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Quo Vadimus

Towards sustainable European seaweed value chains: a triple P perspective

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Seaweeds are seen as important future feedstock for Europe, providing biomass for food, feed, and other applications. Seaweeds can contribute to a circular food system a protein transition and bio-based economy. Europe is a minor player in the world market dominated by the Asian producers and processors. According to the FAO, total production of aquatic plants (dominated by seaweed) was 30 million tonnes in 2016, with China (47.9%) and Indonesia (38, 7%) dominating production. This article discusses the challenges to seaweed production and use in Europe and formulates future directions for upscaling the European seaweed sector. From a People, Planet, Profit perspective, there is no need to focus on producing large volumes of seaweed per se. We need to focus on nature-inclusive production systems, producing the right amount of the right seaweeds, based on the carrying capacity of the European seas. The seaweed sector must avoid developing along the "old" economy's way of cost leadership but develop along the way of the "new" circular economy. Seaweeds should not be seen as a new product "added" to the market but become an integral part of the European food system, being used for human consumption, feed and improving production processes.

Keywords: aquaculture, circular food systems, consumers, LCA, seaweed.

Introduction

Interest in the cultivation and use of seaweeds in Europe is on the rise. Various commercial seaweed producers are nowadays active in, among others, Dutch, Norwegian, Irish, and Portuguese waters, farming seaweeds rather than harvesting them from the wild. To illustrate this, in 2016 the surface area allocated in Norway to seaweed cultivation reached a total of about 277 ha, with 16 companies holding a cultivation permit (Stévant *et al.*, 2017). A multitude of companies sell various species of seaweeds (including brown seaweeds such as *Saccharina spp.*, *Alaria spp.*, and green seaweeds such as *Ulva spp.)* and seaweed-based products, ranging from pasta and seasoning mixes to cosmetics and pharmaceuticals.

These developments are mirrored by an enthusiasm among policy-makers, NGOs and companies alike to expand the European seaweed sector. The European Commission aims for a strong growth of aquaculture in the EU, including seaweed, recognizing that this sector has high potential for sustainable jobs and growth (https://ec.europa.eu/fisheries/sites/fisheries/files/docs/body/2015-aquaculture-facts_en.pdf and https://ec.europa.eu/maritimeaffairs/policy/blue_growth_en). The Dutch climate ambitions, as described in the Dutch Climate Agreement ("Klimaatakkoord"), even talk about developing 14 000 km^2 of sea for combined nature and seaweed cultivation (https://www.klimaatakkoord.nl/binaries/klimaatakkoord/documenten/publicaties/2019/03/12/innoveren-met-een-missie/rapport_innovatie-uitgave_compleet_DEF_HR_bladwijzers.pdf).

Numerous research projects are instigated in many different European countries, focussing on the development of seaweed cultivation techniques, biorefinery processes, and seaweed-based products. But the European seaweed sector is marginal compared with the large-scale production in Asia and, to a lesser extent, Africa and South America. A question left unanswered is how the European produced seaweeds would fit into the existing global value chains and compete on the world market. The pathway along which the future European seaweed sector will develop eventually determines the impact of this activity on the marine ecosystem.

This Quo Vadimus article reviews developments in the European seaweed sector from a Triple P perspective with the objective to formulate a founded argument on the future of the European seaweed sector. The well-known Triple P has been coined by Elkington (1998), consists of profit, people, and planet, respectively as pillars of sustainable development, and provides a useful framework to reflect upon today's and tomorrow's European seaweed sector. First, a *profit* perspective looks at current production volumes, current and new markets and expected and reported costs of production in Europe. Second, we take a *people* perspective, reviewing available data on consumer attitudes towards seaweed products. Third, we take a *planet* perspective, reviewing literature on the environmental impacts of seaweed production and use.

A profit perspective

Questions on the economic viability of seaweed production and processing recur in debates on the future of the European seaweed sector. The ambition in this section is not to present a full-scale techno-economic model, but rather to reflect on the production volumes, estimated costs of production and markets for European seaweed, compared with other producing regions.

Production volumes

According to the latest FAO data on global aquaculture production of seaweeds (FishstatJ, release 3.04.9; http://www.fao.org/fishery/statistics/software/fishstatj/en), the world production of seaweed in 2016 from aquaculture equalled roughly 30 million tonnes, with a value of US$11.6bn. As illustrated in Table 1, by far the majority (both in volume and value) is produced in Asia. Within Asia, China is the largest producer with a production volume of 14-m tonnes, representing a value of US$8.6bn. Second is Indonesia with a production volume of 11-m tonnes, representing a value of US$1.3bn, in volume followed by the Philippines and the Republic of Korea. As of now, 221 seaweed species are commercially interesting, 10 of which are intensively cultivated (FAO, 2018).

The seaweed aquaculture sector grows every year in size and value. The volume of harvested wild seaweeds globally has remained almost unchanged in the last decades, with reported harvests of 1.06-m tonnes fresh weight (FW) in 2006; 1.29-m tonnes FW in 2014 and 1.09-m tonnes FW in 2015.

Seaweed aquaculture in Europe is currently a small sector. The largest producer in Europe is France with a reported production volume of 500 tonnes in 2016. In contrast, the volume of wild-harvested seaweed is much bigger. France alone harvested 55 041 tonnes in 2016 and total European harvest equals 293 324 tonnes. Various initiatives to cultivate seaweed are on their way, not only driven by an academic interest but also by businesses who pilot the cultivation of seaweeds (A map with ongoing initiatives can be found in the European Atlas of the Seas: https://ec.europa.eu/maritimeaffairs/atlas_en.).

Cost of production in Europa, compared with Asia

One of the persistent questions during discussions on the economic feasibility of seaweed cultivation is how the (envisioned) European production compares to current production processes in other regions of the world. There are a number of scientific publications in which the costs for seaweed production are estimated and/or calculated. From 1998 to 2011 a number of studies were published, with widely divergent expected costs for seaweed cultivation (van den Burg *et al.*, 2016). Whereas some studies reported production costs as low as US$155 per tonne dry matter (DM), others estimated production costs to be US$16 630 per tonne DM. In recent years, better information has become available. van den Burg *et al.* (2016) report on the economic feasibility of seaweed production in the North Sea using economic modelling. They conclude that the production costs of seaweed in the North Sea would be approximately €1850 per tonne DM). Bak *et al.* (2018) evaluated a seaweed cultivation method that is applicable and economically profitable in the Atlantic Ocean. An offshore long-line seaweed cultivation system designed by Ocean Rainforest Sp/f was tested in the Faroe Islands and found suitable for cultivation in exposed and deep-water locations (water depth >50 m). High costs of seeding material and costs of deployment were reduced by multiple partial harvesting. The total cost per kg DM of cultivated *Saccharina latissima* decreased when the number of possible harvests without re-seeding was increased (from €3673 to €927 per tonne DM).

The possibility of cultivation seaweed within offshore wind farms has been studied in various research projects. Rockmann *et al.* (2017) elaborated on the economic benefits of multi-use. One of the main hurdles that hinders use of offshore wind energy is the high cost for operation and maintenance (O&M) activities, typically representing a big part of the total costs (25–30%) of the total lifecycle costs for offshore wind farms). It is the logistical problems around O&M where most likely synergy benefits of multi-use platforms can be achieved. Logistic waiting times, e.g. can result in substantial revenue losses, whereas timely spare-parts supply or sufficient repair capacity (technicians) to shorten the logistic delay times are beneficial. The study suggests that a cost reduction of 10% is feasible, if the offshore wind and offshore aquaculture sectors are combined in order to coordinate and share O&M together. This assumption of 10% reduction was also used in various studies investigating the economic prospects of mussel (van den Burg *et al.*, 2017) or seaweed cultivation in offshore wind farms (van den Burg *et al.*, 2016).

Markets

Between 75 and 85% of worldwide seaweed production is used for direct human consumption in Asia. The second important application of seaweed is for production of thickeners (such as alginate and carrageenan), used in multiple food and non-food products. The volume and value of trade of seaweed for these and other applications is summarized in Table 2.

In the Netherlands, representative of the developments in Europe at large, the emergent seaweed industry is driven by innovation in production and the growth of human consumption of seaweeds. There now is a wide range of products based on or containing seaweeds. Highly visible examples include seaweed burgers and seaweed pasta. Other examples include mayonnaise, seasoning mixes, cheese, and even beers and liquor with seaweed. Apart from seaweed as a part of sushi, perhaps the most

Table 1. Production volume of seaweed from aquaculture (based on FAO FishstatJ database).

Continent	Volume tonnes (FW)
Africa	139 313
Americas	15 634
Asia	29 964 105
Europe	1554
Oceania	18 782
Total	30 139 388

well-known seaweed product as such in this niche market is the so-called Dutch Weed Burger. This burger was introduced in 2012, and made its way to consumers via (fastfood) restaurants, canteens, food festivals, as well as the Dutch Weed Burger joint "The house of seaweed" in Amsterdam since 2017. The seaweed used is grown by Dutch seaweed farm "Zeewaar" in the Eastern Scheldt estuary. Also worth mentioning in this respect is the company Olijck, established in 2015, that has brought several seaweed-based products to the market, ranging from seaweed ravioli and tagliatelle to seaweed burgers. The Amsterdam-based company Seamore, in turn, produces pasta and bacon made from seaweed, as well as wraps containing even 50% seaweed. To mention a last example, UmaMeats produces a burger and a sausage that are both hybrids because the beef used is mixed with 15% seaweed.

Globally, many different new markets are considered interesting. The bioactive compounds in seaweed may be applied in a processed or isolated form in food additives (Pérez-López *et al.*, 2014; Radulovich *et al.*, 2015) and pharmaceuticals (Yang *et al.*, 2015). Seaweed species may also contain other chemicals or chemical precursors and macrochemicals (starch, other polysaccharides, as well as proteins) to be used in chemical production (Bikker *et al.*, 2016) or animal feed (Makkar *et al.*, 2016; Peixoto *et al.*, 2016; Seghetta *et al.*, 2016b). There are indications that specific species may even reduce enteric fermentation in ruminants (Kinley and Fredeen, 2015; Li *et al.*, 2016), thus reducing climate change impact of production of beef or mutton. Seaweed-based products for these markets are subject of study or commercially available at small scale.

A people perspective

In principle, various topics could be addressed from a people perspective. With respect to the production and processing of seaweed in the European context, social issues such as labour conditions or employment for women or Asian migrants with skills in seaweed farming could be given attention. However, a people perspective here is taken synonymous with a consumer perspective. After all, consumer attitudes and acceptance are of vital importance to assessing the direction and potential of European seaweed value chains.

Limited research on seaweed consumption

Currently, there is very little research into Western consumer attitudes vis-à-vis seaweed (Understandable as this dearth of research may be given the fact that in Western countries there is little tradition in seaweed consumption, it is perhaps more surprising to notice that neither extensive consumer research is available in peer-review journals concerning countries like Japan, Korea, and China where seaweeds represent a major source of food for humans.). To the best of our knowledge, the first empirical study with a sole focus on—Australian—consumers' appetite for seaweed consumption was published recently in academic journals (Birch *et al.*, 2019a, 2019b). Another rare example of a paper devoting attention to seaweed is a Dutch study by De Boer *et al.* (2013). In this case, seaweed is part of a broader analysis on new meat alternatives such as lentils, locusts, and hybrid meat. In a recently-published US study by Brayden *et al.* (2018) seaweed salad is also included in a wider context of consumer research on seafood products. An exploratory study conducted by Onwezen *et al.* (2018) is also noteworthy and will be referred to in the remainder, but this Dutch research has not been published yet in a scholarly journal.

Unlike various Asian countries in which seaweeds have been consumed for centuries and are part and parcel of daily food intake, in European and other Western countries seaweed consumption is anything but self-evident or surrounded by cultural meanings (see Delaney *et al.*, 2016; Fleurence, 2016). Contrary to major seaweed producing Asian countries, direct consumption of seaweeds is not common practice in Europe. In general, Western consumers differ deeply from their Asian counterparts with respect to the socio-cultural significance attached to seaweed. Seaweed does not have a profound tradition in food consumption habits, and its market penetration in the Western world is still very limited. Irrespective of the involvement of countries like France, Spain, Ireland, Canada, the United States, or New Zealand in seaweed production, and despite the existence of age-old culinary traditions of seaweed consumption in specific coastal communities in Europe and North America, seaweeds are commonly not considered as traditional foods. Seaweed, thus, is a new food category in the Western diet (e.g. Delaney *et al.*, 2016; Fleurence, 2016).

In contrast to Delaney *et al.* (2016: 38), who draw the gloomy conclusion that edible seaweeds have a limited consumption value in Europe and the development of new markets for these seaweeds is qualified as nearly impossible, it is our premise that it is important to gain more insight into motivational drivers and barriers to (potential) seaweed consumers. Without a people perspective it is hard to picture what today's and tomorrow's factors of success and failure could be regarding the European seaweed sector. This is all the more important given the growing need to produce and consume alternative plant-based proteins in order to feed the world in more sustainable ways, as the section The bigger picture briefly addresses.

Triggers to consume seaweed-based food products

A trigger to escape from the marginal market that the market for seaweed-based food products currently is in European and Anglo-Saxon countries, is similar to a prime consumer preference in Asian countries where seaweeds are traditionally consumed as "vegetables of the sea". It is observed that a similar marketing of seaweed as sea vegetables is known in Brittany, France (Delaney *et al.*, 2016: 17; Fleurence, 2016: 154), and the just-mentioned European consumer studies confirm that health is a key growth-driving factor from a consumer's point of view. Many consumers perceive seaweed as healthy, nutritious, and natural, or, more specifically: safe, fresh, a good source of protein and of iodine, and low in calories (Birch *et al.*, 2019a, 2019b). Particularly respondents who are more familiar with eating seaweed give higher scores

Table 2. Industrial applications of seaweeds (from Nayar and Bott, 2014).

Seaweed product	Market value	Raw material		Final product	
	Million US$	Quantity (tonnes)	Value (US$/tonne)	Quantity (tonnes)	Value (US$/tonne)
Carrageenan	527	400 000	1400	50 000	10 500
Alginate	318	460 000	950	26 500	12 000
Agar	173	125 000	1200	9600	18 000
Soil additives	30	550 000	18	510 000	20
Fertilizer (seaweed extract)	10	10 000	500	1000	5000
Seaweed meal	10	50 000	100	10 000	500

to such perceived advantages: information about healthy aspects of seaweed in terms of antioxidants, micronutrients or fibres will sooner gain attention from consumers who are receptive to seaweed products.

With respect to all foods, taste is a key issue in consumer acceptance and consumer appetite. Seaweed is no exception to this rule, and it is encouraging in assessing seaweed's market opportunities that the research by Birch *et al.* (2019a) shows that seaweed is perceived as being tasty by a majority (59.9%) of the Australian respondents in the sample. Good taste is an undisputed precondition, but non-functional or non-hedonistic reasons are also relevant for consumer appetite to eat seaweed: more than half of the respondents noted that being sustainable (52.8%) and environmentally friendly (53.4%) were also relevant reasons for eating seaweed. This finding shows a relationship with the studies by De Boer *et al.* (2013) and Onwezen *et al.* (2018). In both cases, consumers consider seaweed's environmental friendliness as an asset. Overall, consumer studies to date do not give reason to treat seaweed products very differently than other food products: their popularity or rise in popularity among European/Western consumers will depend to a large extent on their perception of seaweed products as tasty, healthy, and sustainable. These are three key factors for consumer appetite and attention for foods which hold much broader validity.

Barriers to dietary change

One of the most important barriers to overcome is undoubtedly that seaweed is not part of the traditional Western diet. Despite the abovementioned beneficial features of seaweed, to most Western consumers seaweed-based food products are unfamiliar foods. Birch *et al.* (2019a, 2019b) find multiple reasons for consumer reluctance to accepting seaweed as edible. Most critical barriers to seaweed consumption appear to be indeed unfamiliarity and lack of knowledge of the product category. Respondents do not know seaweed, feel ignorant about how to prepare and store it, what to serve it with or where to buy it. The study by Onwezen *et al.* (2018) also relates seaweed with such generally perceived drawbacks such as bad smell, unavailability, unclear preparation instructions, and a potentially expensive product category.

Such "defensive" biases are deliberately or unwittingly mobilized to avoid behavioural change in order to stick to the food choices we are used to making. Holding on to our habitual dietary choices is a powerful determinant of food behaviour. Because past behaviour is a prevalent motivational factor, making the unfamiliar choice an easier choice is always a significant challenge. Furthermore, status quo bias, loss aversion, fear of unpredictability, disgust ("yuck factor") and neophobia ("fear of the new") hold consumers back from dietary change, and are notoriously difficult hurdles to overcome to reach acceptance of new foods. And also with respect to rejecting seaweed, it turns out that particularly those respondents who are less accustomed to eating seaweed have higher scores on disliking seaweed, treat it as "weird" or raise doubts or concerns about seaweed consumption as being good for one's health. De Boer *et al.* (2013) suggest that particularly those respondents who are attached more to a traditional high-meat diet are less keen to choose a seaweed product.

Finding seaweed consumers

Dietary change is difficult and time-consuming, as sketched above. This condition supports the idea that a broad perspective is needed when European seaweed consumption is concerned. Persuading European consumers to eat seaweed requires the communication and promotion of various (health, ethical, and sustainable) aspects of seaweed as well as the introduction and innovation of tasty, affordable, available, and appealing seaweed and seaweed-based food products.

The market strategy to use processed seaweed "in disguise" in food is currently a popular one. Introducing seaweed in combination with a well-known product such as a burger or ravioli shows clear resemblance with the market introduction of plant-based meat substitutes. Taking seaweed as an ingredient of a hybrid end product such as a burger, wrap, or pasta could be coined the "seaweed by stealth" marketing strategy. The option of making seaweed-based food products is frequently chosen given the situation that apart from seaweed as "sea salad" or as seaweed salt, it is often added in disguise as flavouring ingredient (umami) and used in hybrid products (see also Prager, 2017).

Today's seaweed consumers will probably set the stage for future seaweed consumers in Western countries. In contrast to laggards, early adopters of seaweed must be searched for primarily among the higher educated and higher income consumer groups as well as the more health-conscious and neophilic consumers (Birch *et al.*, 2019a, 2019b). Also younger consumers and "responsible" consumers are expected to be primary and key target markets for seaweed products. Early adopters of seaweed products may be anticipated to be more adventurous and variety-seeking food consumers too. Onwezen *et al.* (2018) use the adjective "innovative" to typify consumers who are more in favour of seaweed. De Boer *et al.* (2013) point to similar characteristics of trendsetting seaweed consumers in terms of high involvement, taste oriented, and high level of education. A related study on microalgae-enhanced foods by Moons *et al.* (2018) points to sporters, foodies and vegetarians as early adopters of Spirulina-based food products as trendy and healthy.

Seaweed-based food products could possibly be marketed with an emphasis on personal benefits to the consumer, like healthy or luxury food. But symbolic value can also be derived from characteristics of the production process. Birch and colleagues emphasize that the potential seaweed market depends not only on end products but also on the production method ("source of production") or origin of seaweed (see also Brayden *et al.*, 2018). In addition to product value, there is process value too (Dagevos and Van Ophem, 2013). That is, production practices and the story behind the product (unprocessed, natural, ecological footprint, etc.) add to consumer appreciation and appeal. Put differently, seaweed consumption is not only about eating but also about experience and ethics. Such "symbolic" matters are not to be underestimated when it comes to building a future seaweed market in Europe and other parts of the Western world, especially not in times of growing need to incorporate new sources of protein into the Western diet that are more healthy and sustainable than animal-based proteins.

The bigger picture

The "protein transition" is about a dietary shift away from meat- and dairy-rich food consumption patterns towards eating more plant-based proteins. This dietary shift—in the affluent world to begin with—for pressing personal and planetary health reasons could be helpful to accelerate consumer demand for seaweed products. The other way around, seaweed offers a possibility to contribute to this protein transition at large. Given the need to search for new protein sources to improve traditional Western diets, it is to be hoped that seaweed will become part of "the menu of tomorrow" in Europe and the rest of the Western world. In addition, eating more seaweed is helpful to finding sustainable ways to feed the world's growing population (Mahadevan, 2015; Prager, 2017). If seaweed consumption is associated with "responsible consumption," the environmental benefits of seaweed are going to gain prominence. Eating seaweed, then, will be also and perhaps even primarily motivated by ethical concerns and awareness of the environmental impact of the food choices made. Consumers who are more mindful of bigger issues such as protein transition and circularity can easily find "good" reasons here to justify a preference for purchasing and eating seaweed and seaweed-based food products more frequently as part of their new food consumption habits.

A planet perspective

The planet perspective below provides examples of the environmental aspects of seaweed production and processing and identifies improvement opportunities and environmental research needs.

Environmental impacts of seaweed cultivation

Seaweed cultivation can take place close to the sea, using resources from the sea like seawater (on-shore) and in bays or in the open sea (off-shore). The most widely mentioned benefit is that seaweeds remove nutrients from the sea, especially near fish farms, and can limit eutrophication and possibly algal blooms (Alvarado-Morales *et al.*, 2013; Aitken *et al.*, 2014; Yang *et al.*, 2015). Furthermore, seaweed cultivation attracts marine life, increases biodiversity, both flora and fauna (Radulovich *et al.*, 2015; Yang *et al.*, 2015). Seaweed captures heavy metals from its surrounding water environment (Seghetta *et al.*, 2016b), which may also be disadvantageous for food and fertilizer applications of harvested seaweed. Open seaweed farming systems for bioenergy seem very favourable with net carbon and energy balances (Aitken *et al.*, 2014). An upsurge can be observed in research investigating seaweed cultivation as a carbon sink (Duarte *et al.* 2017; Froehlich *et al.* 2019). In other words, several authors propose that more carbon from the atmosphere is sequestrated during growth and processing than is emitted, and more energy is produced than extracted from non-renewable sources.

On the other hand, intensive seaweed farming might encourage disease outbreaks or cause a decrease in the genetic diversity of local seaweed stocks (Cottier-Cook *et al.*, 2016) and non-native seaweed species have caused environmental and economic damage outside Europe already in Hawaii, India, and East Africa (Loureiro *et al.*, 2015). Shading, turbidity and sedimentation are also potential environmental issues during seaweed cultivation (Langlois *et al.*, 2014). The treatment of seaweed diseases can also have a negative environmental impact (Bernard, 2018). Overharvesting is mentioned as a risk, in the context of *Laminaria digitata* in France (Ghadiryanfar *et al.*, 2016).

There is considerable uncertainty regarding both the positive and negative environmental impacts of seaweed cultivation. It is hard to compare environmental impacts and identify environmental hotspots because diversity in cultivation and processing systems and variation in methods across studies. From studies using life cycle analysis (LCA) some hotspots can be identified. For on-shore cultivation, electricity use for pumping can dominate the environmental impact of cultivation and processing, causing climate change (Helmes *et al.*, 2018). In off-shore systems, where conservation of seaweed might be required (and thus included in the assessment), climate change and fossil resource depletion due to conservation dominates the environmental impact, with secondary contributions from hatchery, and mineral resource depletion due to the seaweed farm construction (van Oirschot *et al.*, 2017). The importance of fossil resource depletion was confirmed in another case study by Taelman *et al.* (2015).

Environmental impacts of seaweed processing

The processing of seaweed often produces multiple products or a main product and by-products. Fuel or ethanol production from seaweed is the focus of some environmental assessments (Langlois *et al.*, 2012; Kraan, 2013; Seghetta *et al.*, 2016a). Several species of seaweed have historically been used as fertilizer and a soil conditions improver (Blunden, 1991; Chapman, 2012), and this potential application of the residues or by-products from the biorefinery of seaweed is mentioned in environmental assessments (Pérez-López *et al.*, 2014; Seghetta *et al.*, 2016a). The processing of seaweed for its applications shows a high variability and many processing routes are on an experimental or even hypothetical level, so that it's hard to derive trends in environmental impacts in the processing. Both energy and chemicals use required for processing are estimated to decrease upon scale-up (Taelman *et al.*, 2015). Drying seaweed or its products will demand energy (Pérez-López *et al.*, 2014; van Oirschot *et al.*, 2017) also on an industrial scale, according to field observations. Both energy and chemical resources especially cause climate change and fossil resource depletion. Carbon dioxide emissions during ethanol production can also be a major contribution to climate change (Seghetta *et al.*, 2016a).

The environmental impact of processing seaweed can be reduced by following cascading principles: (i) apply the full mass of the seaweed in products and prevent waste, (ii) take fractionation steps in the order that yield the most valuable compounds and maintain their functionality, (iii) invest energy and chemical resources only if this increases the product value (van Hal *et al.* 2014; Trivedi *et al.* 2015). Producing only energy from seaweed is not advisable according to these principles, while the complete use of the seaweed may require too much processing and may not be the most attractive option (Pérez-López *et al.*, 2014). The waste from seaweed processing can be digested in order to produce biogas (Langlois *et al.*, 2012). The high water content of seaweed could furthermore be reduced before transport, or transport could be eliminated by processing seaweed at the location of harvest.

Knowledge gaps regarding the environmental impact of seaweed

Full carbon and nutrient cycles should be modelled so that it can be evaluated whether the absorptions of carbon and nutrients during cultivation actually contribute to an overall positive environmental effect. Therefore, environmental life cycle assessment of seaweed cultivation and application should consider the application's entire life cycle including its use and end-of-life. The dynamics during cultivation with regards to sedimentation and standing seaweed stock need to be assessed as well for a complete carbon cycle assessment. Positive assessments of the environmental benefits regarding nutrient and carbon sequestration might require redefinition. Comparison with a benchmark (such as a conventional fertilizer or fossil fuel) can also be a way to claim positive environmental effects, but these comparisons are often implicit by assuming specific substitution scenarios (e.g. Seghetta *et al.*, 2017). Such comparisons can be difficult to do in any case, and are a source of methodological issues (Brockmann *et al.*, 2015).

In addition, a critical evaluation of seaweed cultivation and application also requires the evaluation of the potential benefits and impacts that cannot be quantified (yet) by LCA, as well as development of novel LCA impact characterization methods. Directly applicable quantitative methods are under development (Taelman *et al.*, 2014; Cosme and Hauschild, 2017). Such methods should be further developed and tested in relation to seaweed cultivation and application.

Moving forward

The European seaweed market is in development, in part driven by EU and national policy initiatives to stimulate aquaculture (e.g. the Farmed in the EU campaign). Increasing demand from the food market benefits the producers but seaweed still is a niche market; in absolute numbers the production levels are low. Further growth of the sector is expected (Groenendijk, 2016) but not all preconditions for development of seaweed value-chains in the Europe are met. Production costs are high, compared with the producers outside Europe and compared with the prices paid for seaweed in the major global markets. Cost of labour in Europe is high and future production systems will need to be highly automated production and harvesting systems to reduce costs. Consumer demand for seaweed products is currently low and dietary changes are not easily realized. The environmental benefits of seaweed compared with other products are not easily quantified, not only due to lack of data but also because comparison of land-based and sea-based farming systems is inherently difficult.

In response to these challenges, it is often argued that upscaling is needed in the European seaweed sector, assuming that more production, more research and more demand will suffice. This, tempting as it might be, leads to a focus on *linear* solutions in which current practices are intensified focussing on optimizing yields, reducing cost price and increasing efforts to change consumer behaviour.

Upscaling of production and competition with other producers and products impacts the sea environment and creates some unknown environmental risks. It can also result in lower prices paid for raw material if supple exceeds demand. The future perspective should not be one of large volumes and low prices *per se*. Seaweed product innovation can be stimulated to develop attractive products for consumers, by-products from processing can be valuable as feed, fertilizer or bioactive substances, and economic and social benefits of seaweed aquaculture can be generated for society as a whole. In brief, "qualitative" aspects are key. An a priori "quantitative" focus on large-scale seaweed farming obscures these questions.

We believe an alternative pathway for the development of the European seaweed sector is desirable. What we need instead is a perspective on seaweed production that recognizes and values its role in *circular* food systems. The development of the seaweed sector should focus on producing the right amount of seaweed, considering the carrying capacity of the European seas and the optimal applications in the European food system. The biological activity of seaweed extracts (e.g. for plant and animal health) can be used to increase the performance of food production systems at large. We need to aspire maximum positive impact for the European food system.

Rethinking the role of seaweed in circular food production systems highlights different knowledge gaps. We need to know how seaweed aquaculture and use can optimize food production systems globally, while maintaining environmental quality or reaping the potential environmental benefits (Planet perspective). Nature-inclusive production systems can be developed that already at the production stage produce multiple societal benefits as well as generate a socially responsible and ethically and environmentally just image to seaweed consumer products on the food market (People perspective). Viable business models for cultivation of seaweed should be sought, including the potential to combine seaweed aquaculture with offshore wind farms and taking into account the social and environmental benefits and ecosystem services provided (Profit perspective).

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