent source of proteins, vitamins, minerals, fatty acids, amino acids, micro- and macroelements,** therefore they have been present in human diets for centuries. Moreover, many, often unique, compounds which are suitable for pharmaceutical, biomedical or food-related applications have been identified and extracted from seaweeds. There are many products such as **functional food, pharmaceuticals, supplements, nutraceuticals or biomaterials** available on the consumer market, whereas commercial application of some compounds is in the research phase.

It should be kept in mind however, that macroalgae not only absorb nutrients from surrounding water but also various hazardous substances such as heavy metals. Some species even have an exceptional capacity to accumulate metals. Accumulated pollutants may be transferred to the higher trophic levels, including human. Therefore, the limits of harmful substances in food and feed products form macroalgae are strictly regulated.

fot. 123rf / CC

See also:
Rahikainen M., Samson R., Yang B. 2021. *Macroalgae as food in the Baltic Sea region.* Factsheet available online: https://www.submariner-network.eu/grass

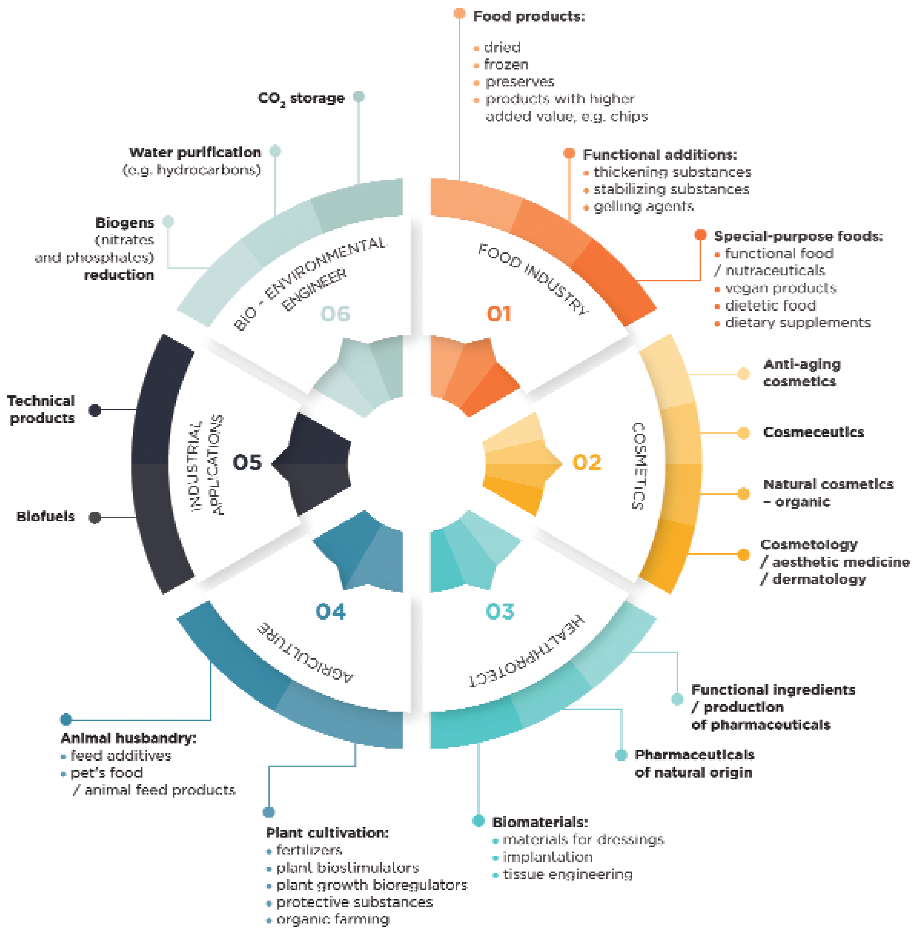


For the development of the economy

Increasing the **processing of macroalgae in fish processing plants is one of the alternatives** to these plants in a situation where market research shows that up to 30% of young consumers under the age of 30 do not eat fish and seafood (among them there are both vegans and people who don't like the taste of fish).

Even partial replacement of the import of raw materials from macroalgae with raw materials produced in crops in the Baltic Sea, will directly and indirectly contribute to an increase in **the added value in the Region**. The implementation of innovative **biorefining technologies** is the direction with the fullest use of raw materials and the highest value added ratio.

During the course of the project, **various industries were identified** that could grow with local macroalgae raw materials (see diagram below). However, the development of industry requires exceeding **a certain critical mass** – therefore it requires an appropriate production potential in the region.



For the labour market

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The Baltic fisheries are in decline. As a result of a significant reduction in catch limits in the last decade for fish species such as cod, Baltic salmon or Baltic herring, many fishermen – despite protective measures from European funds – will leave the profession. Among these people there will be people of working age, professionally active, with high qualifications and qualifications that may be useful in macroalgae breeding. **The dynamic development of macroalgal farming in the Baltic Sea Region would make it possible to use this human potential.**

It is estimated that the development of local seaweed production generates up to 26 direct jobs for every 10,000 tonnes of seaweed fresh mass. Every FTE (full-time equivalent) employee in the seaweed industry is expected to generate 0.75 FTE in ancillary industries and 0.5 FTEs by resulting additional spending in wider economy. In total 10,000 tonnes FW local production generate up to 58.5 direct and indirect FTE jobs in local economy.

In our strategic vision, the production of 3,480 ha of seaweed in 2050 **could generate 1,772 direct and indirect jobs in the Baltic Sea Region,** including jobs for fishermen leaving the profession.

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Seaweed farming as a tool to reduce the eutrophication of the Baltic Sea waters

Elaboration: Department of Marine Environment | Ministry of the Environment of Estonia

Introduction

Sustainable cultivation and harvest of seaweeds (macroalgae) play a key role in meeting the goals of blue growth initiatives.

Due to low salinity and lack of hard substrata, the Baltic Sea and Kattegat coastal areas are characterized by a relatively low diversity of seaweeds. Large parts of the Baltic Sea have been heavily eutrophicated for decades (Almroth and Skogen 2010, Gustafsson et al. 2012)

This has caused substantial compositional shifts in the macroalgal communities, with a general decline in large, perennial species**.** Since the 1980s, the nutrient load to the Baltic Sea has decreased strongly due to improved wastewater treatment and other measures to reduce nutrient emissions from land, but the shift back to a less eutrophic ecosystem state is slow (Gustafsson et al. 2012). Clear signs of recovery of perennial seaweed species are seen in some coastal areas, such as central Sweden or Estonia (Eriksson et al. 1998, Torn et al. 2006, EEA 2018), but not in others, such as Germany or Poland, coastal waters (Rohde et al. 2008, Schories et al. 2009, EEA 2018).

Seaweed consume naturally occurring nutrients found in seawater and in such a way cleans seawater and which could be a way to reduce eutrophication levels in the Baltic Sea (Burkholder et al. 2007). The most effective way to increase available seaweed biomass would be to develop offshore seaweed cultivation systems. Seaweed aquaculture and the growth potential of cultivated species are underpinned by a variety of physical conditions such as temperature, salinity, water motion, nutrient content in the water, and solar radiance. For optimal growth, all of these factors should be in a certain range, and for each of the macroalgal species, this range varies on a rather large scale. The common and most studied seaweed species in Latvian and Estonian coastal waters are *Fucus vesiculosus*, *Ulva intestinalis,* and *Furcellaria lumbricalis* (Balina et al. 2017), in Estonia and Sweden also *Ceramium tenuicorne* (Bergström et al. 2003; Bergstrom and Kautsky 2006).

Washed out seaweeds, beach-cast, produce unpleasant odors and are a nuisance on many tourist beaches. Collected beach cast is in most cases taken to a landfill. At the same time, it constitutes a potential bioresource that is so far has only been exploited to a limited extent for the production of energy and fertilizer. Thus, harvesting and removal of beach-cast and turning it into a marketable product offers an alternative avenue to macroalgal cultivation (Kotta et al 2020).

Furcellaria lumbricalis

Red algae *Furcellaria lumbricalis* is the only macroalgae species in the Baltic Sea that is harvested on a commercial scale (Weinberger et al. 2020). The commercial value of these slow-growing perennial algae is related to the gelling properties of its structural polysaccharide - furcellaran.

F. lumbricalis has attached and unattached thallus forms, which represent two distinctive ecotypes (Martin et al. 2006, Kersen 2013). The attached *F. lumbricalis* is widely distributed on hard substrata in the Baltic Sea and can be found at salinities down to 3.6 psu (Snoeijs 1999, Kersen et al. 2009, Kostamo et al. 2012). The unattached form of the species has a long harvesting history in the Baltic Sea (its industrial exploitation started in the mid-1940s). Nowadays unattached *F. lumbricalis* inhabits only semi-exposed habitats of the West Estonian Archipelago Sea area (Martin et al. 2013). Previously the communities of unattached *F. lumbricalis* were found also in Polish waters (Schramm 1996), where it disappeared due to elevated eutrophication in the 1980s (Kruk-Dowgiałło and Szaniawska 2008). Ten years later a program that aimed to reintroduce *F. lumbricalis* to Puck Bay in Poland was done, laboratory and *in-situ* experiments were performed and recommendations concerning cultivation have been made (Kruk-Dowgiałło and Ciszewski 1994). The attached form of *F. lumbricalis* has considerably higher furcellaran content (Kersen et al. 2017; Tuvikene et al. 2010), but it is characterized by an even lower growth rate (Martin et al. 2006) and therefore the species has not been commercially cultivated (Kersen et al. 2017).

Since 2011 *F. lumbricalis* stocks in Estonia have remained stable, biomass $(110\text{-}120)\cdot10^3$ t, ww, and distribution area 170-180 km^2 (Martin et al. 2006, updated). In 2017 the total community biomass (*F. lumbricalis* accounts for 60–73% and *Coccotylus truncatus* for 13–25%) was estimated to be $179\cdot10^3$ t (ww) and it covered an area of 170 km^2 (Paalme 2017).

Currently, harvesting of *F. lumbricalis* stocks by bottom trawling is limited to 2000 t ww per year (Paalme 2017). In addition, beach deposits of both loose-lying and attached communities of *F. lumbricalis* are collected for commercial utilization of carrageenans. Annual losses of the loose-lying *F. lumbricalis-Coccotylus truncatus* community through wrack deposits were estimated at 4800 t ww per year, i.e. 4% of the community standing stock (Kersen and Martin 2007, Kersen 2013).

Ceramium tenuicorne

The marine red macroalga *Ceramium tenuicorne* is cosmopolitan and naturally found in both brackish and marine waters (Eklund 2005). Small, filamentous red algae *Ceramium* *tenuicorne* is widely distributed in the Baltic sea. It tolerates low salinity, down to 2-3 psu, moreover, it presents a high level of local adaptability and exhibits local ecotypes within different regions (Bergström et al. 2003, Bergström and Kautsky 2006). It grows directly on the substrate, as an epiphyte on other algae or loose-lying form in drift algal mats (Bergström and Bergström 1999; Back and Likolammi 2004). *C. tenuicorne* is sensitive to various contaminants and it is abundant in different areas, therefore its growth inhibition has been proposed a toxicity test for chemicals and water effluents (Eklund 2017). Due to the content of bioactive substances such as phytol, but also to synergistic effects among components, extracts from species belonging to *Ceramium genera* are proved to have anti-bacterial and antiviral activities (Serkedjieva 2004; Bazes et al. 2016).

It has a sexual reproduction but is also capable of asexual reproduction by paraspores and by vegetative propagules released from apical structures (Rueness et al. 2002). *C. tenuicorne* may also reproduce by regeneration from older basal parts, and by detachment and re-attachment of vegetative fragments. The field data suggest that in the Baltic Sea the sexual reproduction is of minor importance (Bergströma et al 2003).

C. tenuicorne is an ecologically dominant species in the northern Baltic Sea, with average biomass up to 15±5 g dw m^{-2} at 0–5 m depth (Bergströma et al 2003). Nutrient enrichment had a clear effect on the growth rate, and the level of response varied among isolates. Isolates from the Baltic Sea were able to utilize very high nutrient levels, however, with decreasing efficiency towards their low salinity limit, whereas the applied levels of nitrate and phosphate enrichment approached the upper tolerance limit of the Gulf of Bothnia isolates. On the other hand, a positive main effect of trace elements was noticeable in isolates from the Gulf of Bothnia. The results suggest that the level of response to nutrient enrichment in one isolate may depend on its level of adaptation to low salinity, and that results from growth experiments obtained from one region of the Baltic Sea do not necessarily apply to populations of the same species in other regions (Bergström ja Kautsky 2005).

Fucus vesiculosus

Fusus vesiculosus is a common brown alga on the hard substratum in the Baltic Sea. Clear hotspots of *F. vesiculosus* production emerge around Danish Straits, however, high production values can be observed throughout the southern Baltic Sea and along Polish, Lithuanian and Estonian coasts. At these hotspots, the production potential of *F. vesiculosus* indicated as high as 3% daily biomass growth rate coasts. Production potential of *F. vesiculosus* gradually decreases throughout the Baltic Sea, when moving northwards. *Fucus* is absent in Bothnian Bay and in the eastern Gulf of Finland as in these areas salinity drops below the threshold value of *F. vesoculosus.* The largest spatial extent in the Baltic Sea is therefore characterized by medium production potential, averaging around 1.5% daily biomass increment (Kotta et al. 2020).

As the species is sensitive to eutrophication the decline in its distribution depth has been observed during the last decades (Eriksson et al., 1998, Ronnberg and Bonsdorff 2004, Torn et al. 2006). Coastal eutrophication has resulted in the reduced abundance of *F. vesiculosus* due to the negative effects of increased turbidity, spatial competition, and grazing. Nutrient enrichment decreased the establishment of *Fucus vesiculosus* on average by 83% (Korpinen and Jormalainen 2008)

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*. (Kotta et al 2020)

Water temperature 20 °C is considered as the highest water temperature *Fucus vesiculosus* was able to grow and survive. At higher water temperatures (≥ 27 °C) growth rapidly decreased and progressive necrosis is observed (Graiff et al. 2015).

Ulva intestinalis

Ulva intestinalis is a green alga, characterized by broad salinity tolerance and widely distributed in littoral zones around the world. It is also the principal macroalga growing on rocky bottoms along the Baltic Sea coasts: coasts of southern Sweden, Germany, Poland, Lithuania, Latvia, and Estonia. The unattached *U. intestinalis* create floating mats and are present and often dominates in coastal biomass (Bäck et al. 2000). In general, Ulva prefers warm, light-filled, and nutrient-rich (specifically phosphate) coastal regions. Higher solar radiance, phosphate, and temperature levels increased *U. intestinalis* production, however, production saturated when radiance, phosphate, or temperature levels were too high (Kotta et al. 2020). Moreover, it tolerates a variety of environmental conditions, seasonal changes and, due to its unique photosynthetic performance (ability to uptake HCO_3^-), it also inhabits conditions that are unfavorable for the other algae (Bäck et al. 2000; Bjork et al. 2004). *U. intestinalis* efficiently uptakes nitrogen in response to its high concentration, thus massively occurs in eutrophicated areas, mainly in summer (Bäck et al. 2000; Fong et al. 2004).

Experimental research indicated that *U. intestinalis* is suitable for the cultivation in a natural environment - in the Gulf of Finland and Puck Bay, near the discharges from the sewage treatment plants, to remove the excess of nutrients from water (Kovaltchouk 1996; Kruk-Dowgiałło and Dubrawski 1998). Increasing nutrient concentration above 2 ml L^{-1} decreases the growth rate of *U. intestinalis* (Balina et al. 2017).

Brundu and Chindris (2018) investigated the capability of *Ulva lactuca* to grow in an integrated system, aiming to optimise the needing of resources and to decrease the ecological impact of wastewater. The nutrients uptake and the growth of *U. lactuca* in grey mullet (Mugil cephalus) wastewater (WW) were evaluated and compared with *U. lactuca* cultivated in estuarine water (EW). The uptake of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorous (DIP) were assessed every two days. At the end of the experiment, *U. lactuca* resulted in a higher assimilation of DIN in EW (95.7 ± 0.3%, mean ± SE) than in wastewater (68.7 ± 1.0%) ($p < .01$). No significant differences were observed in DIP assimilation (>80%), as well as in the biomass yield and specific growth rate. This study demonstrates the efficiency of *U. lactuca* in the assimilation of DIN and DIP from WW, contributing to reduce the release of dissolved inorganic nutrients in the natural environment.

Great growth effectiveness and very high yield (up to 80000 kg fresh weight per hectare from May to September) were obtained, especially when the artificial substrate was used. Several studies conducted in Denmark estimated the regional potential of cultivated *Ulva* sp. for the production of biogas, bioethanol, biobutanol, and more advanced biorefineries (Bruhn et al. 2011, Alvarado-Morales et al. 2013, Hou et al. 2015).

Laminaria digitata *and* ***Saccharina latissima***

Laminariales are known to tolerate a broad salinity range but their occurrence in the Baltic Sea is limited to two species - *Laminaria digitata* and *Saccharina latissima* (formerly *Laminaria saccharina*), which can be found only in the Kattegat (Nielsen et al. 2016). *L. digitata* grows in the upper sublittoral zone on the hard substratum, mainly in wave-exposed sites, while *S. latissimi* grows usually below *L. digitata* as it requires more sheltered conditions (McHugh et al. 2003).

Saccharina latissima is practically the only sea-based commercially aquacultured seaweeds in the Baltic Sea region, currently restricted to Denmark and Germany (Ferdouse et al. 2018, Wang et al. 2019). *S. latissima* is capable of relatively fast growth. However, the species reaches its distribution limit in the Baltic Sea salinity gradient at Bornholm (Møller Nielsen et al. 2016) and is currently only cultivated at locations with annual mean sea surface salinities of at least 16 (Kiel Fjord, Germany), which already cause significantly reduced growth (Bartsch et al. 2008). A disadvantage of longevity in perennial seaweed at mid-and-high latitudes is the necessary reduction of growth rate in summer, even in the presence of sufficient nutrients. This process is controlled and synchronized by the long-day signal in laminarian species (Lüning 1979, 1993).

In 2015 commercial sea-based farming of *S. latissima* was carried out in seven licensed areas in Denmark (Ferdouse et al. 2018) and one area in Germany (Wang et al. 2019). The largest of these farms had a size of 1 km^2 and the production volume in Denmark was 10 t (ww) in 2014 (Ferdouse et al. 2018). In Sweden, the efforts to cultivate kelps *S. latissima* are mainly concentrated on the west coast, where the salinity is >20 psu. The techniques for offshore cultivation of *S. latissima* have been developed since the early 1990s in the SE North Sea area, patented and described in detail elsewhere (Buck and Buchholz 2004, Bartsch et al. 2008, Buck and Grote 2019).

Physiological responses of seaweeds to nutrient availability

Nutrient availability is one of the key factors regulating the main physiological responses of seaweeds, with nitrogen being the most likely to limit their growth in temperate waters

(DeBoer, 1981, Lobban and Harrison, 1997). In seawater, N is available to seaweeds in three major forms: nitrate (NO_3^-), ammonium (NH_4^+) and urea (Abreu et al. 2011). The uptake rates of the different N sources can be affected by environmental parameters as well as by the seaweed species and their respective biology (Lobban and Harrison, 1997). Other factors known to influence N uptake are the nutritional history of the tissue (D'Elia and DeBoer, 1978, Fujita, 1985, Naldi and Wheeler, 2002), the nutrient concentration and its chemical species (DeBoer, 1981, Harrison and Hurd, 2001), and even genetics (Lobban and Harrison, 1997).

The co-occurrence of the different chemical N forms can have an antagonistic effect on the uptake. NH_4^+ concentrations as low as 5 µM have been found to inhibit or even suppress the uptake of NO_3^- by some seaweed species (Haines and Wheeler, 1978, Smit, 2002, Thomas and Harrison, 1987). At the same time, most seaweeds have a higher affinity for the NH_4^+-N source (Lobban and Harrison, 1997, Naldi and Wheeler, 1999, Pereira et al., 2008, Phillips and Hurd, 2003, Phillips and Hurd, 2004, Smit, 2002), probably due to the low levels of energy required to assimilate this nutrient - NH_4^+ uptake often occurs by passive diffusion, meaning that the uptake rate increases proportionally to the substrate concentration (Lobban and Harrison, 1997). Nitrate uptake, on the other hand, typically shows saturation kinetics, meaning that with increasing substrate concentrations, the uptake capacity reaches a maximum. In this case, the N uptake is an energy-dependent process (DeBoer, 1981). Fast-growing marine algae have higher nitrogen requirements than slow-growing perennial species such as *Fucus* sp., *Ceramium* sp. and *Furcellaria* sp. Thus, fast-growing species are positively affected by increased nutrient availability (Pedersen and Snoeijs, 2001, Rosenberg and Ramus, 1982).

Seaweed aquacultures

The low salinity in the inner parts of the Baltic Sea is still seen as a major limitation to seaweed farming (Blidberg and Gröndahl 2012). Commercial sea-based aquaculture of seaweeds in the region is currently restricted to Denmark and Germany. Along other cold temperate coasts of Europe, the main target species is the kelp *Saccharina latissima*, which is generally capable of relatively fast growth. However, the species is currently only cultivated at locations with annual mean sea surface salinities of at least 16 (Sandow 2007). In Estonia several pilot projects funded by the Estonian Environmental Investment Centre and the European Maritime and Fisheries Fund have been initiated to develop cultivation techniques for both unattached and attached forms of *Furcellaria lumbricalis.*

From 2014 the Swedish universities launched research around a cultivated *S. latissima* biorefinery supply-chain, which resulted in the establishment of the first experimental seaweed farm in the Koster archipelago in Skagerrak (Hasselstrom et al. 2018).

The system is now discussed for co-use with offshore structures such as wind farms (Buck and Grote 2019). However, infrastructures exposed to high-energy environments generally require more extensive capital investment and pose larger risks of losses than infrastructures in sheltered sites (Buck and Grote 2019), which reduces the potential margins for profits.

Land-based production of seaweed has been and is still tested on pilot scale in several countries in the region. The target species are diverse, including *Fucus vesiculosus, Furcellaria lumbricalis*, *Ulva intestinalis* and *Ulva fenestrata* .

In conclusion, the suboptimal geographic conditions constitute an important limitation to the production of seaweed and seaweed-based products in both the Baltic Sea. Industrial harvesting of unattached *Furcellaria lumbricalis* is now restricted to Estonia, due to depletion of this seaweed stock in other coastal areas. Current research aims to identify new applications for these and other seaweed species that are present in the area. The non-provisioning ecosystem services that can be provided by seaweeds (Rönnbäck et al. 2007) are also increasingly recognized and valued in the Baltic Sea area.

EXAMPLE: The techno-economic analysis (TEA) to quantify the mass and energy flows through the various unit operations required for a novel free-floating macroalgae biorefinery

(Greene et al. 2020)

This study uses detailed process modeling to quantify the mass and energy flow through the various unit operations required for a novel free-floating macroalgae biorefinery concept. One of the major focus areas of this study was to quantify the costs associated with large-scale offshore cultivation of macroalgae including the high output hatchery required to supply the spores and/or seed string for the operation **(**Greene et al. 2020).

Three different system pathways were explored, yielding a biomass production cost ranging from \$210 to \$565 per dry metric ton. The minimum biomass selling price (MBSP) to achieve a 10% IRR over a 30-year facility life is \$278.13 DMT^{-1}. This result is based upon a 30 kg m^{-1} combined polyculture biomass yield and 100 days per year to release/harvest lines. Furthermore, this baseline cost assumes a 10 km dispersion distance (between incoming 30 km sections of a line) and a total distance of 100 km from the harvesting location to the shore. Following the ideal pathway, the minimum biomass selling price decreases to \$210.18 DMT^{-1} (DMT: dry metric tonne). This minimized cost is the result of assuming short travel distances (100 km to the harvesting location and no dispersion), high biomass yield (35 kg m^{-1}), and a longer cultivation season (120 operational days per year). Outputs from the system include renewable diesel (R100), naphtha, biochar, nitrogen and phosphorus fertilizers, and aqueous/solid waste streams **(**Greene et al. 2020).

Using the baseline, conservative, and ideal system assumptions an analysis was performed to determine the biomass production cost as a function of the combined long line yield, ***Fig. 1***.

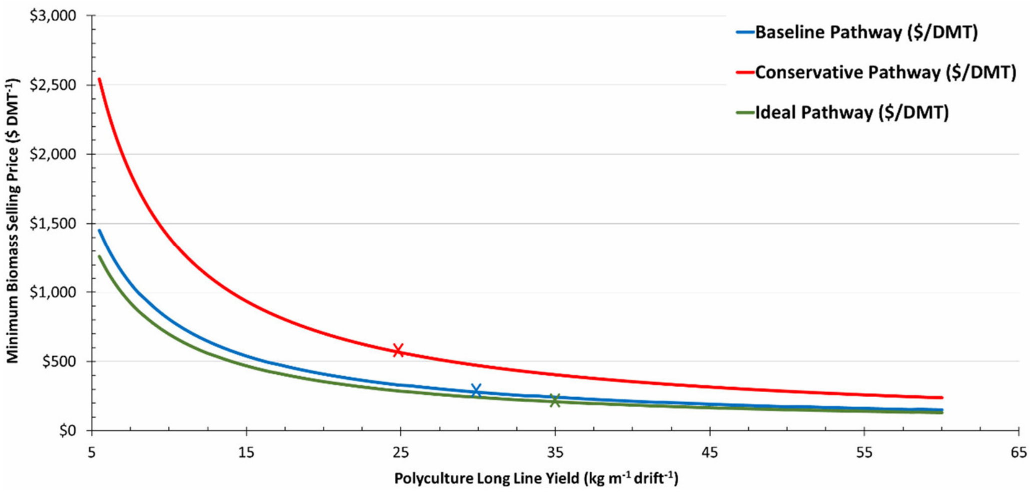

Fig. 1. Impact of long line yield on minimum biomass selling price for the baseline, conservative, and ideal system pathways. The X on each line identifies the assumed yield for each pathway (DMT: Dry Metric Tonne; Greene et al. 2020).

Low yields have a dramatic effect on system performance, however, past the knee of the curve (around 20–25 kg m^{-1}) the impact of increased yield on the biomass cost begins to plateau. The baseline pathway assumes a combined yield of 30 kg m^{-1}, or 15 kg m^{-1} from each species. This assumption is based on several reported yields for the two different species, with values exceeding 15 kg m−1 for both species. A study from Broch et al. (2019) suggests a yield of 31.25 kg wet m^{-1} from *S. latissima* alone. Peteiro and Freire (2013) indicate a yield of 16.1 kg m^{-1} for *S. latissima* alone, and Merrill and Gillingham (1991) report *N. luetkeana* yields as high as 22 kg m^{-1}. It is possible to convert between linear yield (kg wet per m) and hectares using values from Skjermo et al. (2014), who predicted *S. latissima* yield ranges of 170–340 wet weight metric tons per hectares. Using the assumption of 10% solids, this equates to 17–34 DMT per hectares. While increasing the yield above the realistic baseline assumption of 30 kg m^{-1} positively impacts the sustainability of the system, the non-linear impacts seen in the lower yields do not continue past this assumed value.

CONCLUSION

Macroalgae consume various nutrients found in seawater and in such way cleans seawater and even could be a used to reduce eutrophication level in the Baltic Sea. One of the things that has to be done before starting algae cultivation is to explore optimal growth conditions for the algae species.

The low salinity is the major limitation to seaweeds cultivation in the Baltic Sea.

The red alga species *Furcellaria lumbricalis* and *Ceramium tenuicorne* are too small and sensitive for environmentally effective cultivation. The amounts of nutrients the red algae can bind is rather low. To cultivate the red algae in the Baltic Sea is complicated and time-consuming process, the production is low and will not change nutrients content in the ambient marine water in a notable way. It is also important to keep in mind that cultivation success can´t be guaranteed. Cultivation of red algae can be profitable if the biomass is used in the food, pharmaceutical, or biochemical industries to produce high-cost food supplements, farmaceuticals, or chemical products (eg food coloring).

F. lumbricalis unattached form has been and is nowadays harvested on a commercial scale. In the Baltic Sea the unattached form inhabits only the West Estonian Archipelago Sea. Both the unattached attached forms contain furcellaran, but are characterized by a low growth rate. In 2017 the community, *F. lumbricalis* accounts 60–73%, and *Coccotylus truncatus* 13–25%, total biomass in the West Estonian Archipelago Sea was $179{\cdot}10^3$ t (ww). The algae community wrack deposits were estimated at 4800 t ww per year, i.e. 4% of the community standing stock. The wrack deposits of both loose-lying and attached *F. lumbricalis* has been also collected for commercial utilization. Harvesting of *F. lumbricalis* unattached stocks by bottom trawling is limited to 2000 t ww per year.

The second red alga species *Ceramium tenuicorne* is rather widely distributed in the Baltic Sea, but is very small and slowly growing, and therefore not suitable for cultivation for sequester nutrients from seawater.

Fucus vesiculosus is the only large, canopy-forming brown alga, in the Baltic Sea. It occurs as a conspicuous belt along rocky and stony coasts and its biomass and productivity is higher in the Western Baltic Sea coast, where the water transparen. The size of *Fucus* tallus depends on the salinity and is much smaller in the Baltic Sea if compared to the North Sea. *F. vesiculosus* is sensitive to environmental changes. Coastal eutrophication has resulted in the reduced abundance of *F. vesiculosus*. Higher solar radiance and moderate nitrate level increase *F. vesiculosus* production, however, saturation points have been observed when the nitrate level is too high. Higher phosphate concentrations decrease *F. vesiculosus* production. 20 °C is considered as the highest water temperature *Fucus vesiculosus* was able to grow. At higher water temperatures (≥ 27 °C) growth rapidly decreases and progressive necrosis is observed. The mentioned characteristics of *F. vesiculosus* allows to state that the cultivation of *F. vesiculosus* for nutrients binding purpose cannot be economically and ecologically reasonable in Estonian coastal waters.

Ulva intestinalis, the green alga, is characterized by broad salinity tolerance and is the principal macroalga along the Baltic Sea coasts. The unattached *U. intestinalis* create floating mats and often dominates in wrack deposits. *U. intestinalis* tolerates eutrophication, efficiently uptakes nitrogen without observed saturation, tolerates well the seasonal changes and environmental conditions unfavorable for the other algae. *U. intestinalis* has been successfully cultivated near the sewage treatment plants. Based on its characteristics, Ulva is a suitable algal species for nutrients binding cultivation. Bevs et al (2021) conclude from their study that Ulva is ideal for bioremediation of polluted waterways following rain events. Ulva is also excellent for composting due to readily degradable and rich in nitrogen biomass.

Laminaria digitata and *Saccharina latissima* (formerly *Laminaria saccharina*) are not common in the Balic Sea. *L. digitalis* and *S latissima* grow in waters, which salinity is higher than 16 psu. The water salinity is so high only in the most southern part of the Baltic Sea.

The potential lifespan of *Laminaria* species can be up to 15 years. A disadvantage of longevity in perennial seaweed at mid-and-high latitudes is the necessary reduction of growth rate in summer, even in the presence of sufficient nutrients. This process is controlled and synchronized by the long-day signal in laminarian species (Lüning 1979, 1993). The size of these algae is sufficient to sequester excess nutrients from economically viable quantities of seawater. *S. latissima* is the only sea-based commercially aquacultured seaweeds in the Baltic Sea region, currently restricted to Denmark and Germany. In Sweden, the efforts to cultivate *S. latissima* are mainly concentrated on the west coast, where the salinity is >20 psu. The characteristics of *Laminariales* suite well for the biomass-based cultivation, the only problem is the brackish water intolerance of the seaweeds.

The nitrogen and phosphorus content in *Rhodophyta* algal tissue is by Chopin et al (1995) respectively 22-29 $mgN \cdot gDW^{-1}$ and 4,42-4,56 $mgP \cdot gDW^{-1}$. Thus, taking out one tonne of dry red algae (*F. lumbricalis, C. tenuicorne*) from the sea we remove about 25,5 kgN and 4,5 kgP.

Kolb et al. (2010) detected the nitrogen and phosphorus content in the tissue of *F. vesiculosus* collected from coastal waters in the Stockholm archipelago, Baltic Sea. The *Fucus* contained 1,3% nitrogen and 0,05% phosphorus in its dried biomass. It means that each tonne (dw) of Fucus biomass remove from the sea water 13 kgN and 0.5 kgP (dw).

The nitrogen and phosphorus content in green algae, including the species *Ulva intestinals,* vary in great deal. Therefore no suitable numbers for the calculations could be found in the literature.

More than algae cultivation would be economically beneficial the operative disposal (utilization) of the washed ashore algal wracks. The algal wrack utilization reduces the nutrients leaching back to the sea. It olso reduce the cost of beach cleaning if the algal biomass is be utilized, used for the production of fertilizers or biofuels.

Germany has declared that 45,000 t dw of algal biomass is washed ashore along the German Baltic Sea coast each year, Sweden has informed that around 60,000 t dw of seaweeds have been reach to beaches in southern Sweden and up to 2100 t dw on the island of Öland coast every year. When taken into account that macrophytes contain, in general, 1.2% nitrogen and 1.3% phosphorus in their biomass, then only the algae washed ashore along the German Baltic Sea and south Swedish beaches bring out of the sea <u>1285 t of nitrogen</u> and <u>1392 t of phosporus</u> every year, but the shoreline of the Baltic Sea is very much longer.

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GRASS 4.2.

Impact of seaweed aquaculture on CO_2 reduction

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Carbon dioxide (CO_2) is the greatest contributor to greenhouse gas emissions and is also responsible for causing ocean acidification. CO_2 concentration, but this process reduces ocean pH. The CO_2 concentration has increased from 277 ppm to 407 ppm in 2018. Over 40% of anthropogenic CO_2 emissions dissolve into the oceans which slows the rise in the atmospheric (Friedlingstein et al. 2019).

The rapid increase in CO_2 concentration is having severe impacts on global climate patterns. Given the severity of these impact, mitigation of CO_2 emissions is of great importance. Direct air carbon dioxine capture and storage technologies have been developed (Keith et al. 2018) however carbon sequestration through seaweed photosynthesis represents an alternative, more "natural" solution to removing CO_2 from the atmosphere. Seaweed are ranked among the most efficient photosynthetic organisms on earth. They need nutrients and inorganic carbon to grow. The source of inorganic carbon is air-born CO_2 that dissolves into seawater.

CO_2 capture

The main processes providing climate mitigation are carbon assimilation by growing seaweed and carbon retention in soil. Actual seaweed global aquaculture production makes only a small contribution to capturing CO_2. The upper limit of potential based on 2014 data is estimated at 0,68 Tg C per year (2,48 mln tonnnes of CO_2) (Duarte et al. 2017). This estimate was based on the assumption that dry weight is 10% of fresh production weight and the average carbon content of seaweed is 24.8% of dry weight.

Considering the species that can be farmed in the Baltic Sea, growing and harvesting 1 tonne of wet weight macroalgae means capturing of 140 to 220 kg CO_2 (Table 1). However, it should be recognised that the carbon content would be different depending on the growth stage of the macroalgae and the physico-chemical conditions at the site.

Table 1. Estimated amounts of CO_2 capture by growth and harvesting of 1 ton of macroalgae

	Dry matter content (DW)	Average total carbon content	$C0_2$ capture from 1 t of fresh weight FW [kg]
Saccharina latissima	15.10%[1]	26.20%[1]	140
Laminaria digitata	15.50%[1]	29.20%[1]	170

Fucus vesiculosus	16.00%[2]	36.90%[3]	220
Ulva inestinalis	12.50%[4]	35.00%[5]	160

1.(Schiener et al. 2015) 2. (Catarino et al. 2018) 3. (Balina et al. 2016) 4. (Ruangchuay et al. 2012) 5. (Gubelit et al. 2015)

The seaweed cultivations can produce between 20 and 150 tons FW per hectare per year, depending on cultivated species, cultivation configurations and seasonal fluctuations (Kerrison et al. 2015). *Saccharina latissima* potential production in the Oosterschelde estuary was assumed by (van Oirschot et al. 2017) based on the growth rates of experimental seaweed farms in the Netherlands, Sweden, Ireland and France at the level of 72 (single layer design) to 108 (dual layer) ton per hectare per year. However, the yield obtained from a 0.5 ha experimental farm on the Swedish west coast was only 22.6 - 27.6 ton FW/ha (Pechsiri et al. 2016). Based on data collected during 10 years of field experiences on a 2 ha farm (Hasselström et al. 2020) it was assumed that the average yield was 18.7 with a range from 17.5 to 35.1 ton FW/ha.

Data on the growth rate of *Fucus vesiculosus* and *Fucus serratus* at an experimental cultivation from the Kiel fjord in the Western Baltic Sea (Meichssner et al. 2020) suggests that the productivity of the farm can reach 50 tonnes FW/ha under optimal conditions. A similar level of maximum yields of 50-80 ton FW/ha, depending on the location of the cultivation site, results from an experiment with *Ulva* spp growth rate carried out in 1995 in the Puck Bay (Kruk-Dowgiałło and Dubrawski 1998).

Considering the results above, Table 2 shows the estimated values of absorbed CO_2 by cultivation and harvest of 1 hectare of sea surface area for different species of macroalgae under optimal conditions in the Baltic Sea.

Table 2. Estimated amounts of Co2 capture by seaweede cultivation per hectare of sea area under conservative and optimistic scenarios

	Biomass yield [ton FW/ha]	$C0_2$ capture [t]
Saccharina latissima	20	2.90
	50	7.24
Laminaria digitata	20	3.31
	50	8.28
Fucus vesiculosus	20	4.32
	50	10.80
Ulva inestinalis	20	3.20
	50	8.01

The key parameters for a seaweed biomass processing system are not only the productivity per unit of cultivated area but also the harvest season, which determines the chemical composition of the biomass. (van Oirschot et al. 2017) found, that the most sensitive variable influencing the scale of environmental impact were the protein content in the seaweed biomass, the biomass yield from the cultivation and the specific moisture extraction rate of the biomass dryer.

CO_2 release

Calculations of the CO_2 removal potential with seaweed aquaculture also need consider the energy consumption of seaweed farming and the resources produced. Energy or fuels, mostly from fossil sources, are used in all phases of production:

1. Seedling production;
2. Cultivation (including construction, installation and removal of cultivation equipment);
3. Harvesting;
4. Post-harvest treatments including cleaning, preservation and storage;

CO_2 net reduction in algae cultivation depends on multiple factors, some of which are independent of the investor (e.g. the country's electricity mix). However, many of the factors influencing energy consumption can be optimised at the planning stage:

- Site and species selection;
- Selection of the seedling production and spreading technique;
- Selection of the equipment and materials used for cultivation;
- Using the renewable energy sources whenever possible (f.e from off-shore wind mill farms);
- Choice of the target product;
- The chain supply analysis;

The example of the possible improvements to the life cycle resource footprint *Saccharina latissima* cultivation near the West coast of Ireland (18 ha of floating longlines) and France (0.6 ha of raft systems) are presented by Taelman et al (2015). In case of Ireland the distance between hatchery and sea site as well as between sea site and operating company should be reduced to the range of 100 km. In case of France, power of blower devices used in the hatchery was assessed as too high and the use of softwood instead of polyethylene as material for floating tubes was suggested.

An opportunity to optimise production before it starts is to choose the least energy-intensive method of pre-processing a product. In the assessment performed by Thomas et al (2020), who analyzed the supply chain from hatchery to four alternative final product (seaweed dried, ensiled and frozen) showed, that the extent of emissions is most affected by preservation methods. The greatest impact on environment had freezing and air-cabinet drying, both the two most energy-intensive processes (Thomas et al. 2020).

CO_2 reduction through biofuel production

The fast growth rate and net primary productivity for seaweed is sometimes higher than for land-based plants currently used as biofuel for transport fuels (Chemodanov et al. 2017). Moreover, seaweed biofuels, do not compete for resources with agriculture, as they do not require arable land, freshwater or fertilizer, herbicide or pesticide applications and are, therefore in many respects, more environmentally sustainable than current biofuels derived from land crops (Duarte et al. 2017).

An important parameter characterizing biomass used for bioenergy production is higher heating value (HHV). HHV for dried *Ulva lactuca* cultivated in an experimental pond has reached a value 19 MJ/kg (Yantovski 2011). In a case of others seaweed from the British Isles HHV reached values between 15-17.6 MJ/kg dried weight, depending on the species (Ross et al. 2008). For comparison, HHV for switchgrass and miscanthus was estimated at 18.5 MJ/kg (Librenti et al. 2010). A seaweed with a typical HHV of 16 MJ kg^{-1} dried weight and a moisture content of 82% would have an energy content of 2888 MJ $tonne^{-1}$ wet, weight equivalent to the energy required for transport over 7000 km by road (Milledge and Harvey 2016).

Results obtained from experimental cultivation of *Ulva sp* in a shallow, coastal site in Israel indicated that the potential annual ethanol production from *Ulva sp*. biomass was 229.5 g ethanol m^2 $year^{-1}$ (5.74 MJ m^2 $year^{-1}$). Growth intensification could increase the annual ethanol production density of *Ulva* sp. to 1735 g ethanol m^2 year-^{1}, which translates to an energy density of 43.5 MJ m^2 $year^{-1}$ (Chemodanov et al. 2017).

Biofuels made from algae must typically go through a complicated series of unit processes for algae cultivation, harvesting, dewatering, oil extraction, conversion, and other logistical steps. While there are several methods to convert seaweed biomass into energy, some of them requires biomass drying after harvesting which is an energy-intensive process (Milledge et al. 2014).

Designing of an environmentally-benign biorefinery process requires optimisation of parameters:

- energy investment and materials used for cultivation,
- seaweed productivity and composition,
- energy invested in biomass drying, and
- chemicals used for biomass processing

The life cycle analysis for two processes: biogas and bioethanol and biogas production from *Laminaria digitata* performed by (Alvarado-Morales et al. 2013) indicated, that 1 ton of seaweed (dry weight) absorbs approximately 1137 kg of CO_2, Approximately 176 kg of CO_2 are emitted to the environment due to the consumption of fossil fuels and electricity for grow-out phase including transportation and maintenance thus delivering a net total removal of 961 kg of CO_2 from the atmosphere.

A model system including seaweed cultivation, biorefining and usage phases indicated that seaweed conversion to ethanol, fish feed and fertilizer could reduce atmospheric CO_2. From one cultivation cycle, i.e. 1 ton of seaweed (dry weight), a net reduction of 0.035 tons of atmospheric carbon (0.13 tons of CO_2) should be achieved (Seghetta et al. 2016).

(Seghetta et al. 2017) analyzing several production scenarios for seaweed *Laminaria digitate* found, that all of them provide benefits in terms of mitigation of climate change. Biogas production from dried *Laminaria digitata* appeared the most favorable in terms of CO_2 reduction in the amount of $-18.7*10^2$ kg CO^2 eq./ha. This scenario presents also the lowest consumption of total cumulative energy demand, $1.7*10^4$ MJ/ha, resulting in a net reduction of the fossil energy fraction, $-1.9*10^4$ MJ/ha compared to a situation without seaweed cultivation.

However, not any biofuels production scheme is beneficial in terms of reducing CO_2 emissions. The assessment of the sustainability of seaweed biomethane from *Laminaria digitata* in an integrated seaweed and salmon farm in Ireland indicated, that conservative non–optimised system, using unripened seaweed, and fossil electricity in the biogas system, with minimum replacement of mineral fertiliser can be deemed unsustainable generating 76.6 g CO_2 eq as compared to natural gas (105 g CO_2 eq.). Only after optimisation of at least several production steps, including use renewable energy in cultivation processes, the CO_2 emissions projected by the model have decreased to the level of 40.6 g CO_2 eq (Czyrnek-Delêtre et al. 2017).

A similar conclusion follows from the life cycle assessments performed for the theoretical production of biomethane from offshore-cultivated *Saccharina latissimi.* (Langlois et al. 2012) showed that with conventional techniques, the impact from greenhouse emission from seaweed feedstock was higher than those from natural gas. Only complex improvement of the system including use of energy from off-shore wind farm could decrease of 21,9% (in case of the anaerobic digestion of untransformed whole seaweeds) to 54,2% (in case anaerobic digestion of alginate extraction residues) comparted with natural gas.

CO_2 emissions mitigation future potentials

Seaweed aquaculture can mitigate CO_2 emissions in other ways than biofuel production:

- Seaweed are as well considered as promising sustainable alternatives to conventional terrestrial animal feed resources. The advantages include high growth rate, potential cultivation in saltwater, and no occupation of arable land (Øverland et al. 2019).
- The addition of macroalgae to animal feed can inhibit microbial methanogenesis e.g (Brooke et al. 2020; Machado et al. 2014). In vitro experiments showed that fermentation of seaweed, simulating that of ruminant digestion, substantially reduced methane emissions (Maia et al. 2016). When incubated with meadow hay, *Ulva* sp. (among other species), decreased methane production to 55% of the control fermentation.
- Soil amelioration by nutrient-rich seaweed biochar or seaweed compost are reported as factor to increase productivity of agricultural crops (Roberts et al. 2015) (Cole et al. 2016). Agriculture is responsible for about 26% of greenhouse gas emissions (Poore and Nemecek 2018), resulting

intense emissions associated with the production and application of industrial fertilizers and emissions from cattle. Use of seaweed biochar or compost would reduce greenhouse gases emissions involved in mineral fertilizer production.

- Seaweed is a highly potential source for renewable biopolymers and the development of biocompatible and environmentally friendly materials. (Jumaidin et al. 2018)

CONCLUSIONS

The production of seaweed biofuel in the context of reducing CO_2 emissions is economically, energetically and technically challenging. In addition, any successful process appears to require both a method of preserving the seaweed for continuous feedstock availability and a method exploiting the entire biomass at commercial scale (Milledge and Harvey 2016). But the attractiveness of the seawed biorefinary concept is not based on the production of bioenergy itself but on integration of different biomass conversion processes to produce energy and value added product into a single facility. This in turn reduces the cost of fuel production with maximum utilization of the biomass (Balina et al. 2017). Design of a biorefinery, which will generate sustainable food, fuels and chemicals with reduced CO_2 emission is a complex task and is largely influenced by local raw material supplies, advances in multiple technologies and socio-economic conditions. A stepwise approach to maximizing the benefits from seaweed would include to sequentially extract high-value molecules used in the food, pharma or biotech industries, such as bioactive sulphated polysaccharides, pigments, and antioxidants and then convert—after extraction of carbohydrates for the hydrocollid industry or for biofuels production—the lower value residue to protein concentrates with value in the feed industry (Duarte et al. 2017).

Another dimension of seaweed cultivation is the use of the maritime space. Calculations of the area required for seaweed aquaculture to supply 60% of the transportation fuel vary broadly, from <1% of the economic exclusive zone (EEZ) for Norway, to 10% of the Dutch EEZ and about twice of the German EEZ (Fernand et al. 2017). In the case of Israel, achieving the national target reduction in greenhouse gas emissions (26% compared to 2005 emissions) by replacing fossil fuels by bioethanol would require as much as 71% of the national EEZ. (Chemodanov et al. 2017). The sea space is a limited resource for many countries. Its use for seaweed aquaculture may result in a change in CO_2 emissions from other sources (e.g. related to the shipping). The estimation made by (Duarte et al. 2017)[1] of CO_2 emissions avoided per unit area by offshore wind farms (12,500 tons CO_2 km^2 $year^{-1}$) compared with the potential

[1] The CO_2 emissions avoided per unit area by offshore wind farms were derived by dividing the CO_2 avoidance of wind farms by the area occupied by the farms, corrected for a 2% lifecycle CO_2 emissions over a nominal 20 year life span of the turbines (Martínez et al., 2009). The calculations were based on data for the Sandbanks offshore wind farms (Germany, 21 turbines in 61 km^2)1 and for the LINCS offshore wind farms (UK, 83 turbines in 35 km^2).

CO_2 sequestration intensity of seaweed farms (about 1,500 tons CO_2 km^2 $year^{-1}$). However, seaweed can be planned in areas already occupied by wind farms and in areas where they are not possible to construct.

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