Insights on the sustainability of a Swedish seaweed industry

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DOCTORAL THESIS
in Industrial Ecology,
Stockholm, Sweden 2018
Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defense for the Degree of Doctor of Philosophy on Friday the 15th of June 2018, 10:00, in Kollegiesalen, Brinellvägen 8, KTH, Stockholm.

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TRITA-ABE-DLT-1817

Algae, bright order! By Cryptogamists defended—
Translate marine plants as Linnaeus intended.
You collect and admire us, we amuse leisure hours;
‘Then call us not weeds, we are Ocean’s gay flowers.’

(Unknown, early 19th Century)
Acknowledgements

This thesis was carried out both at the Division of Industrial Ecology and the Division of Water and Environmental Engineering, Department of Sustainable Development, Environmental Sciences and Engineering (SEED) at The Royal Institute of Technology, Stockholm between 2014 and 2018, as a part of the Seafarm project funded by the Swedish Research Council Formas (Grant number 2013-92). I would also like to acknowledge the divisions of Industrial Ecology and Water and Environmental Engineering for their financial contributions during my time at KTH.

More than a year before my doctoral journey officially started, in the summer of 2012, my heart became set on exploring the potential of seaweed during a casual chat over a beer with my extraordinary main supervisor, Fredrik Gröndahl. Over the years he has surprised me time-and-again with his vision, compassion and generosity while guiding me through my doctoral education. My deepest gratitude goes out to you, Fredrik. I would have never come near to finishing my thesis were it not also for my two other pillars of sustainability: my co-supervisors, Maria Malmström and José Potting. Your strategic roles in helping develop my research and myself, and the patience you have shown me, cannot be overstated; my sincerest gratitude goes out to the both of you. Monica Olsson and Karin Orve, I would also like to thank you, particularly, for your everything you have done for me and since my arrival in Sweden back in August 2011.

I would also like to thank my friends and colleagues, old and new, Industrial Ecology, SEED and across KTH - Joseph, Mauricio, Linus, Filipe, Rajib, Daniel, Oleksii, Kateryna, Olena, Jagdeep, Emma, Elias, Hanna, Martin, Sanna, Olga, Kosta, Rafael, Miguel, Cecilia, Nils, Björn and many more besides - for your guidance, positivity, encouragement and camaraderie over the years.

Special thanks are also due to the co-authors of the six papers and to the colleagues from the Seafarm project, for your constructive ideas and collaborative spirit. My thanks also to the anonymous reviewers of these papers and to the internal reviewer at KTH, Tove Malmqvist.

I am also grateful to my old friends from the Sustainable Technology program, who have been like family to me these past years. I am both proud to have had the privilege of learning by your sides and truly thankful for your enduring friendships.

Thank you all, my dear friends in the UK, particularly the QPM, to whom I owe so much. My love and thanks also go out to my family abroad and here in Sweden, especially to Monica and Erik for your support these past few years.
I would have never had the courage nor the means to follow my dreams were it not for the unconditional, loving support of my parents Blandine and Scott, and of my big brother Blaise.

To my heart stone, Maria, and to our Lily, born April 2\textsuperscript{nd} 2018, thank you for giving such meaning to my life.

\textit{Jean-Baptiste Thomas}

Stockholm, May 2018
Abstract

Cultivated seaweed biomass is increasingly perceived as having tremendous potential as a multi-value, environmentally friendly and renewable biomass. Momentum is gathering along the Atlantic coast of Europe and across the world to capitalize on the potential of a more global seaweed industry. In Sweden, these developments have largely been sparked by the Seafarm project and its holistic biorefinery approach, which draws on key expertise from five Swedish Universities to lay the foundations for a future seaweed industry. As a part of the project, this thesis principally aimed to effectively assess the sustainability of ongoing developments, most notably through the lenses of viability, environmental life cycle perspectives and potential of a future Swedish seaweed industry. A strategy for assessing sustainability was thus developed with effectiveness in mind and anchored in a broad range of issues highlighted as knowledge gaps by stakeholders; a series of six studies resulted therefrom. Each study contributes insights regarding very specific aspects of the sustainability of a seaweed industry: on the viability of kelp biofuel, threats to viability in the form of potential public aversion to seaweed aquaculture, life cycle perspectives on the cultivation and preservation of seaweed biomass, on the scale and spatial potential of the industry on the West Coast, and finally, on the economic potential of this future industry. This collection of insights contributes six strategic pieces to the vast and dynamic puzzle that is the sustainability of a burgeoning seaweed industry. Together they paint a picture of a viable Swedish seaweed industry with promising potential to contribute positively to key sustainability challenges of the coming decades.
Sammanfattning

List of appended papers


I took part in the research design, data collection, modelling and analysis, and made an important contribution to writing the article.


I developed the research idea, designed and managed the survey and contributed to the analysis. I was also responsible for writing the article and its publication.


I contributed to the revision of the model, which was originally produced as a part of a master thesis, as well as to the analysis and writing the article. I was also responsible for the article’s publication.


I developed the research idea, coordinated data collection, completed the modelling and analysis, and I was responsible for writing and publishing the article.


I developed the research idea, supervised the data collection and analysis, contributed to writing the article and was responsible for the publication process.


I coordinated data collection and analysis of the costs, contributed to the writing of the article and provided comments on the final manuscript.
Additional publications not included in this thesis


List of abbreviations

EEZ – Exclusive economic zone

EPA – Environmental protection agency

EROI – Energy return on investment

EURED – European Union renewable energies directive

FA(s) – Focus area(s)

FA1 – Focus area 1 (hatchery, cultivation and harvest)

FA2 – Focus area 2 (preservation)

FA3 – Focus area 3 (biorefinery)

FA4 – Focus area 4 (biofuel production)

FA5 – Focus area 5 (assessment of sustainability)

GDP – Gross domestic product

GHG – Greenhouse gas

KBB – Kelp for biogas and biofertilizer

MSP – Marine spatial planning

SDG(s) – Sustainable development goal(s)

WLC – Weighted linear combination
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1 INTRODUCTION

1.1 Research context

The potential for seaweed to contribute to the economy has long been recognised in Sweden. During the late 70s and early 80s, a research project led by Torgny von Wachenfeldt (Lund University) explored the potential of seaweed as an energy source, driven by concerns for energy security in the wake of the 1973 Oil Crisis. The project highlighted the potential for cultivating seaweed intensively in shallow and sheltered Swedish coastal waters, reported on potential energy yields and estimated yield potentials using scenarios (Edler et al., 1980). During the early 80s, a series of other reports were also published exploring the potential of a range of marine biomasses that could be subject of aquaculture (Ackefors, 1980, Ackefors et al., 1982). In spite of this preliminary exploration of marine resources, the cultivation of seaweed never took off in Sweden.

In the 90s, another research project called EU Life Algae was launched, though this time with the aim of utilising seaweed biomass to reduce eutrophication in coastal bays in the Swedish waters (Jöborn et al., 2001). Algae mats were harvested using a mechanized process, transported back to land on a barge and downstream uses were explored, notably the production of fertiliser, paper and biogas. Models developed as a part of the project demonstrated algal mat harvesting as a measure for nutrient management in shallow bays (Eilola and Stigebrandt, 1999), and also supported that plaice populations may also benefit from this harvesting (Pihl, 2001). The project also highlighted areas in need of further research, notably the need to better preserve the biomass and identify more profitable end-uses (Jöborn et al., 2001). In the end, the harvesting was considered to be cost-effective only when internalizing projected economic benefits resulting from increased plaice catch as a result of decreased algal covering, however without this external economic benefit, the proposed harvesting and utilisation was not profitable enough to sustain the practice in the long-term (Harlén and Zackrisson, 2001).

Seeking to accelerate economic recovery in the wake of the 2008 financial crisis, the EU Commission issued a communication and call for strategic innovation for sustainable growth by developing the inherently renewable bioeconomy (European Commission, 2012b), in other words, the part of the economy based on renewable biomass-based activities (e.g. agriculture, forestry and fisheries). This was accompanied by another communication which highlighted the potential of Blue Growth (European Commission, 2012a), the development of the marine-side of the bioeconomy. Research momentum was already strong on these topics at the time, for instance with the BioMara project conducted at the Scottish Association for Marine Science (SAMS) which sought to develop seaweed cultivation for bioenergy production to achieve the target of 10% of transport fuels coming from sustainable sources by 2020, set by the Council Directive (2009/28/EC). As such, the EU
Commission calls were not the original triggers of research into blue growth, but they certainly helped to divert funds and catalyse research in these fields.

Across Europe, a series of national and international projects were initiated to explore various aspects of a future European seaweed industry, including for the development cultivation and preservation techniques, and biorefinery processes for the production of food, feed, energy and materials, notably bioplastics. In Sweden too, securing sustainable livelihoods and promoting more sustainable production and consumption of goods are seen as high priorities and sustainability concerns; following the EU calls, research funds were swiftly directed in this direction, including the Swedish Research Council, Formas, that granted the funds for the Seafarm project.

1.2 Case description

The Seafarm project is an ambitious national mobilization of competences from five Swedish universities - KTH, Gothenburg University, Chalmers, Linné and Lund - seeking to lay the foundations of a sustainable seaweed industry for the Swedish bioeconomy. The project was designed with 5 parallel Focus Areas (FAs), see Figure 1.1, which together constitute a supply chain for the cultivation, preservation and refining of seaweed. This approach, to develop an entire supply chain within a single project, provides a holistic opportunity to really gauge the potential of such an industry.

![Diagram of Seafarm project](image_url)

Figure 1.1: The five focus areas (FAs) of the Seafarm project. Reproduced with permission from Gröndahl et al. (2013).
The first FA, cultivation and harvest, aimed to identify suitable species for cultivation, test methods and suitable sites for the cultivation of seaweed near the Sven Lovén Centre for Marine Science, Tjärnö, with the ultimate aim of delivering cultivated biomass to the following steps of the supply chain, while also monitoring local environmental impacts. FA2, storage and preservation, aimed to evaluate alternative preservation methods for seaweed biomass that would be suitable prior to biorefinery treatments, so that the treatment of biomass could be spread out throughout the year rather than be rushed post-harvest. FA3, biorefinery, sought to design a biorefinery process to fraction out products from preserved biomass, e.g. plastics/polymers, biofuel, biochemicals and food/feed components. Both FA2 and FA3 also maintained strong contacts with industrial partners and their specialized competences. FA4, biogas production, aimed to assess the biogas potential of seaweed biorefinery residues, but also of the fresh biomass.

Finally, the project was strategically led by FA5, whose approach should help to coordinate efforts of each FA while also seeking to conduct an integrated sustainability assessment of the process chain. This assessment should be motivated according to recommended practices for effective assessment design and aimed to shed light on the potential of this future industry, highlighting key aspects of performance for instance by conducting energy balances, estimating greenhouse gas reduction potential, performing cost-benefit analyses and inspecting life-cycle impacts – all methods within the analytical scope of industrial ecology. FA5 would also provide recommendations for future sustainability assessments for marine-based production systems. This thesis contributes to the 5th Focus Area of the Seafarm project.
In 2014, at the outset of this research task, no globally recognised frameworks like the SDGs existed for assessing or relating to sustainability, while literature on sustainability assessment methods featured little specific methodological consensus. The influence of industrial ecology, that some consider to be the science of sustainability (but that I prefer to think of as an engineer’s approach to working with sustainability), would become a guide for the assessment of the Seafarm supply chain’s performance. This is no coincidence: the division of industrial ecology at KTH, now absorbed into the department called SEED, was the home of the FA5 research team and acted as a KTH hub for sustainability science, systems thinking and the study of industrial symbioses.

### 1.3 Aim of the thesis

The principle aim of this thesis is to shed light on some of the impacts and contributions (to sustainability) of a future seaweed industry in Sweden. For robustness and enhanced effectiveness, the assessment should be salient to stakeholders in the Swedish context, a legitimate reference for policy makers and stakeholders, and comply with up-to-date literature, research and best practices to enhance credibility. A grounded theory approach (Glaser and Strauss, 1967) allowed for strategic flexibility over the years. Only in hind-sight can specific objectives be stated that reflect the entire journey.

**Objectives**

1. Design an effective and robust assessment process
2. Identify key stakeholder concerns on the development of a Swedish seaweed industry (by means of a participative workshop)
3. Examine key stakeholder concerns (identified during the workshop)  
   a. Public perceptions of aquaculture  
   b. Seaweed cultivation site selection factors and identify suitable sites on the West Coast  
4. Explore the economic potential of the industry  
5. Assess the GHG reduction potential and EROI of seaweed cultivation for biogas & fertiliser production  
6. Assess the life cycle environmental impacts of seaweed cultivation and preservation systems
2 THEORETICAL BACKGROUND

2.1 Why seaweed?

Algae, bright order! By Cryptogamists defended—
Translate marine plants as Linnaeus intended.
You collect and admire us, we amuse leisure hours;
‘Then call us not weeds, we are Ocean’s gay flowers.’

(Unknown, early 19th Century)

These are thought to be the words of a young girl from the British Isles, found scratched onto the back of a folded book with pressed seaweed samples, kept safe in the collections the Natural History Museum in London (Mouritsen, 2017). They highlight the tragedy, the injustice suffered by the many species of macroalgae for having been labelled “weeds” - a label reserved for unwanted plants – and that given their beauty and enigmatic diversity, they should be admired like flowers. Indeed, there is more to seaweed than meets the eye (or nose).

Thought to be amongst the earliest forms of complex multicellular life-forms on our planet (Dornbos et al., 2016), three distinct types of polyphyletic algae (without a common multi-cellular ancestor) emerged early on: red algae or Rhodophyta, green algae or Chlorophyte and Charophyte, and brown algae commonly referred to as kelps. Over 10’000 seaweed species have been identified to date that belong to one of these three families and these have evolved to occupy almost every marine ecological niche, so long as there is some light. Along with microalgae, they are the grasses, the trees, the ferns of the sea, the primary producers that convert sunlight into chemical potential energy providing sustenance to all marine life, from the tiny common shrimp to the Blue Whale. The astonishing diversity of macroalgae species is admirable from a naturalist point of view, but it is also a virtually untapped resource that could be harnessed by man-kind. Indeed, the motivation for the present thesis is to ensure that this development can be sustainable in Sweden, but we’ll get to that...

Production from global seaweed aquaculture in 2014 was estimated at 27.3 million tons wet weight (US$ 5.6 billion), about a quarter of the production of farmed fish by weight, and has experienced tremendous growth in productivity, between 5-8 % per year for several of the past decades (FAO, 2016). More than 85 % of farmed aquatic plants are produced in China (48.8 %) and Indonesia (36.9 %) alone, mainly for human consumption, though the farming of seaweed is now practiced in over 50 countries which are exploring other uses as well (FAO, 2016). The biomass usage only partly fits the classic biomass value pyramid as illustrated in Figure 2.1. Seaweed is used for the production of high-value compounds for the cosmetic and pharmaceutical industries, to produce food additives like phycocolloids, and vast quantities are directly consumed as food and feed. Some argue that seaweed biomass
is one of the most promising bio-resources (Dhargalkar and Pereira, 2005), notably because it does not require land, fresh-water, or other typical agricultural inputs to be produced (like fertilizers or pesticides). To maximize on this potential, therefore, part of the challenge facing a future seaweed industry will be to find ways for environmentally friendly seaweed-based bio-materials, energy and fertilizers to replace the high-volume/low-value fossil-based equivalents.

![Biomass Value Pyramid Adapted to Seaweed](image)

**Figure 2.1:** The biomass value pyramid adapted to seaweed.

Seaweed is prized as a food ingredient particularly in Asia, though attitudes are changing across the Western world as well, particularly in innovative kitchens and in the health foods movement (Mouritsen, 2017). They present a wide variety of textures and ‘mouthfeels’, are a known source of *Umami* and have great aesthetic potential on a plate (Mouritsen and Styrbek, 2017). Seaweeds are also highly nutritious, containing a range of essential components from dietary fibers and fatty acids to trace elements and vitamins, making them significant contributors of a healthy, balanced diet (Cornish et al., 2015). For these reasons, seaweed has also been used for centuries as an animal feed, food supplement (Fleurence, 1999, Cabrita et al., 2016) and in medicine as a vermifuge, anesthetic and ointment, and to treat a range of ailments including iodine deficiency (Dhargalkar and Pereira, 2005). Much of the nutraceutical potential of algae, however, remains untapped (Burton, 2003).

The majority of the value of the seaweed industry comes from its direct consumption as a food, however macroalgae also contain a variety of polysaccharides with unique properties, which the food processing industry harnesses to enhance flavor and extend shelf-life (Roohinejad et al., 2016). Most notable of these phycocolloids are agar and carrageenan, extracted from red algae, and alginate which is extracted from brown algae. The properties that these substances are particularly valuable as
stabilizers and gelling agents, which makes them attractive to both the food and cosmetics industries (Pangestuti and Kim, 2015). Other properties besides, including a wide range of pigments also used to produce non-toxic dyes, add to the cosmetic value of algae extracts (Wang et al., 2015). In terms of future products, algae polysaccharides like alginate are subject of ongoing research to produce plastic-like biodegradable materials that could replace conventional single-use plastics (Maguire, 2016). Sugar rich seaweeds have also been subject of considerable amounts of research for the production of biofuels, notably in the BioMara project (Hughes et al., 2012).

The values of seaweed are not limited to the variety and potential for products, they also hold an important ecological role in nature, a role best illustrated by another pyramid, the trophic pyramid (Figure 2.2). As the autotrophic organisms that convert sunlight into chemical potential energy, macroalgae, microalgae and cyanobacteria (collectively algae) are the primary producers of all biomass and potential energy that will eventually flow through marine food chains. By mass, they are the largest group of organisms in the world, and together they form the base level of the marine trophic pyramid. The second level of the trophic pyramid is populated by the primary consumers, all the herbivorous organisms that consume primary producers, e.g. mussels consuming microalgae. The third level of the pyramid is populated by the secondary consumers, all the carnivorous organisms that consume the primary consumers, e.g. crabs. The pyramid continues to rise, level after level, until the highest trophic level which is reserved for the apex predators of that food chain, e.g. salmon.

![Trophic pyramid of a typical marine coastal ecosystem](image)

**Figure 2.2:** Trophic pyramid of a typical marine coastal ecosystem. Adapted from Sverdrup et al. (2005).
Thus, the trophic pyramid’s vertical axis represents a simplified food chain, from primary producers of energy to the top consumers, with energy flowing upwards. The horizontal axis represents the mass or available energy of each trophic level. The decreasing width of the trophic levels that gives the pyramid its shape is due to energy losses between each trophic level, energy losses inherently caused by digestive inefficiency and by the spending or wasting of energy in metabolic processes and other activities such as movement. In the example of the marine trophic pyramid illustrated in Figure 2.2, energy transfer between each trophic level is assumed to be limited to 10%, meaning that only a tenth of the energy available in the previous trophic level can be transferred upward. Finally, as organisms expire, other trophic levels recycle the available energy and eventually, the left-over nutrients from excrement or decomposed biomass can be re-cycled once again by the autotrophic primary producers. Seaweeds are an important corner stone of coastal food chains, converting nutrients and sunlight into consumable energy.

The absorption of nutrients is crucial for some marine environments, particularly those affected by excess nutrients. Studies have shown seaweed cultivation have potential to help mitigate coastal eutrophication (Fei, 2004, Xiao et al., 2017), reduce the impacts from excess nutrient run-off from fish aquaculture (Chopin et al., 1999, Troell et al., 1999, Buschmann et al., 2008), and that seaweed benefit from fertilization from such nutrient hotspots (Troell et al., 1997). As noted by Hasselström et al. (In Press), the Swedish agency for Marine and Water Management (SwAM) has singled out seaweed cultivation as a promising approach to help shift the state of Swedish coastal waters towards “Good Environmental Status” according to the Marine Strategy Framework Directive (SwAM, 2015). Cultivated seaweed biomass may thus help to “close-the-loop” on nutrients, returning nitrogen and phosphorus from their natural sink back into economic circulation (Seghetta et al., 2016).

As a result of the CO$_2$ captured by photosynthesis, the “blue carbon” that can be captured and stored in marine biomass has also been highlighted as having great potential to mitigate climate change (Chung et al., 2013). It has also been suggested that the CO$_2$ uptake resulting from seaweed cultivation may prevent ocean acidification at a small scale, with seaweed or seagrass beds acting as buffer zones, though research has not yet yielded robust evidence of this in practice nor has this potential been satisfactorily explored to date (Pettit et al., 2015).

In addition to being primary producers, bioremediation agents and potential carbon sponges, it is also thought that seaweed farms provide a host of other ecosystem services, some positive, others negative (Hasselström et al., In Press). Indeed, the ecosystem services provided by established natural kelp forests are well documented, ranging from habitat provision to coastal defense (Smale et al., 2013), and it may not be too big a step to assume that kelp farms could provide similar ecological products and services as do natural kelp forests.
Regarding the acquisition of seaweed biomass, it is important to differentiate between the cultivation of seaweed and the harvest of natural stocks such as that in kelp forests. The harvest of wild seaweed stocks, particularly at a large scale using trawling methods, is amongst the few significant sustainability concerns when it comes to the production of seaweed biomass (Smith, 2017). Indeed, such practices are forbidden in Swedish territorial waters.

Seaweed cultivation requires neither arable land, fresh water, fertilizers, pesticides nor any other typical agricultural input. It does, however, require a series of steps to be carried out both on land and at sea, including controlled reproduction, the installation and maintenance of robust infrastructure at sea, and transport at sea, all of which have their own associated impacts, and unlike agriculture, have not been scaled-up, mechanized and optimized over decades. Past research has examined seaweed cultivation supply chains using scenario and life-cycle methods (Alvarado-Morales et al., 2013, Aitken et al., 2014, Seghetta, 2016), and findings have confirmed that seaweed farming can be low carbon, mitigate eutrophication without significant trade-offs, and thus show promise as a renewable and sustainable, useful biomass. It should be noted, this body of work has been predominantly scenario based, projecting large scale operations or using proxy data. There is a need to recast such studies using robust case-data, notably in view that one of these studies specifically comments:

\[
\text{Future research should bear in mind that the results of this study should however be considered highly optimistic given the early stage of research}
\]

(Aitken et al., 2014)

### 2.2 Assessing sustainability

*Sustainability assessment is [...] a process that directs decision making towards sustainability*

(Bond and Morrison-Saunders, 2013a)

First, the title of this chapter – Assessing sustainability – should itself be clarified. The grammatical significance of using the present participle of the verb to assess emphasizes the ongoing nature of assessing, a point of essential importance when it comes to sustainability. In contrast, an assessment, whether standalone or contributing to a greater assessment process, is usually defined in time by a ‘start’ and an ‘end’ and concludes with the provision of specific information, often in the form of a report. The assessment of sustainability is a process that inherently must account for changes over time, often a long time, by means of historical reference points like baselines or by modelling likely futures, while also supporting transformative action to reduce un-sustainability. Sustainability assessments must therefore be ongoing, which is why in the present thesis, the Seafarm FA5 work is
referred to as the ongoing process of *assessing sustainability*, rather than *an assessment* which would necessarily end.

The vast, interrelated complexities of sustainability can be difficult to grasp. The terms *sustainable* and *sustainability* are highly politicized, contested, and in common-use are often watered-down or misused. This has led to debates on their use in scientific contexts and given rise to alternative formulations such as *societal challenges*, which incidentally, is employed nearly synonymously to sustainability in this thesis. It is essential, therefore, to be clear when using these terms and to frame them within a firm context - hence this chapter’s focus on environmental sustainability, which is carried throughout the rest of this thesis. One must also abide by a few simple ground rules (Bond et al., 2013), a challenge which is hereafter explored.

Perhaps the most basic of these ground rules, the use of the term sustainability must be clearly framed in context to avoid misinterpretation. The great acceleration (Steffen et al., 2004), Planetary Boundaries (Rockström et al., 2009) and the SDGs (UN General Assembly, 2017) frameworks, for instance, are set in the temporal context of the changes that have occurred since the industrial revolution and that threaten the stability of planetary systems and human welfare in the coming decades. They are also spatially contextualized to an intra-planetary scale (*boundary* inherently limiting to what is within the boundary), though the SDGs can also be applied across scales, a practice considered essential in sustainability assessment, by means of gaging the status of targets and indicators at regional, national or even organizational scales. Drivers of sustainability (or unsustainability) are seldom confined to a single, narrow temporal or spatial scale, and “getting the scale wrong, or failing to facilitate adaptation and resilience across scales is destructive of sustainable outcomes” (Howitt, 2013). Establishing contexts – spatial and temporal – is one of the ground rules of good practice when assessing sustainability (Howitt, 2013). Looking beyond the scales defined by the Planetary Boundaries and SDGs, one could also identify other critical sustainability challenges that are not included in these frameworks. At a million or billion-year timescale, for instance, the stability of the energetic inputs (from the sun) to our planetary system become of critical importance too, not just the internal metabolic mechanisms (Kasting, 1988). Neither the planetary boundaries framework nor the SDGs address issues at these scales, nevertheless they remain relevant to sustainability, delimited both in space and time.

Another closely related lose-end to consider is the plurality of meanings that can be attached to sustainability, which is why it is so important to frame it in a context, to not just throw the word around without defining its specific connotation(s). The planetary boundaries framework was developed by researchers and scholars who, one can assume, are relatively well-off. To these individuals, sustainability means overcoming planetary system threats by raising these issues in science and communicating them across the global political arena. Conversely, for millions of
people around the world, sustainability can be more closely related to providing the next meal, or having access to clean water for one’s family. Both are legitimate faces of sustainability, both are societal challenges - but they are separated by differences in culture, circumstance and perceived threats. Though this particular example is extreme, the plurality of meanings in sustainability can also be subtle. Regardless, when it comes to assessing sustainability, that which is attached to the meaning of sustainability and the resulting focus of study must be representative of the plurality of potentially relevant concerns. This is why Bond et al. (2011) suggest a ‘learning while doing’ approach when assessing sustainability, to avoid tainted assumptions of what sustainability means, to be inclusive with respect to the desirable end-goal. In this way, sub-assessments, indicators and efforts to measure sustainability will be grounded in relevance.

There is little debate that there is a need for assessments to provide clarity in complex decisions relating to sustainability, however the process of assessing sustainability is highly contested. Debates are notably ongoing as to the benefits and drawbacks of reductionist and holistic approaches to shedding light on sustainability issues (Bell and Morse, 2012). The reductionist approach allows one to dismember complexity into manageable and often quantifiable parts, by means of methods e.g. environmental systems analysis tools (Finnveden and Moberg, 2005), and indicators e.g. GDP, that have the benefit of enabling comparison between systems and over time to facilitate decision making (Munda, 2006). This temporal dimension is particularly valuable to monitor progress or trigger alarm bells, for instance in the SDGs framework (UN, 2001). The difficulty lies in the selection of indicators that can contribute to representing the sustainability issue in question (Munda, 2006).

Furthermore, indicators often provide conflicting results with one another, for instance, one indicator might suggest that a specific action should take place to improve performance by that indicator, while another indicator might suggest that this same action will worsen performance. Such trade-offs lead to decision making not for sustainable development, but for the ‘least worse’ outcome (Bond and Morrison-Saunders, 2013a). A more holistic approach is argued to provide “a broader understanding” (Steinemann, 2000), an outcome that can be achieved by a greater combination of indicators and sub-analyses, shifting perspectives, and regularly revisiting and updating the strategy as sustainability concerns evolve – an approach with distinct similarities to grounded theory (Glaser and Strauss, 1967). While the terms reductionism and holism might suggest that these approaches may be opposites or alternatives, mirroring the dichotomy between quantitative and qualitative approaches, they can in fact be complementary to each other. Whereas reductionism enables one to gage specifics on the state of a system, holism may help to imbed specific information in a more valuable context (Gasparatos et al., 2008).

As we have seen in the previous paragraphs, spatial and temporal contexts should be established when discussing sustainability, and it is also necessary to be inclusive of
the plurality of meanings that define sustainability and the focus of the assessment. Furthermore, once defined, sustainability issues can be explored by means of alternative complementary strategies, for instance by reducing complex issues into manageable parts while framing them holistically to encompass a bigger, more relevant picture. These key points concern the process of assessment itself. It is, however, also important to consider the outcome (not just the process) of sustainability assessments. Assessing sustainability is, at its core, driven by a transformative need: “to ensure that every one of our potentially significant undertakings is designed to deliver positive contributions to sustainability […] while avoiding persistent damages” (Gibson, 2013). To support this transformative agenda inherent to any sustainability assessment process, six imperatives are proposed by Gibson (2013), whereby a sustainability assessment should:

- Seek the reversal of prevailing (unsustainable) trends
- Integrate all the key intertwined factors affecting sustainability
- Seek mutually reinforcing gains
- Seek to minimize trade-offs
- Respect relevant contexts
- Be open and broadly engaging

In summary, assessing sustainability is an explorative and transformative form of research. The process can be framed in different time and spatial scales, a plurality of meanings of sustainability must be managed, and suitable methods combined to produce relevant information, all in view of achieving desirable outcomes using robust transformative means. Though there is no single best way to approach the assessment of sustainability, this section has sought to highlight some ground rules that have been put into practice in the course of the Seafarm FA5 assessment. The next section will build upon these ground rules of working with sustainability by providing insights into effective assessment strategies.

### 2.3 Effective assessment design

Over the last fifty years, processes of assessment have widely been adopted as knowledge development tools supporting more informed policy development and decision making in complex situations, notably with regards to environmental- or sustainability-oriented decision situations. Some have built lasting legacies as the foundations of important, sometimes global, policy, others have been overlooked, ignored and have ended relegated to the annals of history. Why are some assessments effective in achieving what they set out to achieve while others fail? Interdisciplinary research has been rigorously pursuing this question for decades. In a report prepared for the EEA’s Global Environmental Assessment project, Eckley (2001) presents a valuable review of this research and highlights four key strategic points:
• Effectiveness can be enhanced by balanced and strategic participation, which has a notable effect on users’ perception of an assessment’s credibility, salience and legitimacy;
• Assumptions in assessment design, notably on focus and how to manage uncertainty, should be clearly motivated for transparency;
• Recommendations for action can be included or excluded from assessments, and depending on the aim of the assessment, this can either enhance or subtract from effectiveness;
• Assessments have an important and delicate role to play in boundary organizations, bridging the gap between policy (users) and science.

This section is not to review all strategies for assessment effectiveness, but rather to place emphasis on those elements considered most pertinent to the FA5 Sustainability Assessment strategy, notably the importance of strategies to enhance salience, credibility and legitimacy, as well as the challenge of selecting participation strategies congruent to the problems in question.

**Salience, credibility and legitimacy**

One of the tasks in the EEA’s Global Environmental Assessment project was to review a variety of assessments, in view of identifying and mapping out characteristics that may have contributed positively or negatively to the success of the studied assessments, i.e. to their effectiveness. In line with earlier developments in literature, the project’s final report distinguishes three distinctive and yet interdependent factors: credibility, salience and legitimacy (Eckley, 2001). Since then, these three dimensions have been further discussed in literature, built upon and are commonly referred to when gaging the effectiveness of assessments (Farrell et al., 2001, Cash et al., 2002, Cash et al., 2003, Clark et al., 2006). The significance of credibility, salience and legitimacy for effective assessments and related strategies of the FA5 sustainability assessment are shortly summarized hereafter.

Credibility relates to scientific credibility or trustworthiness of the developed knowledge. Traditionally, scientific work has (perhaps over-) emphasized the importance of credibility - the reputation and impacts of the authors, robustness of the scientific method and thus also of the results - following the belief that the scientist’s purpose is exclusively to develop knowledge, as objectively as possible. Indeed, without credibility, results can hardly qualify as robust knowledge. Without rigorous vetting of findings (validation), these cannot be relied upon as reliable foundations from which to consolidate existing knowledge, build new knowledge or make robust decisions. Credibility is therefore seen as essential for the effectiveness of assessments, contributing to the production of knowledge perceived as being non-disputable by stakeholders.
Salience is synonymous to perceived relevance. Assessments should produce information that is considered to be relevant, that sheds light on complex problems of interest to those who commission the assessment and to those who will use it or are affected by it. If an assessment produces information that is relevant to the involved stakeholders, the assessment is more likely to be successful in achieving its intended purpose. However, this also highlights an important crossover point, whereby lack of relevance can shed doubt over credibility. If an assessment is commissioned to address a specific problem, the top-down commissioning without stakeholder input can affect its credibility even though it may be relevant to its users. Participation - involving users and stakeholders to shift the focus on problems they perceive as relevant, to add relevance without compromising on credibility - is recommended to manage this delicate balance.

The last of the three factors reported by the Global Environmental Assessment is legitimacy, defined by Eckley as “a measure of the political acceptability or perceived fairness of an assessment to a user” (Eckley, 2001). Legitimacy is a function of who participates and who does not, who’s views are included and who’s are not, and of whether the process follows accepted standards and procedures; in other words, legitimacy is about fairness. If a user, stakeholder or participant doesn’t feel that the process has been just, or that their views have not been represented in the final assessment, or that biased compromises have been made, it can undermine the legitimacy and thus persuasiveness of the assessment. Legitimacy can be strengthened by accountability and transparency in the assessment process, and once again, by involving stakeholders and end-users in the assessment process to ensure that their views be granted fair consideration.

Thus, the involvement of stakeholders (participation) of any kind can be an essential part of an effective assessment processes, strengthening relevance and legitimacy, and sometimes credibility (depending on the problem and methods in question). Yet there are many kinds of participation ranging from basic one-way communication to co-production and learning, some of which may be arduous and depending on the questions at hand, unnecessary, inefficient and potentially ineffective. How should one decide who to involve and the degree to which they should be involved, to efficiently ensure effectiveness?

**Participation fit for the problem**

The extent to which one should plan to involve stakeholders depends very much on the nature of the problem being considered, so before developing participation strategies, one must first understand the problem. Complex societal problems to be addressed by decision makers can generally be organized into 4 types, following the quadrant (Figure 2.3) proposed by Hisschemöller and Hoppe (1995). This quadrant is characterized by placing consensus on norms and values relevant to the problem on one axis and the certainty/knowledge about the problem on the other. Hisschemöller and Hoppe (1995) suggest that problems which lack consensus on
norms and values relevant to the problem will require a greater degree of stakeholder participation to account for differences in norms and values, while problems characterized by a lack of robust knowledge will require a lot of science to be undertaken, to reduce the uncertainty. For problems lacking both, which is the case for climate change, the norms and values are highly contested, and while the science is advanced, the problem remains so complex that there is a lot of uncertainty; based on their quadrant, Hisschemöller and Hope might classify climate change as an “unstructured problem”, thus suggesting that for the development of effective policy actions to shift this problem in a more desirable future direction, significant amounts of both participation and science would be needed.

Figure 2.3: Quadrant of four types of policy problems. Source: Hisschemöller and Hoppe (1995)

Understanding knowledge levels and the norms and values associated with a problem situation is valuable to determine effective strategies and congruent methodologies to address it. The challenge therein is the objective gaging of knowledge levels, norms and values: “since policy problems are by definition sociopolitical constructs, the ways people define problems always contain political (inter) subjectivity” (Hisschemöller and Hoppe, 1995). Though pure objectivity can never be achieved, the challenge can at least partly be addressed by explicitly stating motivations of focus for transparency, as highlighted by Eckley (2001), while participation (e.g. by consultation) can lead to inclusiveness of different values (Hisschemöller et al., 2001) and enhanced salience and legitimacy as perceived by stakeholders.
Participation (stakeholder involvement) keeps coming up, time and again, as a necessary part of an effective assessment process: it can enhance the relevance of an assessment’s scope, secure the legitimacy of assessment processes, and even help to define the scoping of problem. Participation itself is a grouping of strategies, all with the same goal of involving ‘others’ in some way, and in practice, it takes on many forms.

Mayer (1997) identifies 7 distinct forms of stakeholder participation and these are ranked by Hisschemöller et al. (2001) in increasing order of “actual participation”. The first and most simple way of involving parties is to inform and educate them about findings so that these may serve their intended purpose. Second is consultation, and conversely to the first, here the transfer of information is from stakeholder to researcher, where stakeholder knowledge and experiences are needed. The third is the anticipation of future developments, whereby stakeholders are tasked with applying their experiences to anticipate and forecast likely futures. Fourth is mediation, which involves debate and discussion to mediate differences and build consensus between stakeholders. Fifth is coordination: it is a form of strategizing, to plan how elements of an inter-disciplinary nature can be coordinated. Sixth is co-production, a form of joint problem solving, working together to co-produce solutions to problems (Susskind and Elliott, 1983). Seventh is learning, and it involves the creative task of strategy exploration and should help to change core-knowledge and attitudes.

Coupled with the quadrant from Hisschemöller and Hoppe (1995), this proposed ordering of participation methods by level of actual participation becomes a valuable signposting tool. During initial scoping of a problem, stakeholders may be consulted or asked about their views on anticipated future developments, leading to a richer understanding of the problem and a more inclusive information basis for its positioning on the quadrant. Such an approach may also simultaneously strengthen the relevance and legitimacy of the problem assessment itself. This approach was key to the FA5 strategy, presented in the next section.
3 ASSESSMENT DESIGN AND METHODOLOGY

In the theoretical background, guidelines for assessing sustainability considered to be most pertinent are presented. In this section, research design, these guidelines are applied to the present case of the Seafarm FA5 task, which aims to assess the sustainability of the Seafarm supply chain and its scaled-up potential to contribute to a sustainable and robust, bio-based economy. First, the sustainability is framed in a Swedish context and in the temporal and spatial context of the Seafarm project. Second, a contextualized interpretation of effective assessment literature is presented, motivating the participative FA5 strategy using the stakeholder future workshop as the starting point of the project. Third, the sustainability concerns that emerged as key results of the future workshop are discussed, particularly those that would lead to studies contributing to the FA5 assessment. Finally, the research design section closes by re-setting the methodology in the wider context of assessing sustainability: that the proposed methodology is merely a first iteration, a form of sustainability scoping, in a longer-term and necessarily ongoing process of assessing sustainability.

3.1 Sustainability in context

When assessing sustainability, scales, contexts and semantics must be established to avoid confusion and frame pluralities of meaning. This section attempts to provide such anchoring of sustainability in this section by elaborating on the spatial and historical context of the thesis, by relativizing the vast, complex and multi-faceted issue of sustainability in the production of seaweed, and highlighting those sustainability issues considered most pertinent in Sweden.

Sweden is often regarded as a beacon of sustainability, regularly making headline news for instance when Växjö pledged to be the first fossil fuel free city in the world by 2030, or for taking the top place amongst participating countries in the SDG Index and Dashboards 2017 (Sachs et al., 2017). At a national level, the government aims to promote more responsible production and consumption of goods; it aims to reduce eutrophication and participate in the cleaning of the Baltic Sea, one of the most heavily polluted seas in the world; and it also seeks development pathways that can sustain GDP per capita growth while decarbonizing the national economy. At a regional level on the West Coast, the last century has seen a rapid decline and near-total loss of a once thriving fishing industry, resulting in an employment societal challenge, the resolution of which has been subject of much effort. As a developed country with high GDP per capita and robust social welfare, many of the most critical issues of sustainability, for instance poverty, are not as relevant as they may be in other places. It does, however, face sustainability or societal challenges relativized to its own circumstances.

In 2012, slowly recovering in the wake of the 2008 financial crisis, the EU Commission issued a communication and call for strategic innovation for
sustainable growth by developing the inherently renewable bioeconomy (European Commission, 2012b), that is to say, the part of the economy based on renewable biomass-based activities (e.g. fisheries, agriculture and forestry). This was accompanied by another communication which highlighted the potential of Blue Growth (European Commission, 2012a), in other words, the development of the marine-side of the bioeconomy. Securing sustainable livelihoods, and promoting more sustainable production and consumption of goods are seen as high priorities and sustainability concerns in Sweden, and following the EU calls, funds were swiftly directed in this direction by research funding bodies, including the Swedish Research Council, Formas, that granted the funds for the Seafarm project.

Thus, as Seafarm set out to lay the foundations of a Swedish seaweed industry by developing seaweed cultivation and seaweed biomass refinery processes, two of the main challenges of the FA5 group were to explore the viability of producing seaweed in Sweden and the potential for generating sustainable livelihoods and environmentally friendly products, contributing to a sustainable and robust, bio-based economy. Internally within the FA5 group, the implications and meanings of sustainability became anchored by viability and potential, with a focus on the investigation of and nudging towards environmental friendliness, seaweed-related livelihoods on the West Coast, and associated risks and bottlenecks for the development of this future industry.

These foci, viability and potential, also inherently helped to shape the temporal scope of the thesis: that the focus should be on the present viability and potential in the near future, up to half-a-century from now. They also help to determine the different spatial scales of study relevant to explore potential and viability while remaining specific to the Seafarm project case. Initially, studies should be limited to scales limited by the project case data, the Seafarm project cultivation infrastructure (initially 0.5-hectares, later scaled up to 2-hectares) and supply chain, to build a robust foundation to explore larger scales. It is within this context that the FA5 assessment is framed.

The original Seafarm application and FA5 deliverables specify that sustainability will be assessed using data-based systems analysis of performance, including cost-benefit analysis, energy balancing and others, and that together, these should form the parts of an integrated sustainability assessment (Gröndahl et al., 2013). However, the assessment process also aimed to be effective, open and adaptable, searching for issues that relate to sustainability at a range of other scales, including at a regional or national level, and that relate to sustainability as perceived different stakeholders with the help of their participation.

### 3.2 A participative FA5 strategy

As established in the theoretical background of this thesis, reviews investigating the effectiveness of assessments highlight the importance of designing assessments to be credible, salient and legitimate (Eckley, 2001), and thus, these three pillars
became key inspirations in the formulation of a strategy for the FA5 assessment. For the assessment to be considered credible, its constituent parts should be scientifically sound; therefore, all contributing studies should be rigorously vetted by peer review and published in trustworthy scientific journals. For the assessment to be considered salient, the issues and problems within its scope should be perceived as being relevant by stakeholders including end-users (local case relevance), and in balance with the state-of-the-art and knowledge gaps identified in literature (contributing to questions considered relevant in scientific journals). Thus, to enhance salience, the aim was for the scope of FA5 to be determined by a balanced approach, selecting from knowledge gaps identified in both in literature and with the help of input stakeholders; to highlight the most locally relevant knowledge gaps, threats or possible contributions to sustainability, and bottlenecks and risks in the development of a Swedish seaweed industry. Finally, for the assessment to be considered legitimate, the assessment process should be perceived as being fair. All methods contributing to the FA5 assessment should be well established, trustworthy procedures, and the transparency and accountability of the assessment process itself should be secured by good communication and the careful consideration of input from stakeholders.

The Seafarm FA5 strategy was anchored at an early stage in the principle of investigating concerns raised by stakeholders and maintaining regular communication with them, following the requirements of the Miljökonsekvensbeskrivning (MKB) or Environmental Assessment standards set out by the Swedish Environmental Protection Agency (Naturvårdsverket, 2017). Hisschemöller and Hoppe (1995) suggest that knowledge levels and associated values surrounding a problem or question can help to determine how much participation and science will be needed to effectively address a problem. In the case of the Seafarm project and perhaps also seaweed farming in Europe more generally, the FA5 group considers that there is a general consensus on the values and norms regarding seaweed farming activities – that it is generally seen as a positive activity, that seaweed biomass is considered environmentally friendly, useful and largely untapped, and that one of the primary concerns for this budding industry is profitability. This is a generalization, however, and there are some conflicts and oppositions to these views, for instance with those that enjoy private leisure boating in regions that may be subjected to the development of seaweed farms in future. Knowledge levels, on the other hand, are not as certain - there remains much research to be undertaken – for instance, few robust case-studies have been conducted to shed light on the life-cycle or the direct environmental impacts of seaweed farms, or on the potential of the industry to contribute to more sustainable regional economics. There are also potential risk factors to investigate, bottlenecks that are being experienced and technical challenges to the development of profitable supply chains. Thus many questions remain unanswered (low certainty of knowledge), yet seaweed is generally seen as a positive thing (relatively good consensus on values/norms), thus it falls in the moderately structured problem
(ends) corner of Hisschemöller and Hoppe (1995)’s quadrant. Their framework would therefore suggest that an effective strategy for this Sustainability Assessment would be to focus on the science and knowledge development in areas of knowledge uncertainty, while at the same time, some of the aforementioned conflicts in values and norms should also be explored by involving stakeholders.

A corresponding strategy for stakeholder engagement in the FA5 assessment process was thus established (Figure 3.1), primarily to identify critical knowledge gaps and to highlight areas in which conflicts in norms and values may need exploring by the FA 5 researchers (problem identification). Subsequent exploring of knowledge gaps (analysis) would be principally conducted by the researchers, though the process would be communicated to stakeholders by means of personal communication, the Seafarm website news feed, by dissemination of results in the press and during annual stakeholder meetings during which ongoing research was presented and discussed to fine tune salience. Together, these media of communication kept stakeholders informed and stimulated engagement, but the main analysis remained in the hands of the research team. Finally, like the analysis, the synthesis of results would primarily be conducted by the FA5 research team, culminating in a final Seafarm conference to showcase the outcomes of the project.

To kick-start stakeholder engagement, it was determined that a stakeholder workshop could serve to highlight key stakeholder perspectives and concerns regarding the viability and potential of each FA of the project. With regards to FA5, the workshop aimed to encourage stakeholders to discuss concerns about specific issues relating to sustainability, viability and potential of this industry, and to highlight key bottlenecks and problem areas that should be the focus of the FA5 research agenda. Thus, a plan was hatched to hold a stakeholder consultation with a focus on anticipating future developments (Hisschemöller et al., 2001). The

Figure 3.1: Stakeholder engagement strategy for the FA5 assessment.
workshop was called the Seafarm Future Workshop and it was held in Gothenburg on April the 2\textsuperscript{nd}, 2014.

3.3 The Seafarm Future Workshop

A total of 50 invitations were sent to include as wide a range of stakeholder groups as possible, including project partners, the research funding agency Formas, municipalities, regional government, government agencies, companies, researchers and relevant research groups, and other interested parties besides. From the invitations sent out, a 40% turn-out was achieved with a total of 21 participants taking part. During the workshop the participants were split into 4 mixed working groups, each moderated by one of the FA5 researchers (Figure 3.2), to facilitate more discussions in parallel. In addition to moderating the groups, each FA5 researcher was also tasked with making audio-recordings of each group’s conversations for future reference, as well as to collect a summary of key discussion points on paper so that these could later be arranged onto a poster.

![Image](image.jpg)

Figure 3.2: One of the working groups at the Seafarm Future Workshop, April 2014

The workshop itself was organized into 3 successive brainstorming sessions, followed by poster presentations from each group. The first of these brainstorming sessions sought to identify problem areas, both currently being experienced or potentially foreseen for the near-future by participants. Each key problem area was defined, discussed and documented. Departing from the problem-focus of the first session, the second aimed to nurture consensus and creativity: each group was tasked with defining a shared and desirable future for this seaweed industry, voicing
specific and relevant targets to aim for. The third and last of the brainstorming sessions built upon the preceding two, with each group being tasked with suggesting possible pathways to their vision or ideas to overcome specific problems. Thus, the workshop began by providing stakeholders with the opportunity to express their thoughts and highlight their concerns, then the second session sought to build consensus on a vision for the industry, and finally, the participants sought ways of reaching that vision.

A wide range of discussions were held reflecting the workshop format, some focusing on problems, long-term visions and potential solutions for each of the focus areas or of the project as a whole, others on the bigger picture and sharing lessons learnt from past projects. These discussions were recorded on post-its and organized into posters by each group moderator (Figure 3.3), then in the month following the workshop, these were organized and condensed into a summary poster (Thomas, 2014), disseminated via the Seafarm website. Discussions held during the future workshop were highly influential in identifying the key problems to be explored by the FA5 assessment; motivations for overall research direction and the aims and objectives of the papers included in this thesis are thus presented in the results and discussions section.

Figure 3.3: Working group poster being developed at the Seafarm Future Workshop, April 2014
3.4 Only a beginning

As a final note to the research design, it is essential to re-state that these studies constitute a starting point, a benchmark to which future studies can compare changes over time and a reference upon which to continue assessing the sustainability of this industry as it develops over the coming decades. In other words, this thesis is a concise and first iteration in a long-term assessment process, whose priorities were determined by stakeholders and whose overall intent was to capitalize on transformative opportunities, studies seeking to nudge development in more sustainable directions (as defined in this thesis).

By no means can this thesis claim to have considered all the many, relevant and complex dimensions of sustainability - quite the contrary, these studies are narrow in scope, snapshots of key issues judged as relevant in this short time-span. A lack of resources, particularly time, meant that many critical issues could not be explored, from contributing knowledge of (direct) environmental impacts of seaweed farming, to the quantification and valuation of ecosystem services, not to mention other stages of the supply chain notably those processes that will constitute the biorefinery (FA3) which are entirely neglected from the present thesis.

In the beginning the section 2.2 “Assessing sustainability”, a point was made on the title of the section, on the use of the present participle to imply a necessarily ongoing nature of assessment processes when investigating sustainability. I re-iterate that point now to motivate my choice of title for the thesis as a whole. Though the thesis follows recommended practices to assess sustainability, in my eyes, it does not yet constitute a sustainability assessment. It is too early to make such an assertion, the constituent studies too narrowly scoped. This thesis is only a collection of insights on the sustainability of a future Swedish seaweed industry, it constitutes only a beginning in the journey of assessing its sustainability.
The principle aim of the Seafarm FA5 was to explore the viability of producing seaweed in Sweden and the potential for generating sustainable livelihoods and environmentally friendly products, contributing to a sustainable and robust, bio-based economy. This journey began with the stakeholder consultation of the future workshop, the results of which motivated the papers that are appended to this thesis. These papers are largely grouped into three parts: first the studies contributing to knowledge on the viability of a Swedish seaweed industry are presented (Papers I, II); second are those contributing to knowledge on environmental perspectives of the supply chain (Papers III & IV); third are the articles that explore the potential of this future industry on the West Coast (Papers V & VI). Following a summary of the Future workshop results and consequent research motivations, each paper is briefly introduced, and key results and discussion points are highlighted.

4.1 The future workshop and research motivations

The stakeholder perspectives raised during the workshop, considered most relatable as sustainability concerns by participant stakeholders, acted like seeds of influence that would sprout into the articles that constitute this thesis. These key problems and sustainability concerns are hereafter represented by quotes from the summary poster and discussed in terms of how these quoted key findings contributed to molding the aims and motivations of each study. There is no particular order in which these concerns and resultant studies are hereafter presented. A range of others discussion points were raised during the workshop, some also relevant to sustainability and worthy of being investigated in further research. The reality of the research process meant that, as a result of lack of time or resources, these could not be included in the present thesis.

“The algae potential of the Swedish West coast should be estimated to assess the long-term potential and sustainability of this industry.”

(Thomas, 2014)

A discussion topic that took place separately in several of the workshop groups was about what some termed the “algae potential”, a topic that broadly encompassed questions of scale: scale of production, economic contribution and occupied marine space. Is there enough space on the West Coast to accommodate a new industry without entering into conflict with existing marine activities? What would be the requirements of seaweed farming in terms of marine space (depth limitations, exposure to currents, waves and storms)? Where and how many seaweed farms can fit into the marine spatial planning puzzle on the West Coast, and how much biomass could be produced? An understanding of these issues would enable the framing of possible futures of this industry in a more grounded context.
Following some preliminary investigations into the Swedish MSP situation, it soon became clear that MSP was in its infancy, very much a work in progress. Public consultations are planned for the end of 2017 and early 2018, and a completed MSP draft is due in March of 2019. The responsibility of marine spatial planning in Sweden is complex and falls at multiple administrative levels each of which with overlapping spatial responsibilities, the two principle administrative levels being municipal and the Swedish Agency for Marine and Water Management (Havs- och vattenmyndigheten); the former is responsible for sea space extending up to 12nm (≈22km) from the coastline, an area known as territorialhavet, and the latter responsible for the sea space from 1nm (≈1850m) away from the coastline up to the edge of the EEZ (Havochvatten, 2017). Data of current and planned sea uses was found on the websites of a number of municipal and national agencies and organizations, however official drafts of marine spatial plans for the Skagerrak had not yet been developed at the time that this study was initiated. As such, it was deemed that to shed light on the algae potential on the West Coast, a GIS-based multi-criteria analysis (GISMCA) of important location factors for seaweed farming coupled with published information on current sea-use (from agency and municipal databases) could enable the identification of the existing gaps in the current sea-uses that would be suitable for seaweed farms. This study became Paper V of the present thesis.

“Economic viability is likely to depend on the results of FA3 research, notably the value and volume of products that can be fractioned from the algae.”

“The provision of ecosystem services should be understood and accounted for.”

(Thomas, 2014)

Perhaps one of the strongest take-home messages from the workshop was the importance of economic viability, an issue largely seen as the Achilles heel of seaweed industries in Europe due to the low value of the biomass, high costs associated with cultivation (notably labor) and the lack of a substantial and established market for high value seaweed biomass (e.g. for food) in Europe. During the workshop, it became clear that previous attempts at developing seaweed farms in Sweden such as those led by Torgny von Wachenfeldt or EU Life Algae did not succeed as a result of the economic challenges to turn a profit; supply chain economics, cultivation costs, returns on investment, business model projections and the development of high-value products to balance the economy were highlighted as key dimensions upon which to shed light. Furthermore, a clear picture of the market for phyco-products would also be key, another point mentioned in the poster summary. Closely linked to the economic issues, the identification and valuation of ecosystem services rendered by seaweed cultivations may help to strengthen their economic situation, to tip the scales towards profitability should nutrient exchanges become mainstream in the future.
In the early stages of the Seafarm project, invoices and costs were documented, particularly for the cultivation and harvesting steps of the supply chain, in view of building a record of the project costs to inform the development of a subsequent business model. Projections for the scale of seaweed farming in the future were based on scenario-based assumptions of growth from today coupled with the results of Paper V, which provided estimates of sea-space that could be both available and suitable for seaweed farming activities. Together the business model and future projections would be combined and assessed by cost-benefit analysis, identified as a useful tool to explore the economic potential of the Seafarm supply chain owing to its ability to internalize valuable (positive and negative) externalities such as impacts on leisure boating or bioremediation at the seaweed farming sites. This would form the methodological core of Paper VI of this thesis.

“Locally adapted and genetically diverse specimens of S. latissima will be the most productive and resilient to cultivate. Furthermore, new cultivation technologies are emerging that could reduce labor requirements, facilitate seeding, reduce environmental impacts and cut costs.”

(Thomas, 2014)

Discussions and recommendations focusing on the cultivation of seaweed covered a range of topics during the workshop. Cultivation infrastructure designs and seeding methods were discussed, notably surrounding the importance of labor- and cost-efficient strategies and different types of infrastructure configurations (e.g. spacing between longlines). The environmental impacts of seaweed farming were also highlighted as critically understudied, particularly effects on benthic habitats, risk of disease from monoculture and risks to local populations resulting from the cultivation of non-native species, a well-documented problem particularly in the bioeconomy, though considered irrelevant in this case as this project will cultivate locally-sourced and -adapted species. Environmental impacts from seaweed cultivation and biomass processing supply chains, notably resulting from their life-cycles, were also raised as key points for which knowledge needs to be developed. Questions such as whether seaweed farming sequesters more carbon than it emits, for example, need to be answered robustly. Whereas the direct and local environmental impacts fell into the research scope of FA1, the less local, more indirect life cycle impacts resulting from supply chain activities would become the focus of the two LCA studies conducted as a part of this thesis, Papers III and IV.

“Permits are likely to be a complicated obstacle for further expansion of a West coast algae industry, due to aesthetics issues and related risks of public aversion from locals and summer residents, competition with other water uses (e.g. leisure boating) and a lack of a legal framework to certify coastal aquaculture.”

(Thomas, 2014)
During the future workshop, public aversion to aquaculture was identified as a significant risk factor that could throw a spanner in the wheels of the development of a Swedish seaweed industry on the West Coast, an area prized for its naturally beauty, cultural heritage and for the opportunities for leisure boating provided by the wonderful coastal land and seascapes. Indeed, with the likely increase in marine-based cultivation activities, particularly that of mussels and seaweed, clashes are expected to occur with activities such as leisure boating, that could lead to conflicts and associated difficulties in obtaining cultivation permits. Perceptions of aquaculture were said to be negative as a whole, particularly as a result of the environmental impacts of fish aquaculture. As such, a study should be designed to determine whether seaweed aquaculture would be lumped in together with fish aquaculture in the public eye as another activity with negative environmental impacts. In addition, the study should also depict plausible scenarios for the development of seaweed farms on the West Coast in an attempt also to gage reactions and thus the potency of this potential risk factor. Mussel aquaculture was also added as a reference due to its relevance as a budding industry on the West Coast. Finally, the study also aimed to provide a baseline of attitudes for reference in the future, once these activities may have developed their production to more significant scales. Given the scope of these requirements, it was determined that some form of surveying method would be required to gage the attitudes of a large sample of West Coast residents. This study forms Paper II of this thesis.

In addition to the sustainability-oriented stakeholder concerns identified during the workshop, another issue was identified in the months following the workshop concerning viability of the biofuels produced within Seafarm. Legislation at a European level poses certain requirements on the environmental performance of biofuels relative to those of fossil equivalents they seek to replace (European Commission, 2010). Thus, an additional study was mapped out with a view on exploring performances of a cultivated kelp to biogas (and fertiliser as a bi-product) supply chain, using data from and mimicking the Seafarm supply chain. Specifically, the study would investigate the GHG reduction potential of kelp biogas in the Seafarm pilot cultivation and a 10 ha scaled-up projection in order to determine whether sufficient GHG reductions are achieved for the supply chain to produce certifiable biogas. In addition to the GHG reductions potential, an energy analysis of the supply chain was also performed with three foci: to identify the most energy intensive parts of the supply chain, to determine reliance on fossil sources and to estimate the EROI as defined by Murphy and Hall (2010). This study is included in the present thesis as Paper I.

4.2 Viability of a Swedish seaweed industry

Paper I – on the viability of kelp-based biofuels

Paper I was, chronologically, the first study undertaken to contribute to the FA5 assessment, and it was based on data gathered from FA1’s first cultivation attempts. It sought to determine the commercial viability of Seafarm FA4’s biogas production
in relation to the GHG emission reductions targets set by the EURED (European Commission, 2010) and by means of an energy analysis of the cultivation, harvest and digestion of kelp for biogas and biofertilizers (KBB), using EROI as an indicator to gain notions of the potential of this energy system. The study included experimental work on the digestion of the cultivated kelp biomass to estimate biogas yields, and a systems analysis of the supply chain operating at case scale (0.5 hectare cultivation) and a 10 hectare scale-up scenario, from both emissions and energy perspectives. Whereas the 0.5 ha cultivation supply chain was built on case data, processes that would not be feasible for a 10 ha cultivation were adapted to the larger scale.

The supply chain was organized into a sequence of steps, providing a useful overview for the energy analysis and enabling its visualization using the energy systems language (Odum, 1972). Following the suggestion by Carlsson and Schnürer (2011) that co-digestions at large scale only achieve 35-90% of the yields obtained in laboratories, a conservative 40% of the maximum biogas yields achieved in the experiments were used for both energy and GHG analyses.

At 40% of experimental yields, the EROI of the 0.5 ha case was found to be below 1 (0.76), meaning that more energy was consumed to produce the biogas than can be yielded from it, and for the 10 ha scenario the EROI was found to be a little above 1 (1.48), meaning that slightly more energy was produced than consumed. In terms of GHG reductions, at 40% of experimental yields, the 0.5 ha case and 10 ha scenario performed with a mean saving of -20% and 37% GHG reductions respectively and relative to the EURED gasoline, which means that the biogas produced at both scales does not meet the 60% GHG savings target required for new biofuel plants by January 2018.

Sensitivity analysis was conducted on the biogas yield limit of 40% and it was found that at 60% of experimental yields, the EROI of the 0.5 ha case surpasses the breakeven point of 1, while at 90% of experimental yields the 10 ha scenario achieves an EROI slightly below 3 (2.7), close to the desirable EROI target according to Hall et al. (2009). For the GHG reductions, the sensitivity analysis showed that at 80% of experimental yields, the 10 ha scenario surpassed the EURED requirement of 60% GHG emissions reduction relative to gasoline, however, even at 100% of experimental yield, the 0.5 ha does not achieve the GHG reduction target. On the whole, the sensitivity analysis highlights that the 10 ha cultivation feeding into a KBB supply chain can be commercially viable in terms of EROI and EURED requirements, so long as the biogas production is effective. It is also worth noting that in the years following this publication, further biogas digestion experiments have been conducted within FA4. These tend to suggest that the 40% limit, imposed in this study for scaled yield relative to laboratory experiments based on the recommendation by Carlsson and Schnürer (2011), may have been overly conservative given that larger scale co-digestions have shown similar or even improved yields relative to the experimental yields. Thus, a re-run of the model with
the biogas yields obtained in these newer experiments and without the 40% limit may produce more favorable results than currently portrayed in the article.

Analysis of the relative energy and emission performances of each step of the 0.5 ha case and 10 ha scenario revealed some key implications relevant for commercialization of the supply chain. Because some processes of the 0.5 ha case needed to be altered to be viable at 10 ha (e.g. harvest and transport) while other steps had the similar requirements at both scales (e.g. adult growth), the share of the total energy consumption and GHG emissions of each step shifted between scales. A clear example of this type of relative shift can be found in the share of emissions for the packaging step, which shifts from approximately 9% at 0.5 ha to 14% at 10 ha, and is a result of the step being defined in the same way at both scales (same amount of plastic packaging used per unit of biomass) while much of the rest of the supply chain achieved some economies of scale. The step that experienced the greatest economies of scale and subsequent shifts in relative energy demand and emissions were those steps that involved transport at sea, adult growth and harvest and transport, principally due to major efficiency gains in the vessels being used at a large scale and the poor performance of the old research vessel being used in the 0.5 ha case.

At a large scale, the model highlights that the most energy demanding and emission intensive steps will be those of the biogas production, notably the emissions from the thermophilic anaerobic digestion resulting from the large amounts of biomass being heated for digestion. Thus, to further improve EROI and GHG performance with commercialization, the model suggests that efforts should focus on reducing the energy requirements and the emissions resulting from biogas production. Similarly, the indoor maturation step of the supply chain shows as having a relatively high share of energy demand at both scales, principally due to the four-week period during which juvenile seaweeds are maturing under controlled, energy intensive conditions (lit, cooled, aerated and filtered water). Improving the efficiencies of these systems (e.g. using LED lights) may therefore also result in significant improvements to the EROI.

Perhaps the most significant finding of the study is that, overall, energy demand and GHG emissions (expressed per kg of biomass or per Nm³ of biogas) were found to have halved by scaling up. This supports that scaling up improves the overall performance of the system and increases commercial viability, as defined by EROI and the EURED GHG savings requirements.

One of the main limitations of this study that becomes very clear with hindsight, is that the model is temporally static, providing a single snapshot of the supply chain back at the beginning of the Seafarm project before any optimization or process adjustments took place. Since this study was published, the Seafarm cultivation has scaled up from 0.5 ha to 2 ha, further increases are expected in the coming years, lessons have been learned and processes are constantly being optimized, some even as a result of the present study. While Paper I succeeds in its transformative, though
temporally limited objectives (to highlight the potential and possible viability of a scaled up cultivation producing biomass for a KBB supply chain and identify steps with the greatest potential for efficiency gains), it does not account for changes and improvements to the supply chain over time. Indeed, one might even say it is too temporally reductionist. This is the first time I experience this in a study of my own, and it acts as a powerful reminder of the limited usability of results from temporally static models. However, it also reinforces the importance and potential of a future re-run of the model with a more optimized supply chain, and the comparison-enabling strength inherent to the indicators employed in this study.

Paper II – on the potential threat of public aversion

An important threat - with the potential to undermine the viability of a future seaweed industry - was identified by stakeholders during the future workshop: the potential of public aversion to the development of seaweed aquaculture along the highly prized national treasure that is the Swedish West Coast. A web-based panel survey held in the summer of 2015 was therefore undertaken, aiming primarily to gage overall attitudes to aquaculture, notably seaweed aquaculture, and thus determine whether public aversion may be a plausible risk factor that could undermine the development of this future industry. The survey was structured into four parts: First some background information was collected from respondents to verify sample representativeness and to test the significance of several variables anticipated to have an effect on perceptions of aquaculture; Second, awareness levels about aquaculture and general perceptions of aquaculture were gaged; Third, differences in perception of different types of aquaculture were explored; Fourth, the survey concluded by gaging reactions to a plausible scenario depicting rapid development of aquaculture on the West Coast. Respondents were selected primarily for their status as living in one of 11 municipalities on the West Coast, stretching from Strömstad to Gothenburg. For each of the municipalities, age and gender targets were set to achieve a moderately representative sample. 695 useable responses were analyzed.

In order to determine the effect of knowledge levels about aquaculture on its perception based on responses to a series of questions, the respondents were grouped into three groups of relative awareness about aquaculture - high, medium and low awareness – according to responses to a series of questions. Awareness was found to have a significant impact on result tendencies throughout the survey. Low and medium awareness respondents tending to select more neutral responses (the middle alternative on the 5-point Likert scale commonly used in the survey), suggesting that these respondents were indeed less informed about aquaculture-related issues. The lack of informed opinion of the low and medium awareness group, who also make up most of the respondents, could also be interpreted as a potential threat to the acceptability of aquaculture in future. The high awareness group, though showing a reduced tendency to select neutral responses also tended to share similar views, though more pronounced, than those of the low and medium awareness groups. The high awareness group also tended to be most favorable
toward aquaculture, suggesting that increasing knowledge levels in the general population with regards to aquaculture could improve its acceptability.

In the first question to reveal the topic of the survey, respondents were asked to rate their “general opinion toward aquaculture”. To this question, slightly more than half of the respondents (391) opted for the neutral response, reflecting a tendency for attitudes to be generally indifferent or uninformed with regards to aquaculture, particularly amongst the low or medium awareness groups. The other half of the respondents, however, were significantly inclined to rate aquaculture in a positive manner (good=204; very good=76) rather than to rate it negatively (bad=21; very bad=3).

Results from the ordered logit model, used to test the statistical significance of a range of variables on responses to the question regarding “general opinion toward aquaculture”, revealed that most of the selected variables were statistically significant with a few exceptions. Notably, respondents of the high awareness group, living in proximity to an aquaculture site or that regularly go out to sea by boat were found to be statistically more likely to have a more favorable perception of aquaculture. Holiday home owners were found to be less likely to have favorable opinions toward aquaculture and more likely to select neutral responses than their permanent resident counterparts. Concerning spatial variables, respondents from the reference region (Stenungsund and Kungälv) were found to be most favorable toward aquaculture, along with respondents from Orust, Tjörn and Öckerö, while respondents living in the northern most municipalities as well as in and around Gothenburg were found to be significantly less likely to state a good or very good opinion toward aquaculture. Finally, both gender and age were found to be statistically significant variables too, with male and older respondents being more likely to state favorable opinions toward aquaculture.

Thereafter, respondents who were not aware of differences between different types of aquaculture (from an environmental point of view) were provided with 6 statements to respond to regarding different aspects of generic aquaculture (e.g. “I am concerned that the cultivation sites will damage the aesthetic beauty of the West Coast”) using a 5-point Likert scale (strongly agree to strongly disagree, with a middle neutral option). Respondents who were aware of environmental differences between types of aquaculture were provided with the same 6 statements, but separately for each type of aquaculture: plant, mollusk and fish. Again, as for the first question about general opinions of aquaculture, the most prominent response across all statements was found to be the neutral option, especially with regards to generic aquaculture, and could reflect that respondents were not well-enough acquainted with aquaculture related issues to form firm opinions.

On the whole, mollusk and plant aquaculture were perceived as being very similar to one another, though very different to fish aquaculture, which was perceived as having greater potential to have negative impacts on other local species and to leak chemicals into the environment. The greatest difference in perceived impacts arose
with regards to the statement on the potential for improving water quality whereby 46% of respondents disagreed that fish aquaculture could improve water quality, whereas 51% and 62% of respondents agreed that mollusk and plant aquacultures (respectively) could improve water quality. This is particularly interesting as these perceptions reflect the trophic roles of mollusks, plants and fish in their respective ecosystems, thus suggesting that the respondents who were aware of environmental differences between types of aquaculture seemed to also be aware of these trophic roles, at least to some extent. All aquaculture types performed similarly with regards to visual aesthetics and the potential for bad smells, with no significant patterns discernable. In the sixth and final statement, respondents were significantly more supportive (than not) of the development of all types of aquaculture on the West Coast, though slight preference was also shown for mollusk and plant aquaculture, relative to generic and fish aquaculture. The strong support also demonstrated for fish aquaculture in spite of recognised environmental impacts, highlights that its potential economic contribution seems to outweigh the potentially negative environmental impacts.

In the final part of the survey, respondents were presented with some background information including the ongoing EU bioeconomy and blue growth strategies, and their potential for contributing to sustainable growth, followed by a scenario for 2030 depicting significant development of seaweed aquaculture on the West Coast which would contribute to these strategies. Most respondents were favorable to the depicted scenario, with 14% and 48% selecting the very positive and positive response options respectively, 6% selecting the negative option and only 1 person out of the 695 respondents selecting the very negative option. In spite of these favorable opinions about the depicted scenario, skepticism with regards to the claims portrayed in the scenario was also high, at around 30% in all awareness groups.

Reactions to the depicted scenario were further explored, again using 6 statements selected to be representative of key areas of concern: proximity of cultivation sites to the shore, potential impacts on leisure boating, potential aesthetic impacts, concern that cultivation sites will be too big, potential economic contribution of portrayed aquaculture, and concerns about environmental impacts of this industry. Responses were found to be very balanced with approximately equal shares of respondents agreeing and disagreeing to each statement, with the exception of the economic-related statement, to which more than 70% of respondents agreed or strongly agreed that the West Coast could benefit from more economic opportunities.

It is important to remember that the perceptions of aquaculture reported in Paper II represent results from a snapshot in time and space, specifically the summer of 2015 and on the West Coast. Given that contextual factors such as location are known to have a significant effect on perceptions detected in survey studies, it should not be assumed that these perceptions can be transferable to other locations. On the other hand, the results of this study could certainly be used as a benchmark for future comparisons of attitudes in the same region: indeed, it was designed to act as a
beginning, a reference point for future studies contributing to assessing the sustainability of a Swedish seaweed industry.

4.3 Environmental life cycle perspectives

Papers III and IV represent slight departures from the other studies in this thesis, with their primary aim of investigating life cycle environmental impacts of seaweed cultivation systems, in compliment to the environmental impact assessments conducted within FA1, in order to shed light on the primary FA5 goal of shedding light on the environmental friendliness of cultivated seaweed-based products. Paper III was written with a master student from Wageningen University in the Netherlands, Roel van Oirschot (first author), whose master thesis model was adapted to explore the life cycle impacts of seaweed cultivation and drying systems for the production of protein, with a specific focus on the design of cultivation infrastructure. Paper IV built on this study by developing a more representative model of the Seafarm supply chain and inclusive system boundary, with a specific focus on hatchery and preservation methods. Both of these studies quantify impacts according to the CML 2001 baseline method and the cumulative energy demand (CED) method from Frischknecht et al. (2007). The key results from these papers are presented hereafter, and their contributions of sustainability insights are discussed.

Paper III – on the environmental impacts of cultivating and drying seaweed

Two seaweed cultivation systems were designed for the purpose of this study, based on a sketch by Buck (2002) and modified to incorporate material data from the 0.5 ha Seafarm pilot cultivation infrastructure. The two cultivation systems are based on a variant of the longline cultivation system, a long line of rope whose buoyancy is maintained by buoys and upon which seaweed grows, though these designs feature four parallel longlines held closely together and large access corridors in between, effectively producing alternating strips of longlines and access corridors, hence the name cultivation strips. Cultivation systems require a range of materials including concrete anchors, metal chains and shackles, different kinds of rope, plastic piping (referred to as strip strengtheners) and buoys to hold the longlines in place, all of which will have life cycle environmental impacts. The two cultivation infrastructure designs in this study differ by means of a doubling of the cultivation strip – longline rope, strip strengtheners and associated tethers - in the water column, thus one of the designs features two layers of strips, one at 2 m depth, the other at 4m depth. The drying sub-system used in this study is assumed to be a thermal air dryer, calibrated not to raise temperatures above 35 degrees Celsius to avoid denaturing proteins and to dry the protein to a maximum of 22 % moisture content, a generally recommended moisture level for seaweed biomass storage.

The cultivated species in this study is *Saccharina latissima*, and the functional unit in terms of which all impacts are expressed is 1 ton of protein in the dried biomass. Based on the average protein content reported in *Saccharina latissima* by Schiener
et al. (2015) and yields from the cultivation of the same species on longlines in the Netherlands, France, Ireland and Sweden, it was estimated that the single and dual layer systems could produce 0.77 and 1.16 tons of protein per hectare per year, respectively.

The results from the life cycle impact assessment are presented and discussed in detail in the article, however the key take-home messages are hereafter reiterated. First, the production intensification by means of a doubling of the strip in the dual layer system improved estimated yields by 50%, however it did not significantly reduce environmental impacts per ton protein, relative to the single layer system, though it may have other valuable contributions, notably for space limited cultivation sites. Second, in the present model it was found that the greatest contribution to environmental impacts originated from the drying of the biomass, specifically from the relatively high energy required. Supply chains producing dried seaweed should therefore, when possible, employ innovative and less energy intensive methods such as solar dryers or perhaps outdoor drying, or look towards alternative biomass preservation methods such as ensilage. In terms of the contributions to overall environmental impacts resulting from the life cycles of material components, the model showed that the greatest single contributions came from the chromium steel chains and the polypropylene longline ropes, materials that should be used conservatively in cultivation designs, or for which lower impact alternatives should be selected instead.

Paper IV – on the environmental impacts of the Seafarm case supply chain

Paper IV was developed as a follow-up study to Paper III, utilising the same method, expanding system boundaries to include two alternative hatchery processes (which produce the line of string seeded with juvenile seaweeds ready to be deployed to Sea, as pictured in Figure 4.1), four alternative scenarios of biomass preservation, and the study is supplied with case data from the Seafarm project. The two alternative hatchery processes (referred to as spray and submersion seeding), cultivation infrastructure, harvest and freezing conducted as a part of the Seafarm project are represented at scale and as faithfully as possible in the model using case data; the preservation methods of ensilage, hang-drying and air-cabinet drying were designed for the purpose of this study, scaled up and based upon practices reported in literature and the experience gathered by the authors during experiments conducted as a part of the project (see hang-drying experimentation pictured in Figure 4.2).

The functional unit of this LCA was selected as 1 ton of fresh harvested biomass, which is the output of the upstream hatchery, cultivation and harvest steps, and the input of the downstream alternative biomass preservation methods. The comparison of hatchery and preservation methods and the overall analysis of the environmental impacts of the Seafarm supply chain, together aimed to recognize supply chain pathways of least environmental impacts or greatest impact mitigation potential, to inform decision makers and the burgeoning seaweed industry in Europe.
On average across all impact categories, the greatest shares of impacts in all supply chain scenarios was found to be resulting from the freezing process (60 to 70 %); thus, the freezing scenario became the reference with which the three other preservation scenarios are compared. The high impacts of the freezing process were primarily due to the high energy consumption of the daily cold storage over the selected total of 90 days, a period considered to be a reasonable representation of the Seafarm case. Sensitivity analysis showed that reducing or increasing storage duration significantly affected impact contributions, signifying that it would be advisable for frozen seaweed biomass to be consumed or utilized in as short a delay as possible. Furthermore, optimization strategies to improve the performance of the freezing process were suggested, for instance to utilise a more energy efficient freezing system, or to use a more thoroughly insulated storage space to reduce daily energy consumption.

The process responsible for the second greatest contribution of impacts on average across all impact categories, was found to be the air-cabinet drying (30 to 50 %), which was also found to be very energy intensive. The development of impact reduction strategies for air-cabinet drying should therefore focus on reducing energy consumption. It is also suggested that further research is needed to better understand kelp drying processes in practice, notably with regards to how varying the temperature and air-flow in controlled drying processes affects the biomass, in view of reducing energy consumption while still effectively preserving the biomass.
Of the two other preservation alternatives of ensiling and hang-drying outdoors, on average and across all impact categories, both were found to contribute only small shares of total impacts of the supply chain relative to the reference case, particularly the hang-drying which was found to be the preservation method that resulted in the smallest impacts when preserving 1 ton of fresh biomass. The ensiling method included a by-product, the effluent of the ensilage, which was assumed to be used as a biogas substrate, resulting in the avoided production of grass as a biogas substrate and thus mitigating impacts most notably in the acidification and eutrophication impacts categories.

The cultivation step of the supply chain - which represents the cultivation infrastructure, its installation and monitoring of the biomass through the growth period - was found to have the third largest contribution (20 to 30 %) to impacts on average across all impact categories. These were principally a result of the use of the plastic longline ropes made from crude oil, suggesting the need to study the use of more environmentally friendly rope materials, and the use of the steel chains and shackles which contributed to the toxicity impact categories to a large extent. Finally, the contributions of the harvest and hatchery processes (spore preparation and the two-alternative spray and submersion seeding methods) were found to be very small,
amounting to less than 10% when combined across all impact categories. With regards to the hatchery processes, which to the authors’ knowledge, have not been subject to study in view of environmental optimization, the results suggest that the two alternatives perform very similarly, though the configuration of the submersion seeding process resulted in slightly higher impacts. This suggests that the methods are equally suitable as configured in the present study, however in practice each method can differ in terms of the quality of the seeded line that is produced; thus, it is suggested that future supply chain developments should select the hatchery method most effective at producing high quality seeded line of the species targeted for cultivation.

One of the main highlights of the study emerged as a result of including the bioremediation taking place when the biomass is harvested from the water, a step that was not covered in Paper III. The uptake of carbon fixed in the biomass, converted to CO$_2$ equivalents, was found to exceed the (CO$_2$ equivalent) emissions of the supply chain by a factor ranging from 1.1 to 2.9 depending on the preservation method selected. This suggests that each of the preserved biomasses produced from by the supply chain scenarios was carbon negative from a life cycle perspective. Similarly, the uptake of nitrogen and phosphorus fixed in the biomass, converted to PO$_4$ equivalents, was found to exceed the (PO$_4$ equivalent) emissions of the supply chain by a factor ranging from 11 to 36 depending on the preservation method selected. The supply chain processes resulting in the production of valuable preserved biomass were therefore found to have significant eutrophication mitigation potential. Bioremediation was also found to mitigate a portion of the marine ecotoxicity and human toxicity impacts resulting from the supply chain processes.

In summary, the results of this study suggest that environmental impacts resulting from a seaweed cultivation and preservation supply chain will be largely determined by the energy intensity of the selected preservation method, as well as by the cultivation infrastructure itself. It is worth noting, however, that supply chains will most likely not be developed according to pathways of lowest impacts; they are more likely to be developed to meet specific market demands. These three types of preserved biomass – dried, frozen and ensiled – are very different from one another in terms of water content, composition, digestibility and a range of other relevant parameters. Thus, the results of the present study will be most useful as a reference for upcoming studies that will explore the effects of preservation methods on biomass composition and properties, and associated costs of biomass processing alternatives.
4.4 Potential of a Swedish seaweed industry

Paper V – on the algae potential of the West Coast

The original aim of paper V was to shed light on the “algae potential” of the West Coast, on the scale that this industry may reach in the future. During the future workshop, many of the hurdles and challenges identified were seen to be amplified or minimized as a function of scale, so gaining an insight on the spatial potential, even a vague estimation, would be useful for long-term planning. Thus, the study set out with the objectives of identifying some of the physical constraints of current seaweed cultivation practices and pairing these with the MSP puzzle of the study area, in view of identifying areas suited to farming but not currently occupied by existing marine activities. In addition, two GIS analysis methods were conducted in parallel for comparison: Boolean and WLC.

First, discussions were held within the Seafarm project to identify aspects considered most pertinent for the selection of cultivation sites (e.g. exposure to storms, waves and currents, bathymetry, etc.), information that may also be of particular value supply chains in the development of MSPs for the region. Data for these criteria were then collected from a variety of sources and parameters were calibrated with fuzzy logic to specifically define relations of each criteria with site suitability. Herein lies the key difference between the WLC and Boolean approaches: whereas the Boolean approach only takes into account binary relationships (e.g. depths shallower than 10m and deeper than 100m defined as not suitable, but between these is suitable), the WLC approach can account for fairly complex, non-binary relationships using fuzzy logic and a graded index (e.g. depth shallower than 10m not suitable, depth of 10-30m considered ideal, depth of 30-100m considered suitable but not ideal, depths greater that 100m considered not suitable).

In parallel, data was collected from a variety of sources to build a simplified overview of the spatiality of marine activities in the study area (e.g. shipping lanes, leisure boating marinas, fishing zones, etc.), and these too were calibrated with regards to their relation with sustainable site selection. Following several iterations of criteria data collection and relating these to site suitability, each criterion was plotted twice, once according to the defined Boolean relationship, the other according to the defined WLC relationship. As a final step, each individual layer from each method was weighted according to their importance for site selection relative to the other criteria, and combined by means of multi-criteria analysis to produce a final map for each method of site suitability in the study area.

According to the parameters defined in the present study, the Boolean analysis identified a total of 544km$^2$ or 7.1% of the study area as being suitable, areas that are primarily distributed along the coastline of the study area. The results of the WLC analysis, identified a total of 6km$^2$ defined as most suitable (achieving a score of 10 on the index of suitability), while areas achieving suitably scores of 9 and 8 covered 182km$^2$ and 287km$^2$, respectively. Areas scoring 8, 9 and 10 were considered to be
most worthy of further scrutiny, and combined they represent 475km$^2$ (6.2% of the study area). Finally, both the Boolean and WLC methods were overlaid to identify and remove discrepancies (e.g. areas identified as suitable by one method but not the other), resulting in a third, perhaps slightly more robust, resulting area of 338km$^2$ considered suitable for the cultivation of seaweed.

Based on the assumption that seaweed cultivations can produce between 20 and 150 tons of fresh biomass per hectare per year, depending on cultivated species, cultivation configurations and seasonal fluctuations (Kerrison et al., 2015), and that 250km$^2$ of sea space on the West Coast were configured to produce seaweed in the coming decades, this would amount to a contribution of between 50 000 and 350 000 tons of fresh biomass per year, representing around 1% of total production globally (FAO, 2014) and an increase in European seaweed production of 100% relative to 2012 (NetAlgae, 2012). In economic terms, assuming a conservative market value of 0.5 USD (5SEK) per kg fresh weight, this would represent a turnover of approximately 25 million USD per year, a significant contribution in a region that has suffered from the decline of the traditional fishing industry. More research is needed to build a more complete picture of the economic potential of this industry, notably including supply chain business models and possible a quantification of externalities (e.g. ecosystem services) and effects on other activities in the region. Nevertheless, given that cultivated seaweed biomass may constitute one of the most environmentally sustainable contributions to a Swedish bioeconomy, the results also highlight the importance of coordinating with marine spatial planners to accommodate the development of a more sustainable Swedish seaweed industry.

Both the Boolean and WLC techniques were found to perform well for the intents of the present study and as spatial decision-making tools, notably in view that their results were to a large extent harmonious in indicating the same areas. While the WLC approach was more time consuming to undertake than the Boolean method, it also had the additional benefit of providing a higher resolution of results.

**Paper VI – on the economic potential of a Swedish seaweed industry**

During the future workshop, not only was the question of “algae potential” raised as a key curiosity, but also the question of whether seaweed farming can cover its costs and eventually sustain itself from a financial point of view, with or without payments for external benefits such as eutrophication mitigation. Indeed, as mentioned in Section 1.1, Seafarm was not the first attempt to develop seaweed-related industrial activities in Sweden. The momentum generated by previous projects like EU Life Algae in the 90s, highlighted that the wild seaweed harvesting may be a multi-value activity with considerable potential, however the business model proposed by EU Life Algae did not garner sufficient returns, and in the long term, harvesting algal mats was seen as financially untenable (Harlén and Zackrisson, 2001).

As such and building on the spatial and scale insights from Paper V, Paper VI aimed to examine the economic dimensions of seaweed farming, particularly the potential
of large-scale seaweed farming of kelp along the West Coast. Specifically, financial costs and returns were examined as well as key positive (eutrophication mitigation) and negative (potential loss of recreation possibilities) externalities of a single-firm 2-hectare cultivation, and these were then scaled-up in line with growth scenarios based on the 338km² identified as suitable in Paper V, to explore potential profitability and tipping points in price and production costs over a period of 40 years. All values are discounted to relativize to net present values in thousands of euros. Costs include material, energy and labor, including maintenance and material replacements, and revenues are based on the market value of dried seaweed biomass. For more details with regards to the methodology, sensitivity analysis, variables and inputs to the model, see appended paper.

First and foremost, both the single-firm and scale-up scenario suggest that the production of dried seaweed has significant potential to be profitable over 10 years. Costs of production for the single-case (€303 thousand) are dwarfed by potential revenue (€2269 thousand), giving a net financial value of €1966. In terms of the externalities effect on the net financial value, the model suggests these are only minor, amounting to an externality value of minus €28 thousand.

Though the model estimates a relatively low impact of the externalities on net socioeconomic value, the valuation of the externalities is considered to be highly uncertain particularly over such time periods, and in reality, may be both much greater and much smaller. The positive externalities resulting from the uptake of nitrogen and phosphorus at the large scale are estimated from willingness-to-pay studies and are valued at €22 million and €37 million respectively, and would sequester approximately 14 % (N) and 100 % (P) of the annual anthropogenic net loading of these nutrients to the study area in 2014 (SwAM, 2016). With regards to the negative externalities, reduced recreational possibilities at the large scale are estimated at minus €123.6 million though in reality, this number can vary to a great extent depending on where seaweed farms would be located, how farms would be designed and the time of year when cultivation would occur. Additional externalities that have not yet been quantified and valued, such as the potential habitat provision happening at a seaweed farm or carbon sequestration resulting from bioremediation, are also not included in the present study and could affect the socioeconomic net to a large extent.

Finally, the model also suggests a break-even sales price for the dried seaweed biomass at €3/kg, which is even lower than the predicted minimum sales value from the model indata. Though the sales value of the biomass was found to be the single most sensitive variable in the model, such a low potential break-even value amounts to one of the most significant findings of this study: it suggests that dried seaweed biomass has real potential as a raw material for the production of cheaper-than-food biomaterials that can contribute to the bioeconomy and replace current fossil-based alternatives, as discussed in chapter 2.1 with regards to figure 2.1 of this thesis.
5 CRITICAL REFLECTIONS

Having presented summaries of Papers I-VI and the journey that led to their development, in hindsight, can these be considered part of an effective assessment? How effective has the FA5 assessment been? The short answer is, for the most part, that it is still too early to tell, and that these questions are too complex for a simple answer. A longer answer is presented in the following paragraphs based on the proposed framework for assessing effectiveness from Bond et al. (2013), including additional reflections on my research journey, the FA5 assessment process and this thesis as a whole. The FA5 strategy attempted to ground assessment effectiveness by following recommended approaches to enhance the legitimacy, salience and credibility of the assessment process, as set out in chapters 2.2 and 3.2. Was this approach effective, in and of itself?

Measuring assessment effectiveness is notoriously difficult and has been subject of decades of research. Bond and Morrison-Saunders (2013a) refer to one of the first global attempts to measure the effectiveness of environmental assessments, which defined an effectiveness as “whether something works as intended and meets the purpose(s) for which it was designed” (Sadler, 1996). From this starting point, Sadler (1996) breaks down the effectiveness of assessments into three sub-types of effectiveness: procedural (does the assessment conform to established procedure?), substantive (does the assessment achieve the set objectives?) and transactive (was it time- and cost-efficient?).

Bond and Morrison-Saunders (2013a) go on to submit a fourth dimension, normative effectiveness proposed by Baker and McLelland (2003), which refers to achieving normative goals set by overarching social values. In this context, Bond and Morrison-Saunders (2013b) propose the six imperatives of sustainability assessment (Gibson, 2013), presented in chapter 2.2, as a foundation to reflect relevant social norms and values in the assessment of sustainability and as a bridge in the relation to normative effectiveness. These first 4 dimensions of effectiveness – procedural, substantive, transactive and normative – are complemented by the consideration of two additional perspectives: pluralism and knowledge and learning; where pluralism refers to managing the many different points of views arising from individual interpretations of sustainability issues; where knowledge and learning refers to the idea that the process of assessing sustainability should achieve designed objectives (contribute with knowledge), but also provide feedback and suggest improvements to the assessment of sustainability itself (contribute to better learning). Together, these six perspectives of assessment effectiveness, selected by Bond and Morrison-Saunders (2013b), are presented as questions in a framework for comparing and evaluating sustainability assessment processes. Though many of these questions can be answered more fully with the input of stakeholders and especially the assessment commissioner, in this case Formas, an inherently incomplete attempt is made in the following pages to evaluate the effectiveness of the FA5 assessment using this framework.
Procedural effectiveness

*Have appropriate processes been followed that reflect institutional and professional standards and procedures?*

(Bond and Morrison-Saunders, 2013b)

As has been discussed regularly throughout this thesis, when the FA5 research began in 2014, the assessment of sustainability did not yet have an established and internationally recognised procedure that we could follow, unlike other more specific assessment methods such as environmental impact assessment or life cycle assessment. In terms of the individual Papers I to VI, each of these follows recognised methodologies from their respective academic contexts. However, assessing sustainability – managing its complexities, pluralities, transformative agenda, etc. – is an explorative process, one that cannot be pinned down by a single procedure but rather it must be flexible within a frame of guiding principles. To the best of our ability, the FA5 research aimed to consider and be molded by such principles, as outlined in the research design section. However, half-way through the research journey, the UNSDGs were published proposing a new framework for monitoring progress towards sustainability-framed goals. Perhaps this is the new professional standard for assessing sustainability in the future, a new language of sustainability monitoring, and to this procedure this thesis does not adhere; however, the principles and literature that have been developing over the past decades and that have contributed to the UNSDGs framework - notably regarding stakeholder participation and strategies for assessment effectiveness with respect to salience, credibility and legitimacy - are to a large extent the same as those that ground this thesis.

Substantive effectiveness

*In what ways, and to what extent, the sustainability assessment lead to changes in process, actions, or outcomes?*

(Bond and Morrison-Saunders, 2013b)

The articles that constitute this thesis have barely been published, yet this question refers to the degree to which this thesis achieved that which it has set out to do, i.e. to gage the potential and viability of a Swedish seaweed industry, and help nudge it in a more sustainable direction where possible. One could say that the articles themselves do gage the viability and potential of this future industry. Paper I explored the viability of algal biofuels, Paper II sought to gage some risk factors relating to public acceptability, and Papers V and VI sought ways of exploring the spatial and economic potentials of this industry, respectively. However, there are many other relevant dimensions of viability and potential that could have also been explored, some highly relevant such as the assessment of products and processes from the Seafarm biorefinery research (FA3) which, due to limitations in the scope of a single doctoral thesis and constraints of resources and time, could not be brought into the fold. As such, in its scope, this thesis presents a snapshot of a fraction of the reality it seeks to assess.
This does not, however, necessarily mean the assessment was substantially ineffective. On those topics that were focused upon as determined by stakeholders, studies were carried-out and their results are having consequences: raising awareness about the importance of public acceptance of aquaculture and the need to monitor it in future, validating the potential of third-generation kelp-based biofuels, and answering questions on the scale and possible economic contributions of this future industry. In terms of the life cycle analyses and their influence in terms of nudging processes in a more sustainable direction, their findings too have had direct substantive effects. The high impact contribution resulting from the use of high-grade stainless-steel chains, identified in Paper III for instance, led to their replacement in the Seafarm infrastructure by lower impact alternatives. Similarly, the results highlighting the importance of low energy preservation methods, identified in Paper IV, are informing decisions regarding the industrialization of the supply chain. To these narrow ends, the assessment has been substantively effective, however it is perhaps also a conclusion of this thesis that a robust and more holistic sustainability assessment cannot be undertaken within the scope of a single doctoral thesis. The true substantive effectiveness of this collection of work will only become clear with the passing of time.

**Transactive effectiveness**

*To what extent, and by whom, is the outcome of conducting sustainability assessment considered to be worth the time and cost involved?*

(Bond and Morrison-Saunders, 2013b)

It is hoped that the undertaken FA5 assessment will be of use to stakeholders, decision makers, regional planners and policy makers working with sustainability issues, blue growth, the bioeconomy and a range of other seaweed industry related topics. This particular question should be posed directly to these end-users who would be able to gage the value of the assessment with more objectivity than the authors themselves. On one hand some might argue that doctoral research is very expensive and that the assessment could have been made with much greater cost- and time-efficiency; others may argue that the specialized doctoral education, by-product of the research journey, will have multiple positive rebound effects in the future, and so within this context the assessment could be argued to be highly cost- and time-effective. Both perspectives are valuable. Perhaps, this question could be raised in the closing conference of the Seafarm project, in June this year, but for now it cannot be fairly addressed.

**Normative effectiveness**

*In what ways and to what extent does the sustainability assessment satisfy the six imperatives set out by Gibson (2013)?*

(Bond and Morrison-Saunders, 2013b)
At the core of the Seafarm project lies the exploration of a novel biomass for the bioeconomy, whose cultivation may sequester carbon, mitigate eutrophication, generate incomes while having other benefits, such as delivering ecosystem services or replacing non-renewable or high impact market alternatives. It is within this context which the FA5 assessment takes place, that it serves to verify and enhance these potentials thus informing the industrialization of supply chains, all in view of supporting the development of an industry with significant potential to provide positive contributions to address societal challenges. There have been some successes in practice, but in the long run, only time will tell the degree to which this assessment will reverse prevailing unsustainable trends.

Strategies seeking mutually reinforcing gains and to minimize trade-offs were integral to the aims of the assessment, in terms of verifying the hypothesized benefits of the contributions of a seaweed industry, exploring possible impacts, and optimizing the supply chain by minimizing trade-offs. In Papers III and IV, for instance, rather than focusing on a limited few though more relevant impact categories such as global warming potential and eutrophication, a broad-spectrum analysis of impacts was undertaken using the CML baseline method to gain perspective on potential impact trade-offs or mutual gains resulting from different scenario configurations. One could speculate that the methods that were employed may have closed doors on other opportunities, for instance undertaking life cycle sustainability assessments – incorporating social, environmental and economic life cycle perspectives – might have highlighted additional trade-offs or potential mutually reinforced gains across those three perspectives. Such studies would be recommended in future iterations of the assessment. The other papers contributing to this study also sought to identify and minimize trade-offs or to enhance mutual gains by other means, whether by exploring economies of scale in Papers I and VI, exploring possible spatial clashes in Paper V or searching for potential overlaps with perceptions of other types of aquaculture in Paper II. Of the six imperatives highlighted by Gibson (2013), these two are perhaps the most inherently captured in all contributing article of the FA5 assessment.

In terms of the attempts to be open and broadly engaging, strategies to this end were followed – from the future workshop and regular media exposure to the publication of open-access articles – though with hindsight it is always possible to say that more could have been achieved. The participative workshop was developed to engage with stakeholders and broaden topical horizons within the assessment, but also as a means to underline issues considered to be fundamentally key with regards to sustainability from an external point of view, in that moment in time. It was not feasible to address all the key intertwined factors affecting sustainability identified during the future workshop, but those aspects that have been addressed were indeed collectively perceived as priorities by both stakeholders and the Seafarm team. With sustainability constantly begin redefined by changing circumstance and context, the sustainability issues perceived as most relevant three years ago may not be considered so today. In contrast with the dynamic nature of societal challenges, the
process of undertaking robust research is slow: by the time articles are published, issues may or may no longer be relevant, while new critical intertwined issues may have emerged in the meantime. This highlights the importance of the necessarily iterative core of assessing sustainability, the need to refer to indicators using acknowledged standards in view of monitoring sustainability over time. To this end, this assessment is incomplete, having only provided a small selection of initial baseline measurements that might be referred back to in the future.

**Pluralism**

*How, and to what extent, are affected and concerned parties accommodated into and satisfied by the sustainability assessment process?*

(Bond and Morrison-Saunders, 2013b)

As mentioned regularly throughout the thesis, concerned parties and those affected by the development of a future seaweed industry on the West Coast were accommodated by a range of different strategies, starting with the future workshop, which was fundamental to defining the scopes of studies contributing to the overall assessment process. Regular communication with stakeholders was also undertaken at a project level, with annual stakeholder meetings, personal contact and regular publication of project highlights on the Seafarm website. The extent to which concerned parties may or may not be satisfied with the assessment process, closely tied to the perceived legitimacy of the assessment (Eckley, 2001), is again a question that cannot be fairly addressed by the authors of the assessment, though could be distributed to stakeholders at the Seafarm conference later this year.

**Knowledge and learning**

*How, and to what extent, does the sustainability assessment process facilitate instrumental and conceptual learning?*

(Bond and Morrison-Saunders, 2013b)

In the context of sustainability assessments, the distinction between instrumental and conceptual learning is that the former refers to changes to the individual case at hand (e.g. seaweed farming and processing practice) while the latter refers to changes in mindsets that transcend the individual case and motivate the need to improve the practice of sustainability assessment itself (Bond and Morrison-Saunders, 2013b). By this definition, instrumental learning has been facilitated by this assessment, notably with the development of useful knowledge in Papers I-VI that can or has been applied as previously discussed. However, this raises another important relevant issue: this project aimed to lay the foundations of an industry by shedding light on difficult questions and by helping to overcome specific hurdles and challenges (i.e. to develop instrumental learning). It did not aim to build companies or actually develop the industry per se. The researchers who have been involved in Seafarm and other sister projects are not entrepreneurs, nor are they experts in the
innovation process. They are merely researchers from their respective fields of chemistry, marine biology, economics or environmental modelling who have shed light on key issues and highlighted the potential, notably economic profitability, of this industry. The next step is to connect to the innovation process; now there is a need for venture capitalists who can turn this into profitable ventures and a genuine industry.

In terms of conceptual learning, the need to improve and develop sustainability assessment methods is indeed clearer than ever from my own point of view. In the first year of my research journey, when reading about assessment iterations and the use of indicators to monitor change over time, these seemed like powerful ideas and I took note of them as being strategically important. With hindsight, I have gained fundamental experience that has shifted my mindset, and I now understand the importance of these points in a way that could never be conveyed by literature. Similarly, while appreciating the methods applied in Papers I-VI and the insights gained from them, I also understand their weaknesses and uncertainties resulting from practical application, the importance of assessment iterations and that as a whole this assessment is just a beginning in the journey of assessing sustainability. Including these thoughts in this thesis is also a way of enhancing conceptual learning, in and of itself. These are, however, only my own views and opinions, and the conceptual learning discussed by Bond and Morrison-Saunders (2013b) should certainly extend beyond the assessment ‘doers’, FA5, to the assessment ‘users’, policy and decision makers, marine planners, entrepreneurs, and so on. With regards to the extent of conceptual learning experienced by these groups, only time will tell, but hopefully they will benefit from the instrumental learning that has taken place.

An additional conceptual lesson perceived by the FA5 team, seems to be based on the advantage of FA5 holding a managerial role within the project. History has shown that research projects can have a tendency to focus too much on the science, on specific sub-studies, often at the expense of developing findings relevant to the real world, or that do not contribute to overcoming important sustainability issues. These latter points, sustainability contributions, may only emerge as an afterthought, a bonus, or because they are a requirement of research calls. This was not the case for the Seafarm project: from the outset, assessing sustainability was a core of the project and became necessarily intertwined with project coordination, notably for supply chain related assessments. FA5 collaborations aimed to enhance the sustainability-salience of each of the FAs, accentuating a grounding in sustainability issues of the project as a whole. The aim of Seafarm was not to fund researchers for some years to produce specific research, rather it was to lay the foundations of an industry that may contribute positively to societal challenges. As such, a conceptual lesson of relevance might be that the provision of strategic coordination roles to sustainability assessment actors may be strategically beneficial, particularly for projects with aiming to contribute to resolve societal challenges.
6 CONCLUSIONS

The development of a European seaweed industry has rapidly been gathering momentum over the past decade, in view of its potential contribution to sustainable growth in the blue bioeconomy as a largely untapped, environmentally friendly resource with many potential values and uses. The Seafarm project originated in view of laying the foundations for this industry in Sweden, bringing together key expertise from five different universities to explore the potential of cultivating, preserving, refining and producing energy from kelp native to the Swedish West Coast, but also to explore the potential impacts and contributions to sustainability of this future industry. It is this latter task - the assessment of sustainability - to which this thesis aimed to contribute.

An assessment process was developed to be effective - salient, legitimate and credible - based on the literature presented in Chapter 2. To manage the plurality of meanings that can be projected onto sustainability, those sustainability issues considered most pertinent in Sweden and with regards to seaweed farming were framed in their relevant spatial and historical contexts. Thereafter, a stakeholder participation strategy was devised based on the Hisschemöller and Hoppe (1995) problem classification quadrant: given the uncertainty of knowledge regarding seaweed-related sustainability issues and the lack of major conflicts in norms and values, stakeholder involvement would not need to be as important as the development of knowledge. In hindsight, this simple problem classification quadrant model was one of the main contributors to organizing the assessment design process, helping to overcome a key challenge in the early assessment process: identifying an optimum extent of stakeholder involvement.

In the course of the Seafarm Future Workshop, stakeholders were thus consulted regarding the bottlenecks, threats and sustainability issues considered to be most salient for research in the course of the project. Stakeholders shared insights on many issues, but a few stood out as key threats or questions - notably regarding threats to viability, environmental impacts of supply chain operations and the “algae potential” of this future industry on the West Coast – topics that were explored in the six papers appended to this thesis, summarized in Chapter 4 and that can act as benchmark studies for future reference. As discussed in this thesis, stakeholder engagement can be critical to the outcome of an assessment; and indeed, the future workshop was instrumental in focusing FA5 research efforts in specific directions.

With regards to the viability of this industry, Paper I highlighted that a viable bioenergy product, as defined by the European Commission (2010), can be produced by similar scaled-up supply chains as that developed as a part of Seafarm, provided processes be optimized and economies of scale capitalized upon to improve greenhouse gas reduction potential and energy return on investment. Paper II explored a key threat to viability identified during the future workshop - the potential public aversion to seaweed aquaculture on the West Coast - and found that on the
whole, public perceptions of seaweed aquaculture were positive, particularly compared to fish aquaculture, primarily as it was seen as a way of bringing economic opportunities to the region but also because it was perceived as being environmentally friendly.

With regards to environmental life cycle perspectives, two LCA studies were conducted (Papers III and IV). In summary, these two papers contribute to the assessment with overviews of impact contributions across typical supply chains, specific analyses of sub-processes and overall recommendations for the optimization of such supply chains’ environmental performance. The second article further contributes with a partial validation of the environmentally friendly reputation of this future seaweed industry, by highlighting that bioremediation resulted in considerable mitigation of eutrophication and climate change impacts, or more specifically, that the production of these four alternatively preserved biomass products was (to varying degrees) carbon negative and resulted in a net mitigation of eutrophication.

With regards to the more future oriented questions regarding the “algae potential” of this future industry, two additional studies were undertaken. By means of GIS MCDA, Paper V contributed to the assessment by providing an analysis of areas most suitable to the cultivation of seaweed biomass by small- to medium-scale farms within the complex puzzle of principle marine activities on the West Coast, and specifically highlighting that plenty of suitable space, as defined by this study, is indeed available for the industry to grow into. Paper VI contributed to the assessment with a cost-benefit analysis demonstrating that this industry shows real promise from a financial returns point-of-view, notably that seaweed farming should be a self-sustaining business activity regardless of payments for ecosystem services, and that with reasonable growth projections, the industry could contribute substantially to sustainable growth of the Swedish blue bioeconomy in the coming decades.

The effectiveness of this assessment, as a whole, has also been evaluated in Chapter 5 using the framework proposed by Bond and Morrison-Saunders (2013b), an evaluation that suggests that the assessment process has been relatively robust and effective in its design and analysis, though the evaluation is limited in that it does not take into account stakeholder opinions, nor yet the passing of time. Identifying, let alone assessing, all of the myriad possible impacts and contributions to sustainability resulting from a not-yet-existent, future seaweed industry in Sweden, is not a task that could be achieved within the scope of a doctoral degree nor a single assessment. Many additional studies could have been and should be conducted in future to complement the present body of work. One example could be to explore alternative seaweed-based low-value/high-volume products in the biomass value pyramid that show particular potential to replace fossil-based equivalents, particularly in light of the fact that preserved seaweed can be carbon neutral and mitigate eutrophication. Similarly, to enhance the transformative potential and
substantive effectiveness of the assessment, policy options could also be explored to encourage and accelerate the shift from a fossil-based economy to bio-based economy. So many questions remain, all of which are relevant. Following the conclusions, this thesis closes with some recommendations for further research.

Since the beginning of the Seafarm project and my own doctoral journey, the momentum of seaweed-related developments has continued to strengthen and accelerate in Sweden: several seaweed cultivation start-ups have emerged, markets for the biomass are developing, companies are increasingly taking an interest and a series of follow-up research projects are already in course. The sustainability of a future seaweed industry in Sweden is like a many-piece puzzle depicting an ever-changing picture; the six articles included in the present study only amount to six strategically important pieces of the puzzle from a single snapshot in time. Producing robust statements about the bigger picture from these limited perspectives, therefore, is almost impossible. This exemplifies why, when discussing sustainability, one always needs to frame the discussion in context. In this case, the bigger picture of sustainability has been focused, narrowed in scope to a salient few topics: the viability of producing seaweed in Sweden and the potential for generating sustainable livelihoods and environmentally friendly products, contributing to a sustainable and robust, bio-based economy. Framed by those terms, this assessment can conclude that a future Swedish seaweed industry shows a lot of promise.
In the course of the four years of research focusing on the sustainability of seaweed cultivation and processing, of the many relevant issues encountered, I have only had the resources to address a limited few. Those few that have been addressed in this thesis have notably shed light on viability, potential and environmental impacts, while also highlighting the need for further research in certain topics. The framework or selecting these studies, their methods and scopes, has been presented, discussed and evaluated through this study, and as particularly highlighted in the section 5.3, a little more time needs to pass before the effectiveness of the FA5 assessment can be evaluated (effectively). At the same time, there has been a rapid development of sustainability assessment practices, notably in the form of the UNSDGs. In this section, some of these ‘other’ sustainability aspects that were not covered in detail in this thesis are presented, highlighting areas in need of further research.

Risks at Sea
As marine-based production systems, seaweed farms are inevitably exposed to the risks and dangers of the sea. Locating seaweed farms in sheltered areas is one way of minimizing such risks. However, there are other risks that are being or have been identified in the past decades relating to larger scale trends over longer time periods in the future, notably acidification and climate change. The effects of climate change and acidification on the cultivation of seaweed itself have largely gone unexplored in this thesis, which has followed a temporal focus on issues on a shorter timescale. Arguably, these risks may also have a significant impact on the development of a Swedish seaweed industry over the next quarter of a century and certainly beyond.

The effects of climate change on marine ecosystems is the subject of a lot of research, much of which supports that climate change is already the cause of fundamental changes occurring in marine ecosystems worldwide (Hoegh-Guldberg and Bruno, 2010). Scenarios investigating the effects of climate change in Europe and Scandinavia suggest that water temperatures on the West Coast will rise slowly though the 21st century, notably with earlier and warmer summer highs, which could affect populations kelps or other cultivated seaweed species directly at a metabolic level or indirectly through new competition in changing ecosystem regimes. Similar risks have been identified as a result of “the other CO2 problem” (Doney et al., 2009), ocean acidification, which is perhaps one of the most alarming and understudied consequences of an increased concentration of carbon dioxide in the atmosphere. The effects of ocean acidification on kelp and other seaweeds have been subject of much research too (Koch et al., 2013), however many questions remain unanswered. A more thorough understanding of these future risks will be essential to the long-term sustainability of a Swedish seaweed industry.

Risks have also been identified relating to the rapid domestication of seaweed species and their monoculture, notably thanks to the work led by Dr. Claire Gachon from the Scottish Association for Marine Science, raising awareness on a range of possible risk
factors. Simply put, when you put any species in a situation where there are many individuals in close proximity to one another, disease often arises. This can be due to pathogens that will spread quickly through a dense population, due to a lack of genetic diversity and associated lack of resistance, and a range of other factors. In essence, disease in seaweed monocultures has been identified as a risk to future seaweed industries, research is ongoing and mitigation strategies are being developed. Close attention should be paid to such practices to ensure that the species cultivated on the West Coast should be healthy, productive and resistant to disease well into the future.

Another topic which is currently subject of research is relating to the possible metabolic release of short-lived bromine substances by seaweeds, and associated impacts on ozone depletion and the climate (Hossaini et al., 2015). Little is known about bromine substance emissions from cultivated seaweeds and their relative contributions to long-term ozone depletion, and for that reason bromine substance emissions are not included in the papers of this thesis, notably the LCA studies. A more thorough understanding of these issues is urgently needed, both to develop potential impact mitigation strategies and to avoid possible knock-on effects, for instance resulting from the development of public aversion due to perceived ozone impacts. Though less of a direct risk factor that could undermine seaweed cultivation or the development of the industry, the role of bromine substance emissions is not yet understood with certainty, and as such it is considered to be a possible threat to the environmentally friendly reputation of seaweed biomass as the “promising plant of the millennium” (Dhargalkar and Pereira, 2005).

Finally, also less related to the cultivation of seaweed itself and more closely related to downstream biomass uses as food and feed, some risks have been identified resulting from the potential for biomass to contain arsenic, heavy metals and (too) high levels of iodine. Unlike the bromine substance emissions this issue is very well documented in literature; there are many studies of compositional analyses of different seaweed species including discussions of associated and recommended uses, e.g. review by Cabrita et al. (2016), and variations between and within studies have highlighted the importance of location factors, notably in terms of heavy metal content. In summary, seaweed biomass is known to approach or sometimes exceed legal limits for certain compounds. Preliminary studies of the seaweed biomass produced at Seafarm, however, has been far from the stated limits of any compounds and has even been awarded organic certification, however this too should carefully be monitored in future.

**Contributions to ecosystem services**

The trophic position of seaweed as a primary producer for marine ecosystems means that it holds a very important role in nutrient cycling and production of primary energy in ecosystems, however seaweed also provide a series of other services, both valuable within their ecosystems and to humans. Such services, that directly or indirectly generate value for humans, are commonly referred to as ecosystem
services. Kelp forests are thought to contribute significantly to ecosystem services in their provision of habitats and a range of other ecosystem services (Smale et al., 2013), and so it seems logical that some of these services may also be rendered by well-established seaweed cultivations. Furthermore, the cultivation of seaweed may also enter into conflict with services rendered by other ecosystem services, for instance the leisure boating that takes place on the West Coast which may be impacted negatively by the presence of seaweed farms. A recent case study of the Seafarm cultivation confirmed the suspected negative impacts on the cultural service of leisure boating, but also highlighted the positive impacts resulting from habitat provision and nutrient sequestering (Hasselström et al., In Press). More research is needed to ascertain exactly how a seaweed cultivation interacts with its environment on an ecological level and the consequent effects with nearby humans from the point of view of ecosystem services.

**Contributions to a circular economy**

As mentioned several times throughout the thesis, seaweed absorb nutrients from their environment during their rapid growth, notably nitrogen and phosphorus. Thus, when cultivated seaweed are harvested, some of the absorbed nitrogen and phosphorus are removed with it, which amounts to a form of bioremediation, counter-acting local eutrophication. Once harvested the biomass can be used to meet a variety of needs in society as food, animal feed, fertiliser or as a range of other products, returning these elements back into circulation in the economy.

**Figure 7.1:** Marine biomass as possible vectors for closing the nitrogen and phosphorus loops: another follow-up project after Seafarm is now on the way.
This is particularly significant with regards to phosphorus, a mineral nutrient essential to all forms of life, of which known stocks are rapidly being depleted and may run out entirely in the coming century, a problem often referred to as the ‘phosphorus crisis’ (Vaccari, 2009). Marine biomass may thus represent an important possible vector for recuperating phosphorus from its primary sinks (seas and oceans), creating a loop and circular economy. The potential of this loop closure to meet current anthropic phosphorus needs, especially with regards to food security, is in urgent need of further research.

The Seafarm FA5 group, in collaboration with other researchers from KTH and a consultancy group Anthesis-Enveco, successfully applied for funds from Formas (Grant number 2017-00213) to look into these issues with a new project in the coming years and provide policy recommendations, evaluating not just seaweed’s potential to close nitrogen and phosphorus loops, but also other useful marine biomass like mussels, beach cast seaweed and algal blooms (see Figure 7.1).

**Optimizing seaweed farming for carbon capture and storage**

This has already been mentioned in the results of the LCAs and in the conclusions of the thesis, however it is reiterated here as a key point in need of further research. The results of paper IV found that, depending on the preservation method that is opted for, the production of preserved seaweed will absorb approximately 1.2 to 3 times more carbon dioxide equivalents than are emitted in the lifecycle of the studied supply chain. Preserved seaweed, particularly dried outdoors or ensiled, shows great promise therefore as a carbon negative resource for use in the bioeconomy, and could contribute to decarbonization strategies in a variety of sectors of the economy, for instance, by replacing carbon-intensive fossil-dependent artificial fertilizers used in agriculture.

Given that the Seafarm supply chain was not designed to be low-carbon, there is also potential for supply chain optimization to enhance the lifecycle carbon absorption to emission ratios. While the biomass production and preservation is optimized on the one hand, there should also be a focus on downstream processing to ensure the low or negative carbon balance of the preserved biomass is carried through to final products and consumers, and not expended in inefficient processing. To these ends, a thorough understanding is needed of the different products that may be produced from preserved seaweed biomass and associated supply chains, which products in the economy these could viably replace, how much relative carbon reductions and net carbon emissions/sequestrations could be achieved, and investigations of carbon sequestration potential in the long-term. In summary, it seems that seaweed biomass could contribute to the bioeconomy with a range of low-carbon, carbon-neutral or possibly carbon-negative products, however further analyses and developments are needed to establish recommended practices for the burgeoning European seaweed industry and to set standards to guarantee or improve carbon performance.
Contributions to the UNSDGs

One of the greatest difficulties when working with sustainability issues is to manage the plurality of meanings and interpretations that can be attached to sustainability, and the hugely complex and often un-anticipatable rebound effect or consequences of actions said to be sustainable. The UNSDGs constitute a brilliant first draft of a global language and standard for managing these difficulties. It is my view that the SDG framework harmonizes both reductionist and holistic approaches, the 17 goals underpin a pluralistic, inclusive and transformative aspiration, the framework is designed to be approachable to stimulate participation, and while the current 169 targets and 232 indicators may not be entirely representative of all the societal challenges we face in the coming decades, the ambition that they embody is the best available and can be built upon in future. Sustainability researchers now have a valuable platform that robustly frames sustainability, removing many of the pitfalls of past approaches. Still the critical issue of capturing slow change over time remains. The use of indicators will enable catching snapshots over time, which when combined, can produce a moving image of 232 dimensions of sustainability, like a time-lapse camera capturing a slow-moving glacier. Now the challenge is constancy of reporting using this new global language of sustainability, ensuring that information is collected and reported upon appropriately and consistently over time, so the whole can exceed the sum of its individual parts.

Figure 7.2: Preliminarily relating the five Seafarm focus areas to the Sustainable Development Goals
It is with this in mind and the experience of four years of working with sustainability that I would conclude this thesis with the recommendation that the mission of assessing the sustainability of this industry as it develops can be enhanced by relating to the SDGs. Figure 7.2 is an adapted version of Figure 1.1, hinting at some of the possible cross-overs between the SDGs and the Seafarm project that could be explored in further research. Regrettably, the SDGs were not finalized when I set off on my journey, and by the time they were published in September of 2015, I had already chosen my path. No SDG reporting was therefore included in the present thesis. In the coming year, however, it is our intension to relate the contributions of both Seafarm as a whole and the emerging Swedish seaweed industry to the SDGs, translating this FA5 assessment and forthcoming studies into this new, global language.
8 REFERENCES


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SEGHETTA, M. 2016. Seaweed utilization for integrated bioenergy and fish feed production: Ecosystem services delivered by circular resource management.


Energy performance and greenhouse gas emissions of kelp cultivation for biogas and fertilizer recovery in Sweden

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HIGHLIGHTS
• Analysis of Energy and GHG was conducted for a Swedish macroalgae supply chain.
• The effects of upscaling on the energy and GHG emissions performances are studied.
• Energy analysis was used to also identify potentials for economies of scale.
• At Sea processes were found to have the highest potential for economies of scale.
• Upscaled system surpassed break even energy return on investment and GHG savings.

GRAPHICAL ABSTRACT

Abstract
The cultivation of seaweed as a feedstock for third generation biofuels is gathering interest in Europe, however, many questions remain unanswered in practise, notably regarding scales of operation, energy returns on investment (EROI) and greenhouse gas (GHG) emissions, all of which are crucial to determine commercial viability. This study performed an energy and GHG emissions analysis, using EROI and GHG savings potential respectively, as indicators of commercial viability for two systems: the Swedish Seafarm project’s seaweed cultivation (0.5 ha), biogas and fertilizer biorefinery, and an estimation of the same system scaled up and adjusted to a cultivation of 10 ha. Based on a conservative estimate of biogas yield, neither the 0.5 ha case nor the up-scaled 10 ha estimates met the (commercial viability) target EROI of 3, nor the European Union Renewable Energy Directive GHG savings target of 60% for biofuels, however the potential for commercial viability was substantially improved by scaling up operations: GHG emissions and energy demand, per unit of biogas, was almost halved by scaling operations up by a factor of twenty, thereby approaching the EROI and GHG savings targets set, under beneficial biogas production conditions. Further analysis identified processes whose optimisations would have a large impact on energy use and emissions (such as anaerobic digestion) as well as others embodying potential for further economies of scale (such as harvesting), both of which would be of interest for future developments of kelp to biogas and fertilizer biorefineries.

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Keywords:
Swedish macroalgae cultivation
Saccharina latissima
Biorefinery
Energy return on investment (EROI)
EURED GHG savings
Economy of scale

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http://dx.doi.org/10.1016/j.scitotenv.2016.07.220
0048-9697/© 2016 Published by Elsevier B.V.
1. Introduction

Third generation biofuels, from algae biomass, are now firmly considered one of the necessary contributors to a sustainable mix to meet future energy demands (Demirbas and Demirbas, 2010). The crucial advantage presented by third generation biofuels lies in the production of their feedstocks, principally microalgae, macroalgae or cyanobacteria (Rowbotham et al., 2012; Singh et al., 2011), e.g. through aquaculture, which does not add to competition for arable land nor to the demand for fresh water, fertilizers or pesticides for agriculture (Budarin et al., 2011; John et al., 2011; Singh et al., 2011), as opposed to first generation feedstocks (Giampietro and Mayumi, 2009). However, in practice, the challenges associated with large-scale macroalgae cultivations at sea coupled with the challenges of handling large volumes of marine biomass have lead to questions being raised on its viability as a feedstock at commercial scales (Aitken et al., 2014).

Aquaculture of aquatic plants is a well-established industry and one of the fastest growing production sectors, with a global average growth of 7.7% annually since 1970 (FAO, 2011), however in the EU it has remained more or less stagnant. As a result from the European Union Commission’s call to develop bioeconomy strategies for Europe (EC, 2012), the Swedish Research Council (FORMAS) funded Seafarm project set out in 2014 to foster research around a cultivated Saccharina latissima (henceforth S. latissima) bioenergy supply-chain to develop and assess the viability of marine biomass based socio-economic utilization strategies for Sweden, or as the EU Commission refers to it, the viability of blue growth strategies (EC, 2014). The potential for seaweed aquaculture to participate toward blue growth strategies are now regarded as significant for coastal communities and the European bioeconomy (Rebouras et al., 2014).

Previous viability studies on marine biomass utilization for bioenergy include, Blas and Kroeze (2014); Budarin et al. (2011); Gao and McKinley (1994); Rebouras et al. (2014); Ross et al. (2008) and within the Baltic area, Rïsén et al. (2013) and Seghetti et al. (2014), who specifically looked at the viability of biofuels by conducting energy analyses in light of GHG savings and using energy input-output based indicators, such as energy return on investment (ER0I). The study of Seghetti et al. (2014) investigated the production of bioethanol from wild kelps harvested in eutrophic waters, by accounting for direct and indirect energy outputs (bioethanol yield) and inputs (harvesting & bioethanol production processes), using an energy systems diagram (Odum, 1972) and EROI (Murphy and Hall, 2010) as an indicator of energy performance. Rather than focus on the harvesting of kelps for biofuels, Rïsén et al. (2013) looked at the harvest of wild reeds in shoreline areas of the Baltic Sea and investigated the bioenergy production and GHG savings from such a venture. However, while both of these papers focused more on the potential of eutrophication countermeasures of these bioenergy production systems from the harvest of wild stocks, neither considered the cultivation of marine biomass.

This study aimed to perform a systems analysis of a cultivated kelp to biogas and fertilizer biorefinery (hereafter KBB) based on the Seafarm supply chain in the perspective of energy and GHG emission performances, in support of future decision making and to shed light on the viability of scaled up kelp cultivations and third generation biofuel biorefineries in a Swedish context. Specific objectives were to:

- Produce an energy systems diagram of the KBB supply chain;
- Establish the viability of the 0.5 ha case and of an explorative 10 ha scale-up, both from an energy input-output and GHG emissions savings perspectives; and
- Identify the specific processes and system inputs that hinder commercial viability (ER0I of 3), from an energy and GHG perspective.

2. Methodology

2.1. Study site

At the crossroads between the salty, nutrient rich waters of the North Sea and the shallow brackish Baltic Sea, the West Coast ecosystem is amongst the most biodiversity marine habitats in Sweden (Gärpe, 2008). There is a long tradition of marine research in the Skagerrak that, amongst other things, has shown that all Swedish waters the Skagerrak has the highest prevalence and diversity of macroalgae (as summarized by Bildberg et al., 2012). In 1996 it was estimated that as much as 10% of this population was S. latissima (Karlsson, 2007), which is the cultivated species in this study.

The Seafarm pilot cultivation site employed in this study is located on the Swedish West Coast (Fig. 1), approximately 20 km from the Norwegian border. Sheltered from storms, with adequate currents, salinity and suitable water depths for the cultivation infrastructure, the area meets all the basic requirements for aquaculture following the criteria laid out by Lindahl et al. (2005). The cultivation sites are within 5 km of the University of Gothenburg’s Sven Lovén Centre for Marine Sciences, Tjärnö, where much of the practical aspects of seaweed production - juvenile hatchery, cultivation preparation, monitoring and harvesting - are undertaken by the Seafarm project. The flows of biomass through the planned Seafarm process/supply chain are outlined in Fig. 2.

Following several deployments of longlines over an area of 0.5 ha, the first successful harvest of cultivated seaweed biomass was made in the early summer of 2015 (to reduce fouling by bryozoans). A gradual expansion of this pilot cultivation is scheduled over the coming years to continue paving the way for this new industry in Sweden, but also to shed light on questions surrounding cultivation spatial/temporal scales, notably about environmental impacts, practical aspects, economies of scale and to identify the principle hurdles for commercialisation. The authors of the present study estimate that a 10 ha cultivation would be representative of a basic commercial scale. As such, a hypothetical 10 ha exploratory scale-up (here after “10 ha estimates”) of the Seafarm system is used in this study to shed light on the commercialization of KBB systems on the Swedish West Coast. Where system processes of the 0.5 ha Seafarm system were neither realistic nor feasible at a 10 ha scale or where economies of scale would be achieved (shaded processes in Fig. 2), processes in the 0.5 ha case were adapted to suit the larger scale (see Section 3.1 for the resulting adaptations to processes). For example, while a 0.5 ha harvest may be loaded onto a small tugged barge with a 30 ton loading capacity, 10 ha worth of harvest would overload this capacity or require ten return trips, thus a much larger 120 ton barge was proposed for the 10 ha estimates. On the other hand, in the case of scalable processes, these were simply multiplied by a factor of twenty to account for the larger 10 ha estimates. For example, the cultivation longlines for the 0.5 ha configuration total 1000 m in length, thus 20,000 m of longline was necessary for the 10 ha estimates.

2.2. System description

To perform the systems analysis, the authors followed the standardised energy systems language (Brown, 2004; Brown and Ulgiati, 2004; Odum, 1972). The Seafarm 0.5 ha case was inventoried using case data (e.g. measurements, invoices and technical specifications) from Seafarm partners and industrial contacts; the 10 ha estimates were constructed therefrom. As defined by the European Union Renewable Energy Directive or EURED (EC, 2010) and exemplified by Alberici and Hamelinck (2010), the permanent infrastructure of the KBB system was excluded both from the GHG savings and energy analyses in this study.

The timeframe for the study was over one cultivation season. Both the 0.5 ha case and 10 ha estimates were analysed as cradle to gate systems (see supplementary material B & C), including biogas and fertilizer production from the cultivated biomass described in Section 2.1 (see...
Supplementary material C & D). The biogas production facility was assumed to be located 10 km from the dock based on their location on the Swedish West Coast (Biogasportalen, 2015; Statens Jordbruksverk, 2011) and given that transport is not considered a sensitive parameter in energy balance calculations of biogas production systems (e.g. Berglund and Börjesson, 2006; Pöschl et al., 2010; Risén et al., 2014). Further definition of system boundaries relating specifically to the energy analysis or GHG savings analysis, are addressed in their relevant following Sections 2.3 and 2.4.

Moreover, as suggested by Carlsson and Schnürer (2011) a realistic scaled up co-digestion only yields approximately 35–90% of the yields achieved in flask experiments under laboratory conditions. Based on this, coupled with the known minimum biogas yield achieved during the experiments, the authors opted for a conservative 40% of the maximum biogas yield obtained in the preliminary lab experiments for the base case. Sensitivity analysis was also conducted across the range from 10 to 100% of the biogas yield obtained in the experiments. The digestate yield from the anaerobic digestion process was estimated as 80% of the volume of the feedstock material (Risén et al., 2013) where the volume reduction is caused by formation of CO₂ and CH₄.

2.3. Energy analysis

This study employs an energy analysis as defined by the International Federation of Institutes for Advanced Study (IFIAS), which is the procedure to calculate the primary energy input to a system for the production of goods and services. Following IFIAS (1978), primary energy was determined from the total direct and indirect energy demand of a given process or system, where direct energy refers to direct energy inputs, such as fuel to power processes, and where indirect energy encompassed all required energy to produce inputs to the processes. In this study, the primary energy input was calculated by coupling each input of the system with a specific primary energy conversion factor identified in literature. For instance, in the Seafarm supply chain, the spore inoculation process requires paper towels. Thus, the energy used to produce that paper (Klugman, 2008) was included in the energy analyses as an indirect energy input. All other energy and material...
inputs of the system were handled in the same manner (Supplementary material C and D).

Following the accounting of all direct and indirect energy inputs to the system, the output side of the balance was determined from the biogas and the biofertiliser products. Anaerobic digestion of wild kelp from the same location as the Seafarm was undertaken in biomethane potential experiments (BMP). The amount of biogas produced and its methane content was measured. The BMP experiments were performed to evaluate the total methane potential of the substrate.

However, while biogas is an energy product in itself, biofertiliser is not and a method was required to allow the embodiment of its energy value in the calculation. As exemplified by Risén et al. (2013) systems expansion was applied instead of allocating energy output between end products, where the biofertiliser energy content was calculated from the indirect energy content of Nitrogen (N) and Phosphorus (P) in artificial fertilizer, following e.g. Berglund and Börjesson (2006); Börjesson and Berglund (2006), and Ahlgren et al. (2012), that would not be used due to its replacement by the digestate (biofertiliser).

Using all the collected input data (see Table 1 and the Supplementary material), the energy performance was evaluated following IFIAS (1978) to shed light on the viability of the KBB supply chain from an energy perspective. Three separate aspects of the energy performance were investigated: the energy return on investment (EROI), reliance on direct fossil fuel inputs, and identification of the most energy intensive processes in the KBB supply chain. EROI was defined by Murphy and Hall (2010) as shown in Eq. (1).

$$\text{EROI} = \frac{\text{Total Energy Output of the System}}{\text{Total Direct and Indirect Energy Input to the System}}$$

EROI studies in the past have yielded conflicting results (Bardi et al., 2011; Mulder and Hagens, 2008) and as a result the EROI standard framework (Atlason and Unnthorsson, 2014; Hall et al., 2014; Mulder and Hagens, 2008; Murphy et al., 2011) is now commonly applied, in line with IFIAS primary energy input standards. Thus, this framework was applied in this study, similarly to Seghezza et al. (2014).

The output from any EROI study is the ratio of all output energy to all primary input energy. Thus, an EROI > 1 means that the system “produces” more energy than it “consumes” (see Eq. (1)). Wider debates have been initiated in the literature regarding the minimum acceptable EROI values for fuels to be considered useful by society at large (Hall et al., 2009). The most commonly accepted EROI is 3, as established by Hall et al. (2009).

### Table 1

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td></td>
<td>Weeks</td>
<td>Indoor cultivation period</td>
</tr>
<tr>
<td>0.00162a</td>
<td>m³/s</td>
<td>Indoor cultivation</td>
<td>Indoor kelp farm</td>
</tr>
<tr>
<td>0.324a</td>
<td></td>
<td>Iwaki MX400 magnetic water pump velocity</td>
<td></td>
</tr>
<tr>
<td>1500₃a</td>
<td></td>
<td>Hailée HAP120 air pump power</td>
<td></td>
</tr>
<tr>
<td>0.004b</td>
<td>kg/m</td>
<td>Polypropylene string for seeding of kelp</td>
<td></td>
</tr>
<tr>
<td>15₄a</td>
<td></td>
<td>m (1 roll of paper towel for rope preparation</td>
<td></td>
</tr>
<tr>
<td>0.3a</td>
<td></td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>0.7₇a</td>
<td>m³/week</td>
<td>Weekly seawater used per tank for juvenile growth</td>
<td></td>
</tr>
<tr>
<td>2₉</td>
<td></td>
<td>Number of tanks used for juvenile growth</td>
<td></td>
</tr>
<tr>
<td>10₄a</td>
<td></td>
<td>Bulbs</td>
<td>Total Osm T12 fluorescents bulbs required</td>
</tr>
<tr>
<td>0.02₇a</td>
<td>MJ/h</td>
<td>1 Osram T12 model LS/60W/640 electrical demand</td>
<td></td>
</tr>
<tr>
<td>50₄</td>
<td>Hours</td>
<td>Total number of hours of artificial lighting</td>
<td></td>
</tr>
<tr>
<td>1.5₅</td>
<td>MJ/h</td>
<td>Electricity needed to keep 10 m³ room at 0 °C</td>
<td></td>
</tr>
<tr>
<td>1/₅</td>
<td></td>
<td>Room</td>
<td>Number of rooms needed for indoor cultivation</td>
</tr>
<tr>
<td>0.00005₆a</td>
<td>ton N/m³</td>
<td>Nutrient requirement per m³ kelp biomass</td>
<td>Outdoor kelp farm</td>
</tr>
<tr>
<td>0.000005₆b</td>
<td>ton P/m³</td>
<td>Nutrient requirement per m³ kelp biomass</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Months</td>
<td>Outdoor cultivation period</td>
<td></td>
</tr>
<tr>
<td>0.015₆</td>
<td>m³/return trip</td>
<td>Gasoline required for a small outboard boat</td>
<td></td>
</tr>
<tr>
<td>0.9₇b</td>
<td>m³/h</td>
<td>Diesel consumption of a small tug boat</td>
<td></td>
</tr>
<tr>
<td>18.5₉</td>
<td>km/h</td>
<td>Maximum speed of tug boat with barge</td>
<td></td>
</tr>
<tr>
<td>10₉</td>
<td>km</td>
<td>Distance between indoor and outdoor ferm</td>
<td></td>
</tr>
<tr>
<td>11.3–13.₈</td>
<td>m³/tote</td>
<td>Density of harvested kelp biomass</td>
<td></td>
</tr>
<tr>
<td>1₄</td>
<td></td>
<td>Density of harvested kelp biomass</td>
<td></td>
</tr>
<tr>
<td>2ₙ</td>
<td>% dry wt</td>
<td>Percentage dry weight of harvested kelp</td>
<td></td>
</tr>
<tr>
<td>5₅</td>
<td>MJ/m³</td>
<td>Electricity demand per m³ wet biomass</td>
<td></td>
</tr>
<tr>
<td>12₃</td>
<td>MJ/m³</td>
<td>Heat demand per m³ wet biomass</td>
<td>Biogas plant</td>
</tr>
<tr>
<td>1.3₃</td>
<td>MJ/m³</td>
<td>Upgrade electricity demand per m³ crude biogas</td>
<td></td>
</tr>
<tr>
<td>21.3</td>
<td>kg N/ton dwt</td>
<td>Approximate amount of Phosphorus in biomass⁴</td>
<td></td>
</tr>
<tr>
<td>7.₉</td>
<td>kg P/ton dwt</td>
<td>Approximate amount of Phosphorus in biomass⁴</td>
<td></td>
</tr>
<tr>
<td>7.₉</td>
<td>³ VS</td>
<td>S volatile solids of Saccharina latissima (wild)</td>
<td></td>
</tr>
<tr>
<td>180₉</td>
<td>³N/m³ CH₄/ton VS</td>
<td>Approx. biogas yield of Saccharina latissima (wild)</td>
<td></td>
</tr>
</tbody>
</table>

Information source:

1Authors operated a 4-week indoor and an 8-month 0.5 ha outdoor kelp cultivation farm.
2Authors measured the biogas experience has shown 35–90% of the total methane potential obtained in BMP experiments to be realistic in full-scale (Carlsson and Schnitzer, 2011). Therefore, a conservative 40% of the measured methane potential 440 NI CH₄/kg VS was used in the calculations.
3PERS. Comm. Francis Kylindustru which specializes in industrial cooling.
4PERS. Comm. Jenkine Marine which specializes and provides coastal workboats and barges.
5PERS. Comm. Joakim Olsson of Chalmers University of Tech. (kelp pretreatment under the SEAFARM project).
6PERS. Comm. Västerbörst Mjö & EnergI AB producing biogas from Swedish fish waste.

Additional information:

10 coils of seeded string and 8 fluorescent bulbs per tank (Flavin et al., 2013; Redmond et al., 2014).
10 °C maintained 10 m² room can hold at least 6 tanks.
Following Flavins medium formulation (Flavin et al., 2013; Redmond et al., 2014).
Biomass yield was between 11.25 and 13.75 kg wet biomass per 1 m polyester longline where 1 m polyester longline requires 1.5 m polypropylene string seeded (0.5 ha cultivation requires 1000 m polyester longlines).
N and P measured by Kjeldahl method and ICP-AES respectively.
2.4. Greenhouse gas emission estimates

For a biofuel to be considered as a viable alternative to fossil fuels in the European Union, certain requirements must be fulfilled amongst which are specific GHG emission saving targets (EC, 2010; Rana et al., 2016). Specifically, the EURED requires GHG emission savings of 60% by January 2018 for new plants, relative to a gasoline fossil reference, $f_{\text{ref}}$, comparator with 83.8 g CO2eq/MJ, following the procedure exemplified by Alberici and Hamelinck (2010). This study included calculations to determine the emission savings of the KBB system, and thus to establish the viability of kelp biogas as an alternative to fossil fuels and to identify the emission intensive parts of the supply chain.

The primary data inputs for the GHG calculations were predominantly supplied by the Seafarm project. The system boundaries extend using the same framework as that used for the energy analysis: to cover material and energy inputs of the supply chain processes, and their embodied emissions, following Alberici and Hamelinck (2010). Emissions of supply chain processes were also included, such as the methane leakage during biogas upgrading. The allocation for bio-fertilizer emission savings were handled in the same way as during the energy analysis: emissions from the production of artificial fertilizers that are not used are subtracted from the total emissions.

EURED proposes two methods for the conversion of GHG emissions into CO2 equivalents: the use of standardized EURED default conversion values; and actual conversion values as provided by literature or measurement (EC, 2010). In this paper, the actual conversion values were applied. For example, the heating requirements for the anaerobic digestion phase were provided by district heating (pers. comm. Västervik AB) and converted to CO2 equivalents using the conversion values (see Supplementary material) from the actual Swedish case (Gode et al., 2011).

With the total emissions accounted for in CO2 equivalents according to the EURED, the emissions savings as specified in Alberici and Hamelinck (2010) were calculated as follows:

$$
GHG_{\text{savings}} = f_{\text{ref}} \times \frac{(\text{Net GHG Emissions in gCO2eq/MJ Energy Output})}{f_{\text{ref}}} 
$$

In addition to the EURED GHG savings, the estimated GHG emissions of the KBB system pinpointed the emission intensive processes in the supply chain, which is also of particular value to future supply chain optimization.

3. Results and discussion

3.1. Systems analysis of the kelp to biogas and fertilizer biorefinery (KBB)

All process data for the Seafarm KBB supply chain (0.5 ha case) was collected from Seafarm partners and industry contacts (see Table 1) and is presented in Fig. 3 using the standard energy systems language (Brown, 2004; Odum, 1972; Odum and Peterson, 1996), where all material inputs are positioned to the left, all energy/fuel inputs are positioned on top, and the output products are to the right. Step A1 involves the sexual reproduction of the kelps and the attachment of the juveniles to plastic seeding lines, comprising preparation of kelp spores and inoculation in a nutrient rich, saline solution. A2 is distinguished as the phase of indoor maturation of juvenile kelps until they reach 1 to a few mm in length. A2 lasts 4 weeks and requires the maintenance of optimal growth conditions through the pumping of air, artificial lighting, cooling, addition of nutrients, and the pumping/filtering of sea water.

Step B1 involves the transport of the juveniles out to sea and their deployment on the cultivation infrastructure; B2 is the adult growth phase, which lasts from the end of autumn until early summer and requires regular monitoring. Step C1 comprises the harvest of the adult kelp using a tugged barge and subsequent transportation back to land (see Table 1 for specific characteristics of the harvested biomass): while C2 involves the unloading of the biomass at a dock. Step D encompasses the energy intensive biogas and fertilizer production: the packaging in plastic (D1), 10 km of transport by truck (D2), cutting (D3) of the biomass, the thermophilic anaerobic digestion (D4), and biogas upgrading (D5), which includes the transport to nearby farms (10 km) and spreading onto a field using agricultural machinery.

As mentioned in Section 2.1, where system processes of the 0.5 ha case were neither realistic nor feasible at a 10 ha scale, or where economy of scale was expected, large scale processes were adapted to suit the larger scale. Table 2 presents a comparison at both scales of the adapted process elements that did not scale up proportionally. All other material or energy inputs to the 10 ha case are multiplied by a factor of 20 from the 0.5 ha case input data. One of the main differences to be observed

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**Fig. 3.** Energy systems diagram of the kelp to biogas and fertilizer biorefinery (KBB) supply chain, where steps A, B, C and D refer to the processes demonstrated in Fig. 2. The horizontal dotted line differentiate the processes conducted on land and at sea. The vertical dotted line differentiate the biogas production processes and the cultivation and harvesting processes.
from Table 2 regards the differences in barges and tugboat fuel consumption: much less energy per kilo of harvested biomass is consumed at the large scale when compared with the smaller 0.5 ha scale.

3.2. Energy analysis and greenhouse gas emissions

3.2.1. Energy return on investment

As can be seen from Table 3 and following a conservative 40% of the laboratory maximum biogas yield (see Section 2.2), the EROI value for the 0.5 ha case is below 1 meaning that more energy is consumed than is produced by the system, while the 10 ha estimates EROI value is above 1 meaning that somewhat less energy is consumed than is produced by the system. An EROI ~1 for the 0.5 ha case is only attainable if at least 60% of the maximum laboratory biogas yield is achieved. Neither the Seafarm case nor the scale up estimates achieved the value of 3 (even at 100% biogas yield) recommended as a benchmark in the “Law of minimum EROI” Hall et al. (2009), however economies of scale seem to be raising the EROI as the system is scaled up.

3.2.2. Greenhouse gas emissions

The estimated CO\textsubscript{2} emissions for both the 0.5 ha and 10 ha systems are presented in Table 3. For the 0.5 ha case, the KBB system performs worse than the EURED gasoline with a mean savings of −25% relative to this reference. However, in the 10 ha estimates, the mean savings are 33% relative to the EURED gasoline, which is a considerable improvement. However, at 33% GHG savings, the 10 ha estimates still do not meet the 60% GHG savings target set in this study, and as required by the EURED for new biofuel plants by January 2018.

3.3. Implications for commercialization

3.3.1. Energy efficiency

Fig. 4a presents the shares of energy input as a percentage of the total for each step (A1-D5) in the KBB supply chain, both for the 0.5 ha case and 10 ha estimates. For the 0.5 ha case (experimental scale, red line in Fig. 4a), the main energy demand is associated with Step B2 (adult growth), followed by C1 (harvest and transport) and A2 (juvenile maturation). However, as revealed by comparing the red (0.5 ha case) and blue (10 ha estimate) curves in Fig. 4a, key differences emerge between the two scales; specifically, these differences occurred in Step B2, monitoring of the adult growth (22% share at 0.5 ha versus 2% share at 10 ha) and Step C1, the mature kelp harvest (19% share at 0.5 ha versus 9% share at 10 ha).

The substantial difference in the shares of total input energy for Step B2 between the scales is due to the fact that while total energy inputs increase significantly with the scale up, this particular process remains almost identical at both scales, with the same number of 20 km return trips (and fuel use) to monitor the kelp farms. The differences in the shares of total input energy for Step C1 result from process adjustments in the scale up of operations: the small harvest vessel of the 0.5 ha case was not suitable to handle the estimated 10 ha biomass yield, thus a larger vessel configuration was required.

As Fig. 4a portrays the percentage energy consumption, the steps that show less economy of scale than e.g., B2 and C1, become more predominant for the larger scale. Thus, for the 10 ha estimate, step D4 (anaerobic digestion) followed by D1 (packaging) and A2 (juvenile maturation) were predicted to be the dominant energy consumers. Hence, our model indicates that overall step D is the most energy intensive at the large scale, and thus further research should aim to improve improvements to step D.

A step with relatively large shares of energy input at both scales is the indoor maturation phase (A2). The relatively high-energy use at both scales is partly due to the need for continuous lighting, cooling, pumping and water filtration, but also that this process takes 4 weeks to nurture the juveniles. This highlights the need to explore energy reduction strategies in A2. As also suggested by Philippson et al. (2014), a reduction in energy investments of the aforementioned processes, for instance by using LED lights or efficient water coolers, could lead to improvements in the EROI.

Our results suggest that spore preparation and inoculation (A1), transport and deployment to longlines (B1), unloading at dock (C2), transport by truck (D2), cutting of algae (D3), and biogas upgrading (D5) are marginal (below 5%) energy consumers at both scales.

3.3.2. GHG emissions efficiency

Fig. 4b visualizes the relative GHG emissions of each step (A1-D5) of the KBB supply chain as a percentage, both for the 0.5 ha case (red curve) and 10 ha estimate (blue curve). The thermophilic anaerobic digestion step (D4) is by far the most intensive in terms of emissions at both scales. This is a result of the large volumes of biomass being heated for anaerobic digestion by district heating, which on average in Sweden is produced from approximately 61% non-renewable sources, including coal, oil, natural gas, wood and peat, amongst others (Gode et al., 2011). Less carbon rich sources for the district heating, the use of low-carbon electricity to heat the biomass, or heat recirculation following e.g.,
Risén et al. (2013) could reduce the emissions of D4 and therefore have a positive impact on the overall emissions.

Another pattern with important implications for commercialisation is the packaging step (D1), which shows a substantial increase in its share of emissions, from 5% at 0.5 ha to 14% at 10 ha. Coupled with a similar increase in energy demand with the scale-up, this relative increase in emissions in packaging highlights the need to use lower emission and energy demand alternatives, particularly at larger scales.

Similarly to in Fig. 4a, key differences emerge between the two systems in Fig. 4b in the steps that occur at sea, specifically B2 and C1, also due to differences in harvesting vessel configurations and the similarity of the monitoring processes at both scales. Finally, Fig. 4b also highlights the marginal relative emissions (below 5%) of a majority of the steps - A1, B1, C2, D2, D3, and D5 in the 0.5 ha case and A1, B1, B2, C2, D2 and D5 in the 10 ha estimates - which are dwarfed by the anaerobic digestion (D4) at both scales. However, perhaps the most important implication for commercialisation is that both “per kg of harvested biomass” and “per Nm³ of biogas”, upscaling from a 0.5 ha to a 10 ha cultivation halves both the energy demand and GHG emissions of the KBB supply chain (Table 4).

In other words, a KBB supply chain capable of handling more biomass to produce more product (scaled up) will potentially have lower emissions and energy demand, per product unit, than a smaller KBB supply chain. This finding supports the notion that upscaling operations pushes the system in the direction of commercial viability, as defined by EROI and the EURED GHG savings requirements for biofuels.

The results presented up to here were based on a conservative estimate of 40% biogas yield at full scale digestion as compared to small scale laboratory experiments (see Section 2.2). Alternatively considering an optimistic biogas yield value of 90% (Fig. 5a and b), rather than 40%, resulted in an EROI of c.a. 1.5 for the 0.5 ha and c.a. 2.7 for the 10 ha, and CO2 emissions reduction potentials of c.a. 38% for the 0.5 ha and c.a. 66% for the 10 ha. These results are not only an indication of the high sensitivity of the model output to uncertainties in this particular input number, but also an indication of the potential for a 10 ha cultivation feeding into a KBB supply chain to be commercially viable, both in terms of EROI and in terms of EURED regulations, given an effective biogas production process. This highlights the need for large scale digestion and co-digestion studies with seaweed biomass, to more accurately discern just how much biogas can be produced.

3.4. Comparison to literature values

Energy analysis using EROI as an indicator can provide a holistic impression of viability (Hall et al., 2009) but only a few studies of this nature have been conducted for marine bioenergy production systems. As discussed by Risén et al. (2013), comparison between similar studies remain difficult due to differences in system design, boundaries and methodological approaches; See Table 5 which presents these differences relative to this work.

Particular strengths of the present study relative to other studies in Table 5 are that the majority of input data comes directly from the Seafarm project, that the scaled up supply chain is modelled directly from case data, and that the selected methodologies align with official standards and regulations in Sweden. While the use of case data for Sweden provides quality inputs for the calculations, it also reduces the relevance of the results for other locations: for instance, the Swedish energy mix is different to that in Scotland or in France, and so replicating this study using case data from different locations may substantially affect results.

4. Conclusions

This study represents the first assessment of commercial viability, in terms of energy return on investment and emissions savings potential, of a kelp to biogas and fertilizer biorefinery supply chain located on
the Swedish West Coast. Commercial viability was defined as reaching an energy return on investment value of 3 (Hall et al., 2009) and achieving the GHG savings potential required under the European Union Renewable Energies Directive (EC, 2010), or EURED. Two scales of operation were considered: the existing 0.5 ha Seafarm project longline cultivation of S. latissima and a set of estimates for a 10 ha scale-up, to shed light on economies of scale and to identify specific processes in need of further development.

Using a conservative estimate for the biogas yield (40% of experimental yield), neither the 0.5 ha case nor the 10 ha estimates reached the target minimum EROI of 3. The EROI value for the 0.5 ha case was below 1, meaning that more energy was consumed than produced by the system, while the 10 ha estimate EROI value was slightly above 1, meaning that only a little less energy was consumed than produced by the system. An optimistic biogas yield (90% of experimental yield) however, at 10 ha revealed an EROI of 2.6 and GHG savings potential above the 60% target. Analysis of the scale up identified processes in need of improvements, such as anaerobic digestion and potential for economies of scale, such as in the at sea processes, both worthy of further investigation.

In terms of GHG emissions savings potential, both the 0.5 ha case and 10 ha estimates fell short of the 80% savings target set by the EURED (EC, 2010) under the conservative estimate of biogas yield. While the 0.5 ha case performed worse than the EURED fossil reference, the 10 ha estimate performed 30% better. Analysis of the scale up also indicated clear improvements and potential for economies of scale worthy of further investigation; based on this model, a 10 ha cultivation of kelp for a biogas and fertilizer biorefinery would approached the emissions savings targets defined in the EURED under beneficial biogas production (digestion/co-digestion) conditions.

Finally, regarding commercialisation, the results of this study confirm that upscaling of operations shifts the kelp to biogas and fertilizer biorefinery system in the direction of viability, as defined by EROI and the EURED GHG savings requirements for biofuels. Specifically, scale up of the system from 0.5 ha to 10 ha cultivation configurations lead to a halving of net energy requirements and GHG emissions.

Acknowledgements

The authors acknowledge data contributions from academic partners of Seafarm, including Assoc. Prof. Eva Albers and Joakim Olsson at Chalmers University of Technology, Sweden, for their assessment of biomass quality and pre-treatment. Industrial data contributions from Jenkins Marine Ltd. (data on coastal tugboats and barges), Franck’s Kylindustri AB (data on cooling during indoor cultivation stages), and

Table 5

<table>
<thead>
<tr>
<th>Type of analysis</th>
<th>Location</th>
<th>Biomass Source</th>
<th>Biomass type</th>
<th>Energy product</th>
<th>Co-products</th>
<th>EROI target</th>
<th>EROI result</th>
<th>EURED GHG savings</th>
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</thead>
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<tr>
<td>Energy, ghg savings,</td>
<td>Swedish west coast</td>
<td>Cultivated</td>
<td>S. latissima</td>
<td>Upgraded fuel</td>
<td>Fertilizer</td>
<td>3°</td>
<td>0.76</td>
<td>20%</td>
</tr>
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<td>scale-up model</td>
<td>(Skagerrak)</td>
<td></td>
<td></td>
<td>(from biogas)</td>
<td></td>
<td></td>
<td>1.48</td>
<td>37%</td>
</tr>
<tr>
<td>Energy, GHG savings,</td>
<td>Swedish east coast</td>
<td>Wild°</td>
<td>Red</td>
<td>Heat and upgraded</td>
<td>Fertilizer</td>
<td>1°</td>
<td>3.1°</td>
<td>80%</td>
</tr>
<tr>
<td>NAP recovery</td>
<td>(Baltic Sea)</td>
<td></td>
<td>algae</td>
<td>fuel (from biogas)</td>
<td></td>
<td></td>
<td>2.7–3.8°F</td>
<td></td>
</tr>
<tr>
<td>Energy, energy, scenario</td>
<td>Swedish south coast</td>
<td>Wild°</td>
<td>Red</td>
<td>Heat and electricity</td>
<td>–</td>
<td>1°</td>
<td>0.4°F</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Baltic Sea)</td>
<td></td>
<td>algae</td>
<td>or upgraded fuel</td>
<td>(from biogas)</td>
<td></td>
<td>0.98°F</td>
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<td></td>
<td>Fuel (from bioethanol)</td>
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<td>1°</td>
<td>1.7°F</td>
<td></td>
</tr>
<tr>
<td>model</td>
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<td></td>
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<tr>
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<td>Danish Koge Bay</td>
<td>Cultivated</td>
<td>P. australis</td>
<td>Heat and electricity</td>
<td>–</td>
<td>3°</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>(Baltic Sea)</td>
<td></td>
<td></td>
<td>(from biogas)</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>Chilean coast</td>
<td>Cultivated</td>
<td>M. pyrifera</td>
<td>Fertilizer</td>
<td>Animal feed</td>
<td>1°</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>cost analysis°</td>
<td>(Pacific)</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>Canadian coast</td>
<td>Cultivated</td>
<td>E. sp.</td>
<td>Heat and electricity</td>
<td>–</td>
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</tr>
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<td>(from biogas)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brown algae</td>
<td>Cultivated</td>
<td></td>
<td>Fuel (from bioethanol)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Brown algae</td>
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<td></td>
<td></td>
<td></td>
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<td>–</td>
</tr>
<tr>
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<td>M. pyrifera</td>
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<td></td>
<td></td>
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<td>–</td>
</tr>
<tr>
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<td>Saccharina latissima</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>–</td>
</tr>
</tbody>
</table>

* These studies do not consider cultivation. Therefore, scales are not comparable with this study.
*° Other previous LCA studies (e.g. Langlois et al., 2012) have not been considered due to the lack of clarity in either the case study description or energy analysis standards employed.
° EROI method used following Murphy and Hall (2010).
°° EROI method used but no referenced standard provided.
°°° Scenario and product dependent (Risén et al., 2014).


Garpe, K., 2008. Ecosystem Services Provided by the Baltic Sea and Skagerrak. Natuurbesvarket (Swedish Environmental Protection Agency), Bromma, Sweden.


Hall, C.A, Boleigh, S., Murphy, D.J., 2000. What is the minimum EROI that a sustainable society must have? Energy 2, 25–47.


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REPORT

The perception of aquaculture on the Swedish West Coast

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Received: 10 March 2017 / Revised: 10 June 2017 / Accepted: 11 September 2017

Abstract Efforts are on the way on the Swedish West Coast to develop the capacity for cultivation of marine resources, notably of kelps. Given that this is a region of great natural and national heritage, public opposition to marine developments has been identified as a possible risk factor. This survey thus sought to shed light on awareness levels, perceptions of different types of aquaculture and on reactions to a scenario depicting future aquaculture developments on the West Coast. When asked about their general opinions of aquaculture, respondents tended to be favourable though a majority chose neutral responses. On the whole, respondents were favourable to the depicted scenario. Finally, it was found that the high-awareness group tended to be more supportive than the low or medium-awareness groups, hinting at the benefits of increasing awareness to reduce public aversion and to support a sustainable development of aquaculture on the Swedish West Coast.

Keywords Aquaculture · Bioeconomy · Blue growth · Macroalgae · Perception survey · Social acceptability

INTRODUCTION

There is a rising tide of interest in the cultivation of seaweed biomass in Europe. Cultivated seaweed provide distinguished advantages over other cultivated biomasses: they require little or no arable land, fertilisers or fresh water (Subhadra and Edwards 2010; John et al. 2011; Wei et al. 2013) while providing a variety of other ecosystem services, including nutrient bioremediation (Chung et al. 2002) and possibly habitat bioremediation (Phillips 1990). Seaweed biomass shows promising potential as a material in the production of biofuels, fertiliser, materials, chemicals, feed and food (Jung et al. 2013; van Hal et al. 2014; Chapman et al. 2015; Peetsiri et al. 2016; Tayyab et al. 2016; Molina-Alcaide et al. 2017). Coupled with a significant projected growth in the fisheries sector to meet a growing demand for protein (OECD/FAO 2015) and calls for the development of marine biomass within the blue growth initiative to support more sustainable bio-based economies (EU Commission 2012), the coming decades are likely to see significant increases in the development of off- and near-shore production systems, not just of seaweed, but also of fish, crustaceans and molluscs. Efforts are thus being directed to nurture a sustainable, low-impact and socially beneficial aquaculture industry (World Bank 2006; Gibbs 2009; Krause et al. 2015).

As detailed in Culver and Castle (2008) in numerous contributing case studies from Canada, coastal transformations such as the development of aquaculture in the wake of declining of fisheries can have significant implications for affected communities. Perceptions of aquaculture in Canada have been influenced by clashes with community values and further complicated by unpredictable aversion to innovation (Culver and Castle 2008). Given that studies have shown that perception of aquaculture seems to be linked to perceived environmental impacts (Katranidis et al. 2003; Whitmarsh and Wattage 2006), public perception of and potential opposition to aquaculture have been identified as an area of particular concern (Gibbs 2009; Schlag 2010; FAO 2015). However, on the whole, only a handful of studies have been conducted that look into perceptions of aquaculture among stakeholder groups, notably in New England (Robertson...
et al. 2002), Canada (Culver and Castle 2008; Barrington et al. 2010), Australia (Mazur and Curtis 2008), Spain (Bacher et al. 2014), Scotland (Whitmarsh and Palmieri 2009), Greece (Katranidis et al. 2003), a comparison between Germany and Israel (Freeman et al. 2012) and most recently two international (European) studies of stakeholder perceptions and acceptability of integrated multi-trophic aquaculture (Alexander et al. 2016a, b). Amongst these studies, a multitude of factors affecting perceptions are identified, ranging from awareness and knowledge levels, to credibility of information sources and environmental risks. Few of the studies, however, consider different types of aquaculture, and most assume the use of the generic term ‘aquaculture’ as pertaining exclusively to the culture of fish (with the exception of the last two mentioned above).

Significant differences in environmental performance between fed (e.g. finfish) and non-fed (e.g. seaweed and mollusc) aquacultures, resulting from different trophic positions of cultured species, have led to the assumption that there may be greater social acceptance of the latter, e.g. in Costa-Pierce (2010), though to the authors’ knowledge no studies have been conducted to validate this. There is also a lack of studies conducted on the perceptions of fed and non-fed aquacultures, and, most critically, on their perceived differences and associated concerns. The aim of this study is therefore to provide a baseline of current knowledge levels and awareness relating to aquaculture practices amongst residents of the Swedish West Coast, as a point of reference for future studies as aquaculture practices emerge and diversify on the West Coast. The study also aims to shed light on perceived differences between types of aquaculture likely to be developed in Sweden (fish, mollusc and seaweed) and their associated impacts, and to assess reactions to development scenarios of seaweed cultivation in view of identifying socio-oriented opportunities and risks.

**MATERIALS AND METHODS**

A web-panel survey was conducted in 2015 with help of the fieldwork agency, Norstat. Members of the Norstat Panel with registered addresses in the study area (see Fig. 1) were randomly selected and offered financial compensation, SEK 40 (US $5), to respond to the online questionnaire. The survey was distributed in Swedish and translated to English for analysis. The questionnaire was designed in four parts, featuring questions requiring answers from a five point Likert scale including a middle/neutral option (e.g. very bad, bad, neutral, good, very good) or polar questions including a neutral option (e.g. yes, no, or don’t know). Some questions additionally offered discretionary comment sections. The first part of the survey aimed to provide ancillary information about respondents for subsequent use in statistical cross-referencing and analysis of patterns revealed by the main body of the survey. Their selection was based on authors’ knowledge of particularities of the region—location factors being considered important in studies of social acceptability (Freeman et al. 2012)—that may affect, or help to explain, specific attitudes toward aquaculture (e.g. the dichotomy between permanent residents and secondary holiday home owners, high levels of boat ownership, distance of property from the coast).

The second part of the questionnaire was the most extensive and sought to shed light on three key areas: (a) to assess aquaculture-related awareness levels and opinions toward aquaculture, including of different types of aquaculture and the differences between them; (b) to determine perceptions of five key aquaculture issues revolving around aesthetics and pollution; and (c) to gauge preliminary support for, or opposition to, the development of aquaculture on the West Coast.

The third part of the questionnaire presented some background information about the EU call for blue growth, coupled with a specific scenario for 2030 depicting the development of seaweed aquaculture on the West Coast and anticipated, associated changes, in an effort to determine reactions to this plausible future. A copy of the
survey as seen by respondents is provided in the supplementary material S1. In light of the background information and the development scenario, respondents’ reactions were gauged and once again, they were asked about their support for or opposition to the development of aquaculture on the West Coast. The fourth and final part of the questionnaire covered basic information such as gender, age, education and income to the extent to which the sample could be considered representative of residents of the West Coast.

To explore the effect of knowledge levels and awareness on perceptions toward aquaculture, respondents were sorted into low, medium and high-awareness groups defined according to responses to a statement and a closed question (see Table 1). “No” responses for the statement placed respondents in the low-awareness group, “yes” responses to both questions placed respondents in the high-awareness group, and those who responded “yes” to the statement then “no” or “don’t know” to the question were placed in the medium-awareness group.

For statistical analysis of the results, an ordered probability model was used to test the relationship between perception (revealed via the Likert scale response variable) and a number of explanatory variables. The explanatory variables were selected to cover demographic and geographical variables, as suggested by Alexander et al. (2016b), as well as some additional factors the authors anticipated may have an effect based on their knowledge of the particularities of the region. These were as follows: distance between home address and coastline, visibility of the sea from respondents’ houses, the respondents’ aquaculture awareness, whether respondents go out to sea by boat, residence type (holiday house owner/permanent residence), awareness of a cultivation site near respondents’ homes, gender, education, age, income and the region that respondent lives in (or has a holiday house).

Table 1 Grouping of respondents by awareness levels according to answers to a question and a statement

<table>
<thead>
<tr>
<th>Level of awareness</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statement: “aquaculture may mean the cultivation of aquatic animals and/or plants. It depends”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Question: “are you aware of any differences in the farming of aquatic plants (seaweed), mollusks (mussels) and animals (fish), from an environmental point of view?”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of respondents</td>
<td>255</td>
<td>357</td>
<td>83</td>
</tr>
<tr>
<td>Percentage of sample</td>
<td>36.7</td>
<td>51.4</td>
<td>11.9</td>
</tr>
</tbody>
</table>
applying an ordered probability model, compared to the logit model in Alexander et al. (2016b) is that the former accounts for the natural order of the alternatives on the Likert scale in the estimation of the probabilities (see, e.g. Greene and Hensher 2010). The ordered probability model was built around the regression

\[ y_i^* = \beta x_i + e_i, \quad i = 1, \ldots, m, \]

where \( y_i^* \) is individual \( i \)'s stated option on the five point Likert scale (e.g. one of the alternatives very bad, bad, neutral, good, very good); the vector \( x_i \) is a set of explanatory variables; \( \beta \) is a vector of parameters to be estimated, and \( e_i \) is the residual. For an overview of estimation and interpretation of ordered logit models, see, e.g. Greene and Hensher (2010), or Wooldridge (2010).

In the analysis, the 11 municipalities in Fig. 1 have been grouped into six different regions: (1) northern municipalities (Strömstad, Tanum, Sotenäs, Lysekil and Uddevalla), (2) islands (Orust, Tjörn and Öckerö), (3) middle municipalities (Stenungsund and Kungälv), (4) central Gothenburg, (5) areas north and south of central Gothenburg, (6) the most southern part of Gothenburg. Descriptive statistics for the explanatory variables are presented in Table 2.

### RESULTS

#### Effects of awareness on perceptions of aquaculture

The results from the awareness sorting show that approximately a ninth of respondents qualified in the high-awareness group, half in the medium-awareness group and the remaining third in the low-awareness group.

Overall analysis of results from all questions in the survey revealed some interesting awareness-related patterns that were consistently repeated throughout the survey (e.g. see Fig. 2). The low and medium-awareness groups showed similar responses, dominated by neutral responses on the five graded Likert scale, with neutral as the middle alternative. Higher proportions of neutral responses in the low- and medium-awareness groups confirm the notion that respondents in those groups were less informed on (or do not care about) aquaculture issues. The high-awareness group, while showing fewer neutral responses, tended to represent the same views as the low- and medium-awareness groups. General attitudes toward aquaculture were found not to significantly vary with awareness in this study; however, increased awareness did tend to lead to more

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coefficients</th>
<th>Standard errors</th>
<th>P-values</th>
<th>Mean of the explanatory variable</th>
</tr>
</thead>
<tbody>
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<td>Constant</td>
<td>5.16</td>
<td>0.55</td>
<td>0.00</td>
<td></td>
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<tr>
<td>Distance home address and coastline</td>
<td>-0.04</td>
<td>0.07</td>
<td>0.48</td>
<td>2.82</td>
</tr>
<tr>
<td>Sea visible from home</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>-0.06</td>
<td>0.22</td>
<td>0.80</td>
<td>0.24</td>
</tr>
<tr>
<td>No</td>
<td>0</td>
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<tr>
<td>Awareness</td>
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<tr>
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<td></td>
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<tr>
<td>Go out to sea by boat</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Yes</td>
<td>0.47</td>
<td>0.19</td>
<td>0.01</td>
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</tr>
<tr>
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<td>0.52</td>
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<td>0.01</td>
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</tr>
<tr>
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<td>0.88</td>
<td></td>
<td></td>
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<tr>
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<td>Education</td>
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</tr>
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<td>Elementary school or high school &lt;3 years</td>
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<td>0.22</td>
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<tr>
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<td>Higher education &lt;3 years</td>
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</tr>
<tr>
<td>Higher education ≥3 years</td>
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<td>0.24</td>
<td>0.17</td>
<td>0.28</td>
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<tr>
<td>Region</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Islands (Orust, Tjörn and Öckerö)</td>
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<td>0.22</td>
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</tr>
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<td>0.32</td>
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<tr>
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<td>0.49</td>
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</tr>
<tr>
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<tr>
<td>Middle municipalities</td>
<td>0</td>
<td>0.19</td>
<td></td>
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</tr>
</tbody>
</table>

1 The region where the respondents have the most positive attitudes for aquaculture will be treated as the reference region in the ordered logit model, to facilitate the interpretation of the results.
pronounced opinions. A more thorough analysis of the respondents’ opinions is given in the next section.

Perceptions of aquaculture

The focus of the survey was revealed to the respondents by the first question of part two, whereupon they were asked “how would you rate your general opinion toward aquaculture?” The results from this question are presented in Fig. 2 and sorted by awareness level. By selecting the neutral option, a majority of respondents demonstrated an initial tendency to be indifferent toward aquaculture and/or uninformed about aquaculture, but crucially, the rest of the respondents also tended to be favourable toward aquaculture rather than be opposed to it. In terms of awareness levels, the medium- and low-awareness groups showed almost identical results, with approximately 60% neutral/mid-scale responses and 40% rating their general opinions of aquaculture as either good or very good. This is in contrast to the opinions of respondents of the high-awareness group, a much smaller proportion of which selected neutral responses, and 25% and 35% of which selected ‘very good’ and ‘good’ ratings, respectfully. Also, a small number (less than 7%) of the high-awareness group selected the ‘bad’ and ‘very bad’ opinion responses.

The regression result for this question is presented in Table 2. In the ordered probit model, the dependent variable had the following distribution: very bad (n = 3), bad (n = 21), neutral (n = 391), good (n = 204), and very good (n = 76).

As seen from the table, most parameter estimates were statistically significant. The exceptions were as follows: distance between home address and coast line; whether the sea is visible from the respondents’ home (house/holiday house); and income.

According to the results in Table 2, individuals with high aquaculture awareness had a significantly more positive opinion toward aquaculture than individuals with a low level of awareness. The same result was found for individuals that had a cultivation site near their home, and individuals that go out to sea by boat. The sign of the point estimate must, however, be interpreted with caution, since it does not tell us how all cell probabilities (the probabilities that the individual’s state a specific alternative on the Likert scale) will be affected by a change in the explanatory variable. It is only for the first and last alternatives on the Likert scale (very bad and very good) that we can be sure about the sign of the change in the cell probability.

Table 3 reveals that the sign change in cell probabilities occurs between cells 2 and 3 (between neutral and good) for the explanatory variables in the model. Thus, a positive point estimate increases the probability of having a good or very good opinion toward aquaculture, whereas a negative point estimate increases the probability of having a very bad, bad or neutral opinion. However, as seen from Table 3, a negative point estimate mainly affects the probability of having a neutral opinion, whereas the marginal effect on the two lowest cells (very bad and bad) is much smaller.

The largest marginal effects were found for groups of individuals with a high aquaculture awareness and for

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coefficients</th>
<th>Standard errors</th>
<th>P-values</th>
<th>Mean of the explanatory variable</th>
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<td>0.05</td>
<td>0.00</td>
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<tr>
<td>Income</td>
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<tr>
<td>One</td>
<td>2.11</td>
<td>0.21</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Two</td>
<td>6.06</td>
<td>0.15</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Three</td>
<td>7.93</td>
<td>0.17</td>
<td>0.00</td>
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<tr>
<td>Number of observations</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

* Age is divided by 10. Northern municipalities (Strömstad, Tanum, Sotenäs, Lysekil and Uddevalla), middle municipalities (Stenungsund and Kungsåv)

Fig. 2 General opinions of aquaculture sorted by level of awareness

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### Table 3 Marginal effects (in percentage units) on the probability that the respondent state a specific alternative on the Likert scale (very bad to very good), due to a change in the explanatory variable by one unit

<table>
<thead>
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<th>Variables</th>
<th>Cells</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Very bad</td>
</tr>
<tr>
<td>Distance home address and coastline</td>
<td>0.02</td>
</tr>
<tr>
<td>Sea visible from home</td>
<td>0.02</td>
</tr>
<tr>
<td>High-awareness(^a)</td>
<td>-0.17</td>
</tr>
<tr>
<td>Medium-awareness(^b)</td>
<td>-0.05</td>
</tr>
<tr>
<td>Go out to sea by boat(^c)</td>
<td>-0.15</td>
</tr>
<tr>
<td>Holiday house owner(^d)</td>
<td>0.37</td>
</tr>
<tr>
<td>Cultivation sites near home(^e)</td>
<td>-0.16</td>
</tr>
<tr>
<td>Female(^f)</td>
<td>0.12</td>
</tr>
<tr>
<td>High school (\geq 3) years</td>
<td>0.03</td>
</tr>
<tr>
<td>Higher education (&lt;3) years</td>
<td>-0.16</td>
</tr>
<tr>
<td>Higher education (\geq 3) years</td>
<td>-0.11</td>
</tr>
<tr>
<td>Islands (Orust, Tjörn and Öckerö)</td>
<td>0.12</td>
</tr>
<tr>
<td>Areas north and south of central Gothenburg(^g)</td>
<td>0.40</td>
</tr>
<tr>
<td>The most southern part of Gothenburg(^h)</td>
<td>0.40</td>
</tr>
<tr>
<td>Central Gothenburg(^i)</td>
<td>0.22</td>
</tr>
<tr>
<td>Northern municipalities(^j)</td>
<td>0.22</td>
</tr>
<tr>
<td>Age(^k)</td>
<td>-0.06</td>
</tr>
<tr>
<td>Income</td>
<td>0.02</td>
</tr>
</tbody>
</table>

1.0 Denotes a change in the probability of one percentage point
\(^a\) The marginal effect represents a change in age with 10 years

holiday house owners. Compared to permanent residents, holiday house owners have 11 percentage units lower probability for having positive opinions, and 13 percentage units higher probability for having a neutral opinion toward aquaculture.

Concerning the regional variable, individuals living in the reference region (the middle municipalities: Stenungsund and Kungälvs) have the most positive opinion toward aquaculture. People living in the northern municipalities, central Gothenburg and in areas north and south of central Gothenburg have a significantly lower probability of stating a good or very good opinion towards aquaculture, compared to groups of individuals living in the reference region. The probability for stating a good opinion is about 9 percentage units lower. Individuals living in the northern municipalities, central Gothenburg and in areas north and south of central Gothenburg, have instead a more neutral opinion towards aquaculture. These findings may be another example of the importance of location, specifically rural and urban locations, in the variability of perceptions toward aquaculture as identified by Katranidis et al. (2003).

There is no significant difference in the opinions toward aquaculture for groups of individuals living on the islands (Orust, Tjörn and Öckerö) and groups of individuals living in the reference region (Stenungsund and Kungälvs). These islands are also located close to the reference region.

The results also suggested that there is a significant difference between women and men in their general opinion toward aquaculture, where men are more positive than women. Older people also had a more positive opinion toward aquaculture compared to younger people. The marginal effects for the gender and age variables are smaller than for other statistically significant variables.

### Perceptions of different types of aquaculture

Following this initial exposure to aquaculture, respondents were asked “Are you aware of any differences in the farming of aquatic plants (seaweed), molluscs (mussels) and animals (fish), from an environmental point of view?”. 17% of respondents answered that they were aware of differences between different types of aquaculture, while 83% were not aware of any differences. Those unaware of differences were provided with six statements about generic aquaculture only, whereas those aware of differences were provided with the same six statements but separately for each seaweed, mollusc and fish aquaculture. The responses to these six statements—for each generic aquaculture, fish aquaculture, seaweed aquaculture and mollusc aquaculture—are presented in Fig. 3.

A series of key results should be highlighted from Fig. 3. First, the “neither” agree nor disagree option is on average the most prevalent across all statements. Notably, it is systematically larger in the responses for generic aquaculture (always above 59% of respondents, excepting Statement 6), compared to those for fish, mollusc and plant aquaculture. This could be a sign that, as a whole, respondents are not sufficiently acquainted with aquaculture issues to have well-formed opinions. Second, when comparing aquaculture types, responses reflected that mollusc and plant aquaculture are perceived as being quite similar to one another, but quite different from fish aquaculture. This is with the exception of Statements 2 and 4, regarding the visual aesthetics and potential for bad smells, respectively, for which all aquaculture types performed similarly with large neutral fractions and balanced opinions across the sample. Fish aquaculture was perceived as having much more potential to have negative impacts on other local species and to leak chemicals into the environment (e.g. feed), when compared to mollusc, plant and...
Statement #1: "... can have negative impacts on other local species"

Statement #2: "... is visually appealing"

Statement #3: "... can leak chemicals into the environment"

Statement #4: "... can cause bad smells nearby"

Statement #5: "... can improve water quality nearby"

Statement #6: "Overall I am supportive of .... on the West Coast"

Fig. 3 Reactions to six statements regarding fish, mollusc, plant and generic aquaculture
generic aquaculture. For Statement 5, 46% of respondents disagreed with the statement that fish aquaculture could improve water quality, however 51 and 62% of respondents agreed that mollusc and plant aquaculture (respectively) could improve water quality.

In spite of the various concerns emphasised by responses to the previous statements, Statement 6 revealed a significant inclination for respondents to be supportive of all of the aquaculture types on the West Coast. A slight preference for mollusc and seaweed was also clear, while fish aquaculture showed the most opposition of the four options, and generic aquaculture saw more neutral responses than the other types. Finally, it should be noted that the responses regarding generic aquaculture were quite similar to those for mollusc and plant aquaculture on the whole.

Aquaculture development scenarios on the West Coast

The third part of the questionnaire began by presenting some background information, introducing respondents to the EU bioeconomy strategy and the need for renewable biological resources, notably marine ones, to secure sustainable economic growth. Thereafter, a scenario was presented depicting a future for the Swedish West Coast, whereby in 2030 there would be seaweed aquaculture sites spread along the coast, covering a total area of approximately 10 km², both providing some ecosystem services and biomass for biorefineries and thus employment opportunities and incomes for the region, but also having some unknown environmental impacts on the sea bed. See supplementary information S1 for a copy of the survey as seen by respondents.

A large majority of respondents were favourable toward the depicted scenario: 14 and 48% of respondents were very positive and positive, respectively, while 6% selected the negative option and only one respondent (out of 695) chose the very negative option. Respondents were, however, of mixed opinions when asked about their scepticism of the economic and environmental claims portrayed in the scenario, with notable variation across the awareness groups. Approximately 30% of each awareness group confirmed they were sceptical about the claims. However, there is a shift from mostly neutral responses in the low and medium-awareness groups to a tendency for the high-awareness group to trust the scenario claims: while the low and medium-awareness groups had between 40 and 50% selecting the neutral responses, almost 50% of the high-awareness group disagreed or strongly disagreed with the statement that they were sceptical of the portrayed claims.

To further explore reactions to the scenario, respondents were asked whether they agreed or disagreed (also on a five point Likert scale, with a neutral option) to six statements representative of key areas of concern. The results are presented in Fig. 4. Overall responses were more or less evenly distributed for each statement, with approximately equal numbers agreeing and disagreeing to each statement and with large portions selecting the neutral options. Once again this may be a sign that residents of the West Coast are not sufficiently informed about aquaculture issues to have well-formed and consistent opinions. However, the fifth statement was found to be the exception: 22% of respondents strongly agree and 50% agree with the statement that “the West Coast could benefit from new economic opportunities”.

Ordered logit models with the same set of explanatory variables as in Eq. (1) has also been estimated for the six statements in Fig. 4. Most point estimates in these regressions where insignificant, with the exception of the gender and age variables that turned out to be statistical significant at a 5% significance level ($P$ value $<0.05$). The point estimate for the gender variable was negative, which suggests that female respondents were more concerned than males across the six concern statements of Fig. 4. The point estimate for the age variable was positive, which indicates that older individuals were less concerned than younger individuals across the six statements.

The final question of part three of the survey, relating to the scenario description, asked respondents: “Would you say that you would be supportive of such blue-growth developments?” with only yes and no as answer options. On average, four out of five respondents (78%) expressed that yes, they were supportive of such blue growth initiatives, with the high-awareness group showing an even stronger majority (89%). These results suggest that West Coast residents, on the whole, may have some scepticism toward the benefit claims and lingering concerns regarding the potential impacts of seaweed aquaculture, but nevertheless, a consistent majority are supportive of its development.

DISCUSSION AND CONCLUSION

Awareness

Throughout the survey, opinions of the high-awareness group were found to be marginally stronger due to that group being less prone to select neutral responses. This seems an indication that opinions of these respondents are

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2 Whereas the five other statements covering key areas of concern all specifically refer to aquaculture, it should be noted that this statement does not. However, given that the other statements are in reference to aquaculture, it is assumed that respondents frame the context of this statement accordingly.
more developed than those of the lower awareness groups, which also acts as a validation of the efficacy of awareness categorisation applied in this study. Furthermore, given the relatively more favourable perceptions toward aquaculture expressed by the high-awareness group, it may also indicate that increased education and regular communication with stakeholders of aquaculture (defined in the broadest of terms) could improve the acceptability of aquaculture. This resonates within literature where similar studies have supported that effective communication and increasing education about aquaculture can improve its social acceptability (Kaiser and Stead 2002; Robertson et al. 2002; Barrington et al. 2010).

The large fraction of consistently neutral responses that represent individuals who may be uninformed and/or indifferent toward aquaculture is also consistent with other aquaculture perception studies, such as the pan-European perceptions study by Alexander et al. (2016b) and that conducted by Barrington et al. (2010) in Canada. Social aversion to innovation is notoriously unpredictable, though as raised by Culver and Castle (2008), it is thought that it can be particularly strong when the beneficiaries of this innovation are not aware of, or do not need, said benefits. In the case of this study however, it would seem that the benefits, particularly the regeneration of the West Coast through economic opportunities and environmental improvements, are desirable for now and thus may be generating part of the support evident in the results in spite of the large neutral fraction. Increasing and maintaining awareness on the benefits of sustainable aquaculture practices—coupled with vigilant monitoring of aquaculture’s social impacts and its perceived value—will be essential for a healthy relationship between aquaculture on the West Coast and the people who live there.

**Types of aquaculture and impacts**

The perceived differences between fish, plant and mollusc aquaculture by the high-awareness group, with the added comparison to perceptions of generic aquaculture of the medium and low-awareness groups, are some of the key highlights revealed in this study. In ecological terms, plants, molluscs and fish belong to different levels of the classic trophic pyramid, each characterised by different relationships with their shared ecosystem, notably in terms of the flows of energy and nutrients through the food chain. Increasing the population of a species from one trophic level, for instance by conducting finfish aquaculture, can change a local ecosystem. This study identified that respondents who were aware of different types of aquaculture also showed a tendency to be aware of associated impacts. The perceptions of fish aquaculture are clearly contrasting to those of seaweed and mollusc aquaculture, as seen in Statements 1 and 5 from Fig. 3, respectively concerned with impacts on other local species and the improvement of water quality (i.e., classic environmental impact and ecosystem service). Whereas the trend for seaweed and mollusc aquaculture was for respondents to disagree that they have impacts on other local species and to agree that they could improve water quality, the exact
opposite was true for fish aquaculture. This may both be a reflection that many of these respondents are aware of these different trophic roles, but also of the relatively high impacts of the fish aquaculture industry. This latter aspect, the perceived high impacts of fish aquaculture, is echoed in the results of Statement 3 wherein fish aquaculture was thought of as having a high potential to leak chemicals into the environment (e.g. feed), whereas respondents were more balanced and/or indecisive regarding the potential for chemical leakage in mollusc and plant aquaculture. These results are in line with similar findings in literature, for instance in Alexander et al. (2016b).

Finally, the responses to Statement 6 carry particular significance. Though not an example of the value-action gap per se, this is similar and could be said to exemplify a perception-support gap: in spite of a clearly negative perception of one option, all options are given similar support. While fish aquaculture received slightly less support than mollusc and plant aquaculture, given the high perceived environmental risks associated to it, one might have expected more opposition. In the next section, a key potential reason for this support is identified.

Looking forward

As a whole, it would seem that the perceived environmental aspects of different aquaculture types, though clearly important factors affecting support for or aversion to aquaculture, represent only relatively minor influences. The much greater factor at play here, as seen in Fig. 4, is the potential for economic betterment of the West Coast by developing aquaculture. This is a significant finding, revealing a key popular pressure—the popular desire for more economic opportunities—in the drive to develop aquaculture on the Swedish West Coast. These views are further reinforced by the support expressed by respondents for the scenario portrayed in the survey, which depicts further development of seaweed aquaculture on the West Coast in the coming years.

It is also clear from Fig. 4 that respondents were of mixed opinions regarding some key concerns such as the aesthetic and environmental impacts of the cultivations described in the scenario, contrary to what the authors had anticipated. For instance, it had been expected that there would be significant opposition from respondents who go to sea regularly due to the farms occupying valued sea space, yet those respondents were statistically less likely to be opposed or neutral and more likely to be supportive of aquaculture (see Table 3). On the whole, there was a lack of specific opposition about impacts on leisure boating (see Statement 2 of Fig. 4). On the other hand, both age and gender variables were found to be statistically significant in their effect on responses to the areas of concern presented in Fig. 4, though seemingly in contradiction to other studies (Fernandez-Polanco et al. 2008): older respondents showed less concern across the six statements than younger respondents, while gender was found to show no effect in previous studies. Possible reasons for these differences are unclear; however, it should be noted that though both of these studies pertain to perceptions of aquaculture, each focuses on different types of aquaculture. Furthermore, opinions and perceptions of aquaculture will change over time and should be re-evaluated in the future, particularly as aquaculture infrastructure becomes more common and obstructs larger spaces of the West Coast.

In addition, a large number of respondents were sceptical towards some of the other claims made in the scenarios. This again exemplifies the aforementioned perception-support gap, possibly resulting from a desire for more economic opportunities, whereby a majority of respondents remained favourable to the notion of more aquaculture on the West Coast in spite of being divided on a range of issues and while being sceptical of the scenario. This scepticism and division of opinion, but especially the minority of respondents who were opposed to aquaculture developments on the West Coast, represent important potential risks to a stable development of aquaculture on the West Coast. They highlight the need to raise awareness, particularly about impacts, how aquaculture developments will affect individuals, the potential for generating work in the region and on the ecosystem services of sustainable aquaculture practices.

As seen with the controversy surrounding the carrageenan industry (Bixler 2017), an important portion of the global seaweed industry, hostility to the seaweed industry has been—and can be—rapidly mobilised on a global scale by a minority of opposed individuals, in spite of scientific evidence refuting the hostile claims (McKim 2014; Weiner 2014). Further research should be undertaken to ascertain reasons for opposition to aquaculture on the West Coast and to pre-emptively identify solutions.

The complexity of aquaculture practices and the unintended consequences of their development are known to contribute to social aversion to aquaculture, as documented in extensive contributions in Culver and Castle (2008) relating to a range of issues such as the social transformations experienced by coastal communities in Canada. There are lessons to be learnt from such cases. By providing a benchmark of current perceptions toward aquaculture on the Swedish West Coast, it is hoped that this study may provide valuable information to policy makers and industry to avoid mistakes made elsewhere (like in Canada), but also as a point of reference for future studies of social aversion toward aquaculture. It should not be assumed, however, that the support for seaweed aquaculture development scenarios revealed by this study will be
maintained. Location factors are considered important in surveys of social acceptability (Freeman et al. 2012). The results of this survey are a unique snapshot of attitudes toward aquaculture on the Swedish West Coast in 2015 and attitudes may not be the same in 10 years. As such, the authors assert that there is a genuine need for systematic monitoring of potential drivers and barriers, as proposed by Krause et al. (2015), for a more transparent, socially, environmentally and economically sustainable development of seaweed aquaculture on the West Coast.

Acknowledgments We gratefully acknowledge helpful comments from both colleagues at the Division of Industrial Ecology (SEED, KTH) and the anonymous reviewers in the reviewing process. Special thanks are due to Linus Hasselström and Misse Wester for their insightful advice during the development of the survey, as well as Linn Larsdotter-olsson and Susanna Larsson from Norstat for their roles in the surveying. The study was funded by the Swedish Research Council Formas and conducted within the Project ‘Seafarm’ [Grant Number 2013-92].

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Explorative environmental life cycle assessment for system design of seaweed cultivation and drying

Roel van Oirschot, Jean-Baptiste E. Thomas, Fredrik Gröndahl, Karen P.J. Fortuin, Willem Brandenburg, José Potting

ABSTRACT

Seaweeds are presently explored as an alternative source to meet the future protein demand from a growing world population with an increasing welfare level. Present seaweed research largely focuses on agri-technical and economic aspects. This paper explores directions for optimizing the cultivation, harvesting, transport and drying of seaweed from an environmental point of view. An environmental life cycle assessment (LCA) and detailed sensitivity analysis was made for two different system designs. One system design is featuring one layer of cultivation strips (four longlines side by side) interspaced with access corridors. The other system design is featuring a doubling of cultivation strips by dual layers in the water column. Impact profiles and sensitivity analysis showed that the most important impacts came from drying the harvested seaweed, and from the production of the chromium steel chains and polypropylene rope in the infrastructure. This indicates that caution should be used when designing cultivation systems featuring such materials and processes. Furthermore, the high-density productivity of the dual layer system decreases absolute environmental impacts and so found to be a little more environmentally friendly from a life cycle perspective.

1. Introduction

Seaweeds, similar to terrestrial plants, have been used for centuries as a food source. There is evidence of seaweed food products from the 4th and 6th centuries in Japan and China, respectively [1]. Some archeological digs have suggested their use in agricultural soil management as well in the 2nd Century BC in Cornwall and perhaps even earlier in Estrucian Malta [2]. The use of wild harvested seaweed for feed, food and fertilizer is known to have evolved in isolation in various parts of the world from Scotland and Ireland to Japan and Peru [3,4]. The development of seaweed cultivation, however, was until recently mostly restricted to Asian societies for local consumption in coastal areas [5]. In Europe, the majority of seaweed production comes from wild harvesting. However due to concerns over environmental impacts, wild harvests have decreased significantly in the last decade and there is a drive to meet the increasing demand by shifting production toward cultivation [6].

Today, both wild harvest and cultivated seaweeds are exploited around the world for many purposes [4]. They still serve as a fertilizer in agriculture and as food and feed [7]. Seaweeds are now also increasingly seen as useful ingredients for products in other sectors, notably the pharmaceutical, cosmetic and food industries. Seaweed extracts can be applied as dyes or hydrocolloids [8], i.e. non-crystalline compounds forming jelly-like substances with water. Seaweed dyes and hydrocolloids have a large variety of applications in the food and cosmetic industry [1]. The main application of seaweeds globally, however, remains for human and animal consumption.

Seaweeds contain significant levels of essential nutrients such as carbohydrates, proteins, minerals, vitamins and trace elements like iodine [9,10] as well as antioxidants [11]. This makes some seaweed species highly suitable for both human and animal consumption [12]. The protein content may vary significantly over the different seasons and amongst different species [5,13] but can be up to 47% of the dry mass in a seaweed species such as Porphyra spp. [14]. Their relatively
high protein content makes seaweed a relevant alternative for animal proteins [15]. Seaweeds Furthermore, have extraordinary growth capacities, several times higher than for terrestrial energy or food crops such as rapeseed or sugar beets [16], which makes them suitable alternatives for these crops.

Seaweeds are presently explored as an alternative source to meet the future protein demand [17,18] from a growing world population [19] with an increasing per capita welfare level [20]. The cultivation of seaweed is also seen as an opportunity to reduce agricultural land use and related environmental burdens [21] and to remove elevated levels of nitrogen from estuaries and coastal waters [22]. Studies have furthermore suggested that seaweed growth rates can increase while providing bioremediation services to nearby fish farm cultivations by absorbing nitrogen [23–26]. Nonetheless, seaweed cultivation may also have negative consequences for the environment and these are likely to be amplified by increasing the scale of operations. Apart from possible direct consequences for marine ecosystems, other and indirect environmental consequences of seaweed cultivation are limited in their description in literature [16]. Indirect environmental consequences refer to upstream production of the means needed in seaweed cultivation, and downstream transport, drying and processing of harvested seaweed into, for example seaweed meal.

The direct and indirect environmental impacts of seaweed cultivation, i.e. the overall environmental performance of the production system for dried seaweed, can be quantified with life cycle assessment (LCA). LCA is a well-established tool to shed light on the environmental performance of product (and production) systems by quantifying their cradle to grave (or gate) contribution to a range of impact categories [27–29]. Some LCA studies have been conducted with a focus on specific aspects of seaweed supply chains, for instance wild harvests and valorisation strategies [30], photobioreactor cultivation and oil extraction [31], macroalgae biorefinery [32,33], and production of biofuels from cultivated seaweed biomass [34]. This study adds to this body of literature by exploring optimal system design for commercial seaweed cultivation and drying. The drying of seaweed reduces biomass weight for transport, it makes it readily suitable for further processing, and is a reliable way of preserving protein and nutritional values [35]. Such future commercially cultivated seaweed is initially expected to be applied in the agric- and aquaculture sectors, as it is considered a sustainable alternative to soy- and fishmeal and a valuable additive to feeds, but may in the long run serve for human purposes in the food industry [36–38].

The LCA in this paper is of an explorative character since commercialised, large-scale seaweed farms are not yet established in Europe. Some small and medium-scale pilots have been established such as in the Oosterschelde estuary, Netherlands, and the Seafarm near Strömstad, Sweden. These pilots provide insight in agri-technically optimal and economically viable seaweed cultivation. However insight is also needed on how to minimise the environmental impacts of the dried seaweed production systems, i.e. of seaweed cultivation and upstream production of means, as well as of its downstream transport and drying. The design of a potential commercial production system for dried seaweed, particularly the design of the cultivation infrastructure sub-system and associated seaweed yield, has not gained much attention to date.

The design of the cultivation infrastructure sub-system might be of great influence to the overall environmental performance of the dried seaweed production system. Two hypothetical infrastructure sub-systems for future seaweed cultivation have been designed, one with single and the other with dual layer longline configurations. First an LCA has been performed for two reference dried seaweed production system designs, one with a reference design for the single layer and the other with a reference design for the dual layer seaweed cultivation infrastructure sub-system. Next an extensive sensitivity analysis was performed, varying the design of the cultivation infrastructure, transport and drying parameters of the two reference dried seaweed production systems. The aim of the LCA in this paper was to explore potential designs of the future dried seaweed production system in order to identify directions for its optimization from an environmental point of view.

2. Methodology

Life Cycle Assessment (LCA) consists of four methodological phases. The first phase, goal and scope definition, specifies why and how a given LCA is performed. The second phase, life cycle inventory, quantifies all environmental inputs and outputs of the production system under consideration. The environmental inputs and outputs are translated in the third phase, life cycle impact assessment, into their contribution to a range of environmental impacts. The fourth phase, interpretation, evaluates the results of life cycle inventory and impact assessment in relation to the defined goal and scope in order to draw conclusions [27–29].

The goal and scope definition basically sets how the other three phases are performed. The goal or aim of the LCA in this paper, as mentioned already in the introduction, was to identify directions for optimizing the future commercial dried seaweed production system design from an environmental point of view. The scope of the LCA in this paper, i.e. its methodological approach, is further specified here in terms of the software and databases as well as data processing, the functional unit, description of the dried seaweed production system and life cycle inventory, life cycle impact assessment and finally the sensitivity analysis.

2.1. Software, databases and data processing

The software SimaPro 7.3 is used for life cycle inventory analysis and impact assessment calculations. Ecolinvent v3.0, included in the software SimaPro 7.3, is used where relevant as the source for life cycle inventory data (see Table 1). The impact results for the reference systems are presented in stack-diagrams, produced in excel. Impact results for the sensitivity analysis are processed in excel into graphical representations showing the changes in impact resulting from changes in the amount of inputs.

2.2. Functional unit

The function of the dried seaweed production system in this LCA is the production of dried seaweed with a protein content of one ton, suitable for further processing. In other words, all LCA results are expressed per ton of protein (and thus not, e.g., per ton dried seaweed). Downstream processing of the dried biomass into commercially available products is not included in the present study.

2.3. Dried seaweed production system and inventory analysis

The dried seaweed production system is schematically depicted in Fig. 1. The processes in the grey shaded boxes are included, and the processes in all other boxes are excluded in this LCA. In other words, grey shaded processes are inside and other processes are outside the boundaries of the system. The final product of the system is dried seaweed biomass. Data for sprouting of seedling lines is not available. The materials for production of the service vessel and the diesel used for harvesting are included in seaweed transport. The production of other products used for other harvesting tools, e.g. knives and nets, are excluded in this LCA as they are considered negligible compared to materials used in the boat.

The cultivation of seaweed in a European context still has an experimental character, and only small to medium scale pilots are being implemented to our knowledge. Some pilots are testing different types of cultivation infrastructures, such as those described by Taelman et al. [42]. We have limited information about what large-scale commercial
<table>
<thead>
<tr>
<th>Economic inputs used</th>
<th>Life (years)</th>
<th>Input characteristics</th>
<th>Source of input information</th>
<th>Quantity of input used</th>
<th>EcoInvent v3.0 process applied to calculate environmental outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding lines</td>
<td>1</td>
<td>Polypropylene, 2 mm ø, 0.0014 kg/m</td>
<td>Author measurement</td>
<td>0.00021 ton/100 m of longline/y</td>
<td>0.016 ton/tongprotein/20 y = 0.022 ton/tongprotein/20 y</td>
</tr>
<tr>
<td>Cultivation &amp; infrastructure rope</td>
<td>5</td>
<td>Polypropylene, 22 mm ø, 0.22 kg/m</td>
<td>Touwfabriek Langman BV [39]</td>
<td>0.030 ton/100 m of longline/5 y</td>
<td>0.028 ton/tongprotein/20 y = 0.058 ton/tongprotein/20 y</td>
</tr>
<tr>
<td>Chains</td>
<td>20</td>
<td>Chromium steel, 19 mm ø, 8.3 kg/m</td>
<td>Author calculation</td>
<td>0.048 ton/100 m of longline/20 y</td>
<td>0.024 ton/tongprotein/20 y = 0.12 ton/tongprotein/20 y</td>
</tr>
<tr>
<td>Anchors</td>
<td>20</td>
<td>Concrete, rectangular block, 1000 kg</td>
<td>Author assumption</td>
<td>2.033 ton/100 m of longline/20 y</td>
<td>1.017 ton/tongprotein/20 y = 5.3 ton/tongprotein/20 y</td>
</tr>
<tr>
<td>Small buoys</td>
<td>20</td>
<td>Polyvinyl chloride, 0.31 m, 1.2 kg/buoy</td>
<td>Chandelry World Ltd [40]</td>
<td>0.011 ton/100 m of longline/20 y</td>
<td>0.0005 ton/100 m of longline/20 y = 0.043 ton/tongprotein/20 y</td>
</tr>
<tr>
<td>Large marker buoys</td>
<td>20</td>
<td>Polyvinyl chloride, 0.59 m, 4.1 kg/buoy</td>
<td>Chandelry World Ltd [40]</td>
<td>0.045 ton/100 m of longline/20 y</td>
<td>0.054 ton/tongprotein/20 y = 0.12 ton/tongprotein/20 y</td>
</tr>
<tr>
<td>Strip Strengtheners</td>
<td>20</td>
<td>Polyvinyl chloride, 1.8 kg/m</td>
<td>Author calculation</td>
<td>0.030 ton/100 m of longline/20 y</td>
<td>0.021 ton/tongprotein/20 y = 0.028 ton/tongprotein/20 y</td>
</tr>
<tr>
<td>Transport</td>
<td>n/a</td>
<td>5 × 20 km return trips for delivery of seeding lines and monitoring 1 × loaded barge with harvest 10 km</td>
<td>Author assumption Validated by pilot researchers at Sea farm</td>
<td>15 tons/100 m of longline/20 y (of evaporated water)</td>
<td>11 tons/100 m of longline/20 y (of evaporated water) = 59 tons/tongprotein/20 y = 59 tons/tongprotein/20 y</td>
</tr>
<tr>
<td>Thermal drying of seaweed biomass</td>
<td>n/a</td>
<td>85% moisture content of S. latissima 83% moisture content at start of drying 22% moisture content at end of drying</td>
<td>Schiener et al. [13] Author assumption</td>
<td>15 tons/100 m of longline/20 y (of evaporated water)</td>
<td>11 tons/100 m of longline/20 y (of evaporated water) = 59 tons/tongprotein/20 y = 59 tons/tongprotein/20 y</td>
</tr>
</tbody>
</table>
Seaweed cultivations in Europe could look like. As a part of the dried seaweed production system, two reference seaweed cultivation infrastructures have been designed for high productivity per hectare. The design is after a sketch from Buck [43] included in Wald [44], but adjusted according to suggestions from Brandenburg [45] and Nylund [46]. High productivity in these systems is facilitated by two particular design elements. The first involves the use of an innovative "cultivation strip" configuration consisting of four longlines running parallel to one another 1-meter apart, at a depth of 2 m (single layer configuration). A gap between each strip is maintained throughout the cultivation to facilitate access for service vessels. The second high-productivity element involves the doubling of cultivation strips in the water column, in other words, two strips are held in place one on top of the other, the upper layer at a depth of 2 m and the lower at a depth of 4 m (dual layer configuration). The infrastructure design (Fig. 2) and the amounts of materials used (Table 1), both relevant outcomes of this study, are described in more detail in Section 3.1.

The purpose of the infrastructure is to provide stable longlines at a depth suitable to the cultivation of *S. latissima*. Once seeded with juvenile *S. latissima*, thin polypropylene (PP) string (henceforth referred to as seeded/seeding lines), are unfurled around the far thicker PP longlines that form the cultivation strips. Seeding lines are considered an operational component, to be replaced for every cultivation cycle, as opposed to being considered a permanent infrastructural component. The longlines with seeding lines coiled around them provide a stable anchorage for the growth phase of the seaweed lifecycle. The authors estimate biomass yields for one cultivation cycle per year based on a combination of literature and personal experience gained at pilot sites (see Section 3.2 for more details). The species of seaweed used in this study is *Saccharina latissima* (henceforth *S. latissima*). It is able to thrive in both temperate and polar regions and is commonly found along the European Atlantic coast, from Norway to Portugal. By selecting local specimen adapted to local conditions (e.g. tidal ranges, temperatures, salinities, etc.), populations of *S. latissima* have been successfully cultivated in pilots across Europe, including the test sites in the Oosterschelde estuary, Netherlands, and the Seafood site near Strömstad, Sweden. From such trials in sheltered/near-shore environments, it is recognised as fast growing and suitable for cultivation on infrastructure systems known as longlines, with negligible levels of accidental loss. The harvested seaweed biomass is assumed to be dried in a thermal air
design and inputs of both systems, it was considered unnecessary to keep other input values the same. Given the close similarities in collected LCI inputs of the reference seaweed production system while available in the EcoInvent database.

It provides characteristics and quantities of all economic inputs and outputs used and the sources for this information. Also given are the Ecolow v3.0 processes applied for calculating the environmental LCI inputs and outputs. These are provided for all processes in both reference systems for dried seaweed production, i.e. the one with single layer and the other with dual layer seaweed cultivation configurations (harvesting, transport and drying kept similar for both sub-systems). Values for the ‘quantity of input used’ in Table 1 are expressed both per 100 m of longline (per strip divided by the 4 longlines in each strip) and in terms of the functional unit, i.e. per ton of protein. The types of material in the life cycle inventory are based on the pilot cultivation of the Seafarm project in Sweden [46] and adapted to the materials available in the Ecolow database.

Sensitivity analysis was performed by changing, one by one, selected LCI inputs of the reference seaweed production system while keeping other input values the same. Given the close similarities in design and inputs of both systems, it was considered unnecessary to conduct sensitivity on both the single and the dual layer configurations; sensitivity was only conducted for the single layer strip configuration. LCI inputs for the sensitivity analysis were selected based on two main factors: large impact contributions (i.e. potential to influence results) and data quality/certainty. The selected LCI inputs were transport distance to the shore, the moisture content of the harvested seaweed, relative humidity of air going out of the drying process, biomass production per ha cultivation area, protein content of seaweed biomass, replacement frequency and diameter of sprouted seeding lines, and replacement frequency of the infrastructure. The analysis was conducted by changing input values by 10% increments varied from 50% to 150% of the values used in the reference seaweed production systems. For example, the maize drier’s specific moisture extraction rate (SMER), a value commonly used as an indicator of a dryer’s moisture removal efficiency, is set at 3 MJ/kg\textsubscript{water}, in the base case was re-run at 10% increments to a maximum of 4.5 MJ/kg\textsubscript{water} (50% added to base case) and a minimum of 1.5 MJ/kg\textsubscript{water} (~50% from base case).

3. Results: system description and inventory analysis

Since large-scale commercial seaweed cultivation does not yet take place in Europe, the possible design of the infrastructure and the drying sub-systems are relevant outcomes of this exploratory LCA. The results for the possible design of the seaweed cultivation infrastructure sub-system, more importantly of their permanent infrastructure in the marine environment, are therefore first described in more detail. The results for the biomass and proteins yields are then presented, followed by a description of the drying process.

3.1. Design of seaweed cultivation infrastructure sub-systems

Two reference seaweed cultivation infrastructure sub-systems have been designed, one featuring a single layer longline strip design and the other a dual layer longline strip design. The designs for both reference infrastructure sub-systems follow a sketch from Buck [43] included in Wald [44], but are adjusted according to suggestions from Brandenburg [45] and Nylund [46]. Seeding lines covered in juvenile S. latissima (replaced once a year) are coiled around longlines (replaced every 5 years), in turn held in place by the rest of a permanent infrastructure with a lifetime estimated at 20 years. See Fig. 2 for a schematic presentation and below for further description of the single layer seaweed cultivation infrastructure sub-system.

Seeded PP string (2 mm ø) is coiled around PP longlines (22 mm ø). The longlines are 1.5 times the length of the longlines. Four longlines next to each other, with 1 m in between, together form a cultivation strip with a width of 3 m. A cultivation strip, i.e. each of its four longlines, is 100 m long. To avoid tangling of the lines, they are held in place by rigid polyvinyl chloride (PVC) rods (henceforth “strip strengtheners”) every 10 m. Between each strip, a 4 m gap acts as a corridor providing access for service vessels (e.g. for harvesting), reducing shadowing in the water column (to avoid negative consequences for the marine ecology) and may also provide passages for migrating wild life.

The cultivation strips are held in place by rope (22 mm ø) and steel chains (19 mm ø) at both ends and at their centre, connected to 1 ton concrete anchors on the seafloor. To further secure the cultivation strips and add tension to the longlines, additional lateral concrete anchors sit at each end of, and in between, each cultivation strip. Even buoyancy is maintained by buoys (31 cm ø, PVC, 1.2 kg each) located either side of each strip every 10 m, i.e. directly above the ends of the PVC rods, while marker buoys (59 cm ø, PVC, 4.1 kg each) located at each end and in the middle of the strips, i.e. directly above the 1 ton concrete anchors, serve both for buoyancy and to make the cultivation more visible at Sea. Together, the elements represented in Fig. 2 form the permanent infrastructure in the marine environment, and were selected based on their ability to carry a significant burden in dynamic marine conditions over their expected lifetimes. The material end of life scenarios for the PP seeding lines, PP longlines, PVC buoys and PVC strip strengtheners are incineration in municipal incinerators with energy recovery. The end of life of the chromium chains and of the concrete anchors are recovered for recycling and left on the seafloor, respectively.

The design of the reference single layer and dual layer seaweed cultivation infrastructure sub-systems are similar. The main difference is a doubling of the strips (longlines, strip strengtheners and seeding line) and associated tethering lines (to lateral anchors and to buoys). The number of buoys, anchors and the amount of chain used are the same in the single and dual layer systems.

3.2. Seaweed biomass and protein yield

Seaweed biomass production is estimated based on adequate conditions for seaweed cultivation in the Oosterschelde estuary, on the growth rates of seaweed farms in the Netherlands [45], in Sweden [46], and in Ireland and France [42]. The estimated seaweed biomass production for a single layer cultivation is 1.2 ton fresh weight (FW) 100 m$^{-1}$. For the lower cultivation strip in the dual layer system, the authors assume that seaweed yields are 50% (0.6 ton FW 100 m$^{-1}$) of the single layer yields as a result of shading from the upper cultivation
Yield estimates include consideration of biomass degradation in early summer when sea surface temperatures increase, but also because the fastest growth period for *Saccharina latissima* is winter/spring. The aforementioned estimated yields are also representative over one year. These yield estimates include consideration of biomass detachment from the infrastructure as they are based on yield measurements at the time of the harvest; specific quantification of biomass losses from the infrastructure before the harvest are not included in the present study as they are considered negligible given the location of the site is sheltered, protected from storms and strong currents. Seaweed protein content was based on the average for *S. latissima* (7.1 ± 1.7% of dry matter) provided by Schiener et al. [13]. These values translate to 0.77 tons protein per hectare per year for the single layer and 1.16 tons protein per hectare per year for the dual layer (see Table 2 for a further specification of the seaweed biomass composition). The biomass yield (and subsequent protein yield) from a dual layer seaweed cultivation is thus 50% higher per ha than from the single layer cultivation. All environmental impact results in the following sections relate to per ton protein in dried seaweed (the functional unit) based on a 20-year life expectancy of the infrastructure.

### 3.3. Drying sub-system

The water fraction adhered to the seaweed contains part of the available proteins. Mechanical drying would result in loss of the protein contained in this water fraction through drippage and thus is supposed not to be suitable as drying method. The harvested seaweed biomass is assumed to be dried in a thermal air dryer to 22% moisture, a generally recommended moisture level for seaweed biomass storage and subsequent use [41,47]. Due to an increased risk of denaturation and loss of proteins at temperatures above 35 °C and a need to preserve these proteins in the dried seaweed, the heated ingoing air is limited to 35 °C. The energy requirements for the drying are calculated in two sections: the first by means of a simplified mass balance, to determine the amount of water in the seaweed following the harvest, transport to shore and overnight storage. During transport and temporary storage prior to drying, the seaweed will be compressed under its own weight and partly dewatered [49]. It is assumed that 20% of the harvested biomass water content is lost during this time, while preserving the protein containing water adhered to the seaweed. The second step calculates the impacts resulting from the removal of the rest of the water, reaching 22% moisture, using the process in SimaPro called “maize drying”.

The maize drying process was used as a proxy due to a lack of literature regarding energy requirements to dry seaweed and the lack of a marine biomass drying process in SimaPro. The process was deemed adequate when adapted to the drying of seaweed biomass by changing the amount of water to be evaporated. Drying related parameters such as moisture content in the ingoing biomass and the specific moisture extraction rate (SMER) of the drier, were considered key sources of uncertainty and were included in the sensitivity analysis. The drying process also includes the production of the drying infrastructure machinery, as well as a share of impacts from the premises to house the drying equipment and undertake the drying process. The Ecoinvent v3.0 process “light fuel oil burnt in an industrial furnace” is used as a fuel source for the drying. This gives the advantage over an electrical drying process by decoupling the electrical input impacts from varying national energy mixes, as discussed in Raghavan et al. [50].

### 4. Results: LCIA

In this section the environmental impact results are presented, first for the overall dried seaweed production system and then for the infrastructure alone. This section concludes with the results from the sensitivity analysis.

#### 4.1. Dried seaweed production

Fig. 3 shows that, on the whole, the contribution of the seeding lines as well as the harvesting and transport to the overall impacts is insignificant. Both the infrastructure and the drying process share the majority of all impacts, but not equally. The drying dominates ozone depletion, abiotic depletion, acidification, climate change and photochemical oxidation, whereas the infrastructure dominates human toxicity, freshwater ecotoxicity and marine ecotoxicity. Eutrophication and terrestrial ecotoxicity are shared more or less equally by both drying and infrastructure. All of the main system components, except infrastructure (see Section 4.2), are described in more detail here.

The drying process makes a large contribution to all impact categories, with the exception of human toxicity and fresh water ecotoxicity. It particularly dominates ozone layer depletion due to emissions of methane, bromotrifluoro- , halon 1301) from the burning and refining of light fuel oil for production of heat. Other dominated impact categories (by over 70% contribution) include abiotic depletion, climate change, photochemical oxidation and acidification. The majority of non-renewable CED also is a result of the drying process. In terms of the drying process, it is worth noting that the

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Formula</th>
<th>Single layer</th>
<th>Dual layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh weight</td>
<td>m_{dry}</td>
<td>72</td>
<td>108</td>
</tr>
<tr>
<td>Dry matter</td>
<td>m_{dry}</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>Dried mass</td>
<td>m_{dried}</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td>Total protein</td>
<td>m_{protein}</td>
<td>0</td>
<td>0.77</td>
</tr>
</tbody>
</table>

- * The fresh weight of the harvested biomass is estimated by the authors as being 12 kg/m of longline on the cultivation strip of the single layer configuration. For the dual layer configuration, the upper strip is assumed to be the same, while the lower strip is estimated as half of the upper layer, at 6 kg/m.
- b The water content of the *Saccharina latissima* is approximately 85%, giving a dry matter content of 15% [13].
- c 22% moisture content is a commonly acceptable level of moisture for the preservation and storage of seaweed biomass [41,47].
- d The yearly average protein content of *Saccharina latissima* [13].
The single layer (S) and dual layer (D) configuration. Fig. 4. One can see that the impact contributions per ton of protein in the dried seaweed, or more specifically per ton of protein, requires the same amount of energy and material investment, regardless of total volumes of each scenario. As such the contribution of the drying process does not change per ton of protein between the single and dual layer systems, however it remains the single most dominant impact contributor in the overall dried seaweed production system.

The seeding lines, which are considered an operational component and thus separate from the infrastructure, make a very small contribution to overall impacts and make no visible contribution to any impact category in the stack diagrams. Their impacts can be considered negligible, in spite of their yearly replacement. Harvesting and transport also make a very small contribution to the overall environmental impact of both reference systems with the distance from the cultivation area to the shore set to 10 km. As a precaution and to shed light on the contribution of transport to overall environmental impacts over much larger distances, the authors recalculated using a distance of 100 km (from cultivation to shore). Contributions across almost all of the impact profiles remained below 5%, except for the acidification and eutrophication categories, for which the contributions rose to 6% and 7% respectively. To summarise, the overall contribution of harvesting and transport is considered almost negligible in our model over the 10 km distance and remains small over 100 km.

Finally, from Fig. 3 it is also clear that, per ton of protein in the dried seaweed, the dual layer system performs slightly better than the single layer system in almost all impact categories. This is principally due to the 50% higher yields of the dual layer system (see Section 3.2). The only impact categories where the dual system performs worse, but only marginally (less than 1%) are the abiotic depletion and non-renewable CED categories. The explanation for this lies in the greater infrastructural requirements of the dual layer configuration compared to that of the single layer configuration. The impacts of the infrastructure are further explored in the next section.

4.2. Infrastructure

The stack diagram in Fig. 4 shows the relative contributions of each infrastructural component, both for the single layer and dual layer configurations. The chains have the highest contribution followed by the ropes, then the anchors, the buoys and finally the strip strengtheners. Ropes and chains dominate the environmental contribution of the infrastructure of most categories. Particular dominance comes from the chains in human toxicity due to the emissions of chromium VI and arsenic from the production of chromium steel and terrestrial ecotoxicity due to the emission of mercury and chromium VI from the production of chromium steel. The main relative contributions of the ropes are in abiotic depletion where it represents a majority of the infrastructure contributions due to the use of crude oil for the production of PP. The ropes also have a large contribution to climate change as a result of the CO2 emissions from the production of PP granulate and incineration of the PP ropes at the end life. The ropes also contribute an important share of impacts in the photochemical oxidation, marine and freshwater ecotoxicity categories. The anchors contribute little to all impact categories, but are notable in the ozone depletion and climate change categories. Both PVC components, the buoys and strip strengtheners, have small contributions overall.

The main differences in terms of impacts between the single and dual layer are also clarified from the infrastructural component fragmentation in Fig. 4. One can see that the impact contributions per ton of protein of the ropes are clearly higher in the dual layer system, while the chains are lower in the dual layer system. Less easy to see, because their impact contributions are relatively small, is that the strip strengtheners and seeding lines have slightly greater impacts in the dual layer system, while the contributions of the buoys and anchors are lower in the dual layer system. This is a reflection of a 50% higher biomass yields per hectare in the dual layer system relative to the single layer system, in parallel with a 100% increased use of ropes, strip strengtheners and seeding lines to double the number of strips in the dual layer. This is opposed in most impact categories, however, by a reduced share of total material inputs for the buoys, chains and anchors, which are the same in both the single or dual layer configurations. These patterns are clearly visible in the impact categories where those materials have the largest impacts. For instance, as mentioned in above, the ropes have a large contribution to abiotic depletion as well as several other categories. The increased contributions of the ropes in the dual layer system are thus evident in this impact category in Fig. 4. Similarly, the chains are noted to have a particular dominance of the human toxicity category. Their decreased contribution to the dual layer system is thus evident in this impact category in Fig. 4.

4.3. Sensitivity of LCIA

The sensitivity analysis exposed the specific moisture extraction rate (SMER) of the biomass drying process, protein content and biomass yield as the most sensitive parameters (see Fig. 5). The SMER value is the most sensitive parameter in the all impact categories except the toxicity and eutrophication categories, showing a linear change whereby higher SMER values resulted in higher impacts, and lower SMER values resulted in lower impacts. As to be expected, across every impact category, higher protein content was found to decrease absolute impacts while lower protein content increased absolute impacts. Overall, protein content was found to be the second most sensitive parameter, closely followed by biomass yield. These two parameters are central to this LCA model, both having a direct influence on the functional unit. Hereafter, the highlights of the parametric sensitivity analysis are presented.

The replacement frequency of the total infrastructure is assumed to be 20 years, with the exception of the longline ropes, whose life expectancy is assumed at 5 years. Since replacement frequency values remain uncertain factors, these were included in the sensitivity analysis. Replacement frequency of the infrastructure was found to be very sensitive, particularly in the toxicity, acidification and eutrophication categories, but only slight in the acidification and eutrophication categories.

A preliminary analysis of the sensitivity of infrastructural components showed negligible sensitivity for all of them with the exception of...
the chains (diameter) and ropes (diameter), so only these components were included in the final sensitivity. Both were found to be highly sensitive: increasing their diameter rapidly increases their mass, which in turn increases the magnitude of impacts. The chains are particularly sensitive for the impacts in the toxicity categories, eutrophication and acidification. The impact categories most affected by the ropes are the freshwater and marine aquatic ecotoxicity categories, as well as climate change and abiotic depletion. Beyond these aforementioned categories, both diameters of the ropes and chains demonstrated moderate sensitivity.

Sensitivity analysis was also conducted for the key variables in the drying process, including assumed water lost during harvest, moisture content in outgoing product and the SMER of the biomass dryer. As mentioned above, the SMER was exposed as the most sensitive parameter in the model. The water loss during harvest and the moisture content in the dried seaweed have only minor sensitivities relative to the other parameters, with the exception of ozone layer depletion, where water loss during harvest is the most sensitive parameter second only to the SMER.

5. Discussion

The LCA in this paper used EcoInvent v3.0 for calculating the environmental LCI inputs and outputs, and the CML 2001 (baseline) method (version 2.5) and CED [48] for converting these environmental inputs and outputs into their environmental impact contributions. EcoInvent v3.0, the CML 2001 (baseline method) and CED are considered robust and authoritative. The uncertainty in the present study comes largely from the design of the dried seaweed production system, in particular from the seaweed biomass and thus protein yield, the cultivation infrastructure sub-system design, and the drying process. These sources of uncertainty are discussed in the following section and the results of the study are also discussed in relation to broader literature to provide environmentally friendly recommendations for dried seaweed production system designs.
5.1. Robustness of dried seaweed production system design and inventory analysis

Life Cycle Analyses of macroalgae, or seaweed, cultivation systems are fairly scarce in literature [51]. Some have emerged in the last few years relating to cultivated macroalgae as a feedstock for biofuels [34, 42, 52] and other sustainability related modelling tools have also been applied [47, 53]. To the authors’ knowledge, a gap in the literature remains in regards of LCAs of seaweed products that require biomass drying, e.g. seaweed food products, which are broadly recognised for their potential health benefits to both humans and in animal husbandry [54, 55]. As such there are few studies to conduct full comparisons with, thus the following sections discuss the robustness of the dried seaweed production system and provide comparative insights with literature, where possible.

5.1.1. Seaweed biomass and protein yield

It was assumed that the biomass yields per hectare were approximately 50% higher in the dual layer system relative to the single layer system. This assumption has a high influence on the comparison of the dual and single layer configurations. It was also found that the material and energy inputs of the dual layer system (per ton protein) were greater, resulting from the additional material components in the dual layer system. These two sets of factors - higher yields and more system inputs - almost balance each other out. One may have expected 50% lower impacts in the dual layer resulting from the 50% higher yields per hectare, however the increased material and energy inputs per ton protein offset the savings to an average below 10% (see Fig. 4) across all impact categories. In other words, it was found that the dual layer system, on average, reduced impacts per ton of protein compared to the single layer system, but only to a small extent.

Some limitations and uncertainties about seaweed biomass and protein yield in our LCA should be highlighted. Rather than being obtained from measurements at a pilot or commercial cultivation site, the seaweed biomass yield and protein content were conservatively estimated from literature and from personal communications with seaweed cultivation researchers [45, 46]. As knowledge of seaweed cultivation develops in Europe, it is expected that yields will increase and it may even be plausible to anticipate multiple harvests every year by, for instance, coppicing the biomass rather than removing it entirely from the infrastructure at Sea at the first harvest. In addition, annual variability to yields and protein content are also inherent sources of uncertainty, thus impacts are likely to be affected from year to year. The absolute impacts per ton of protein produced in this study should thus be considered with caution (see next paragraph), both given the uncertainties surrounding biomass yields and protein content, and the high sensitivity of these parameters. However, neither biomass yield nor protein content affects the relative shares of impacts from different infrastructural components as the functional unit is per ton of protein. The results thus remain robust in their provision of recommendations for dried seaweed production system designs, and cultivation infrastructure sub-system designs in particular.

A recent study by Angell et al. [56] concluded that the commonly used conversion factor of 6.5 from nitrogen to protein may be over optimistic and that a conversion factor of 5 may be more accurate. This suggests that the protein levels used in this study, from Schiener et al. [13], may also be overoptimistic and thus the absolute impacts should be considered with care. Digestibility of seaweed and seaweed proteins is also not considered in the present study [57, 58]. S. latissima may therefore not be the best-suited seaweed for further processing as a protein source but it was selected nonetheless since it is a well-documented, cultivable species, well adapted to the marine conditions (e.g. tidal ranges, temperatures, salinities, etc.) of European latitudes, and because of the additional health benefits from the nutritional value of using seaweed as food supplements both for humans and in animal husbandry [10]. However, there are also species of seaweed such as P. palmata (also known as dulce) with higher protein content and digestibility than S. latissima [36]. These species could also be cultivated using longlines [59], i.e. with the same cultivation infrastructure sub-system as designed in this study. This illustrates that there is much room for further optimisation of protein production in systems in addition to the design of the cultivation system evaluated in the present study. Once again, however, varying protein yields only affects absolute impacts, not the relative contributions of processes in dried seaweed production.

5.1.2. Seeding process

Another important decision taken by the authors was the exclusion of the seeding process also commonly known as the indoor cultivation: controlled seaweed reproduction, seeding of spools and juvenile maturation. There are several reasons for this, the first being that alternative technologies are still being developed and tested, each with important differences in energy, material, process, temporal and labour requirements, and the selection of any one of these methods in this explorative LCA would have been inherently arbitrary. Second, the different indoor cultivation methods are significantly affected by the scale of operations [60], i.e. economies of scale are achieved in a system producing 10 km of seeded line compared to a system producing 100 m of seeded line. The setting of a specific scale of seeding operations for this explorative study would have also been arbitrary and a source of uncertainty. There is indeed a need for elucidation of seeding methods, across a range of time and production scales and from a life cycle perspective, however it was not in the scope of this study to conduct such an investigation.

5.1.3. Drying process

A lack of studies in literature documenting the drying of seaweed biomass lead the authors of the present study to use a simple model for the dewatering and drying processes. The amount of water lost during the harvest, transport and overnight storage of the biomass is particularly uncertain, as it was based on literature and personal communications, not practical measurements. Furthermore, the use of a dryer designed for a different form of biomass (maize) provides only a vague idea of energy use. Both of these uncertainties affect the absolute impacts and the relative shares of impacts of the system. The result from the drying calculation was nevertheless found to be a little higher than other calculations in literature. Where our calculations estimated that 9.9 MJ were required to produce 1 kg of dried biomass, Philippens et al. [47] estimated 4 MJ were required, both to reach 22% moisture content. Another potential proxy, the drying of cotton textile in a tumble dryer was found in a study by Uitdenbogerd and Vringer [61] to require 6.3 MJ/kg of dry cotton, a result which is higher than Philippens et al. [47], though lower than those estimated in our model. Both of these comparisons illustrate the conservative approach applied to the present study. Practical studies are needed to ascertain energy requirements of seaweed drying with greater certainty, and to gain a better understanding of the trade-offs between the SMER of driers, different heat energy sources and potential life-cycle environmental impacts. The effect of alternative drying methods such as the use of wind or solar dryers on direct and indirect environmental impacts, as well as the biomass itself, should also be subject of further research. Finally, the drying of biomass was selected as a post-harvest preservation strategy in the present study as drying is a suitable process to preserve seaweed for further use, e.g. as a food. Other preservation methods can be applied to seaweed for other uses and lifecycle analyses of such methods should also be compared.

5.1.4. Seaweed cultivation infrastructure sub-system

A main source of uncertainty in the present LCA is the design of the seaweed cultivation system, or in other words, the infrastructural design. Existing small-scale pilots have been established in Europe to gain an insight in agri-technically optimal and economic viability of seaweed
culmination, for example those described in the study by Langlois et al. [34]. However, seaweed cultivation infrastructure designs are described only vaguely and in a limited number of publications in literature. Due to a lack of specific data and definitions of conventional seaweed cultivation systems, two hypothetical reference systems were designed, one with single and the other with dual layer longlines. Though these designs have not been tested at sea, they are considered advantageous, structurally sound and similar systems are being developed in the Netherlands.

The greatest impacts from a single source in the infrastructure come from the use of marine grade stainless steel chains made of chromium alloys. This represents that, although it may be essential for certain aspects of a seaweed cultivation design, the use of marine grade stainless steel should be minimized whenever possible, and as portrayed in this model, attempts should be made to recycle as much of it as possible.

Finally, it is worth noting that the particular strip configuration of both single and dual layer cultivation systems provide significant advantages in terms of impacts, when compared to a conventional longline cultivation. In a conventional system, each 100 m longline is held in place by its own set of buoys, anchors, chains and ropes; in comparison, a strip requires twice the number of components but for four longlines rather than just one. The strip configuration requirements per 100 m of longline are thus approximately half that of the conventional longline, with the exception of the additional strip strengtheners, which add only a minor contribution of impacts. In other words, it would seem that the cultivation of seaweed using a strip configuration would be more environmentally friendly than seaweed cultivated on a conventional longline.

5.2. Other environmental issues

Although practised for centuries, the impacts of seaweed cultivations on benthic environments for instance, are still largely undetermined. Oceans, seas, estuaries and coastal zones are amongst the most complex, dynamic and unrevealed environments on our planet. The cultivation of seaweed in near- and offshore areas is likely to have impacts, environmental or other, that have not been covered by this study and that LCA methods are not designed to address [62], for instance, the degradation of plastic materials at sea that contribute to plastic soup.

Seaweed cultivation infrastructure represents a three-dimensional, man-made structure consisting of a mixture of metals, concrete and plastics, usually stretching from surface to seabed. Its physical presence can act as an agent of opportunity for some species or of liability for others. The partial shading of the benthic environment could, for instance, favour the establishment of some species that may eventually outcompete the original flora. Similarly, a set of longlines at one-meter intervals may block access or even entangle larger fauna, such as whales. Unintended consequences of human interference in marine environments are a real challenge to determine with certainty. More research is needed to further our understanding of a broad spectrum of potential interferences and mitigation measures when introducing structures into marine spaces.

It has been suggested that seaweed cultivations could act as agents for nitrogen and phosphorus bioremediation in estuaries or along coastlines of particularly agricultural regions [22], or in integrated multi trophic aquaculture (IMTA) to mitigate impacts of fish aquaculture [23-26]. This kind of so-called ecosystem service presents significant potential for contributions to long-term human well-being. Technologies have also been proposed to enhance ecosystem services, for instance by using mooring anchors designed with tunnels and holes that act as shelter and provide habitat, e.g. for lobsters [63], or to use even larger structures known for their ability to foster the development of coral reefs. Other ecosystem service opportunities resulting from the cultivation of seaweed, for instance carbon uptake and mitigation of ocean acidification [64], are critically unexplored and should be subject of further research.

The complexity of marine ecosystems is such that the ecosystem services rendered by a cultivation have the potential to be both positive and negative; for instance, habitat provision services may serve an invasive species which could thrive, affect the local environment and result in a chain of unintended consequences. While the LCA method is limited to providing insights into life-cycle impacts, a thorough appreciation of environmental impacts can be achieved by complementing LCA with an understanding of the ecological interactions in and around a cultivation system, and the linkages between ecological and socioeconomic systems resulting therefrom. Ecological interactions of seaweed farms with their environment are not yet thoroughly understood, nor are the risks or impacts of certain inevitable consequences of seaweed farming such as those resulting from the detachment of biomass during storm events.

Further transdisciplinary research is needed to develop reliable methods that can help determine the extent and nature of ecosystem service provision and broader ecological interactions.

5.3. Lessons learnt

The present study provides the life cycle environmental impacts of two dried seaweed production system designs, one with a single layer strip cultivation configuration, the other with a dual layer strip cultivation configuration. Some key highlights of the study are highlighted hereafter.

Intensification of seaweed cultivation by the use of a dual layer configuration does not significantly reduce environmental impacts per ton protein compared to a single layer configuration. Much depends on the specific materials and design differences between the conventional or intensified cultivation designs. In the cultivation systems of the present study, the use of some components remains the same (chains, anchors and buoys) in the two systems, however other materials are used to a greater extent in the intensified cultivation design (ropes, seedling lines and strip strengtheners). Those that remain constant have smaller net shares of impacts resulting from the larger yields (50% higher yields in this case) of the intensified cultivation (dual configuration), whereas those that were increased in their use show slight increases in their relative contributions. Overall, the dual layer system was found to be only a little more environmentally friendly than the single layer system in the production of 1 ton of protein in dried seaweed. It should also be noted that an intensification such as that presented in this study could offer significant productivity advantages for seaweed cultivations limited by permits/licenses of small areas. In such cases, a similar intensification of cultivation systems could enhance productivity in their small designated space, without significantly affecting life cycle environmental impacts.

The drying of the seaweed was the process with the highest contribution to environmental impacts. Any seaweed production system requiring the drying of biomass should approach dewatering strategically, look for innovative uses of the energy available at sea (e.g. wind, waves or currents) that could initiate the drying process during harvest and transportation, and adopt low energy alternatives, for instance using solar dryers. Alternative biomass preservation methods, such as ensilage, should also be considered when possible. Chromium steel chains and PP ropes were the material components of the infrastructure with the highest contributions to environmental impacts. When designing cultivation systems, one should minimise their use or look for alternative materials with lower life cycle impacts. Finally, the direct environmental impacts of seaweed cultivation are not within the scope of this study, for instance the degradation of plastic ropes at sea contributing to “plastic soup”, or the potential ecosystem services delivered by the cultivation of seaweed.
6. Conclusions

An explorative environmental life cycle assessment was performed of two dried seaweed production systems, using one ton of protein in the dried seaweed as a functional unit. The difference between the two systems was limited to alterations in the configuration of the seaweed cultivation infrastructures (Fig. 2). Harvesting, transport and drying were kept the same. Both were designed featuring access corridors for the cultivation longlines using a strip configuration. One of them was designed for increased productivity per hectare relative to the other, by doubling the number of strips in the vertical water column.

An analysis of the life cycle environmental impacts of the system (Figs. 3 and 4) showed that the highest impacts came from the biomass drying process followed by key elements of the infrastructure, notably the chromium steel chains connecting the infrastructure to the concrete anchors on the sea floor, and to a lesser extent the PP ropes that constitute the majority material (by mass) of the infrastructure (excepting concrete). Comparing the two cultivation systems, the dual layer system delivers 50% higher yields per hectare but has slightly lower impacts relative to the single layer system per ton of protein in the final dried seaweed product. This is due to the larger biomass yields offsetting the higher environmental impacts from the higher material inputs in the dual system. In other words, the dual layer configuration produced more biomass per hectare but was only slightly more environmentally friendly in the production of 1 ton of protein in dried seaweed, relative to the single layer system.

A sensitivity analysis (Fig. 5) revealed that the most sensitive aspects of the model were the protein content in the biomass, the specific moisture extraction rate of the biomass dryer, the biomass yield from the cultivation and the diameter (and therefore mass) of the chains. As a result of the sensitivity of certain parameters, the absolute impacts of the present study should be considered with caution, however the recommendations in this study are based on relative contributions which are considered robust.

This paper set out to shed light on the life cycle environmental impacts of commercial scale cultivation designs, and in so doing, highlight some recommendations for cultivation infrastructure designers. Further research is recommended to validate these results as commercial scale cultivation infrastructures emerge and also to further explore the direct and indirect environmental impacts of alternative cultivation systems (such as the degradation of plastic ropes at sea and ecosystem services, which were beyond the scope of this study) and seaweed biomass processing at industrial scales.

Acknowledgments

Our gratitude to Dr. Gøran Nylund at Göteborg University for valuable discussions and for providing data regarding material use and infrastructure design. We gratefully acknowledge helpful comments from both colleagues at the Division of Industrial Ecology (SEED, KTH) and for the anonymous reviewers in the reviewing process. The study was funded by the Swedish Research Council Formas and conducted within the project ‘Seafarm’ (Grant number 2013-92).

References


Dry, ensile or freeze? A comparative environmental life cycle assessment of kelp cultivation and preservation alternatives


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Abstract

The race is on in coastal Europe to develop seaweed cultivation and processing industries that could contribute to blue growth and the European bioeconomy with a valuable and sustainable biomaterial. This paper builds on an explorative environmental life cycle assessment (LCA) of seaweed cultivation and drying undertaken by van Oirschot et al. (2017) by broadening the system boundaries to include additional processes and applying robust case data from the Seafarm project. The common longline infrastructure configuration is investigated and multiple supply chain pathways are compared, including two hatchery approaches and four alternative preservation methods: hang drying outdoors, drying in a heated air-cabinet, ensilage and freezing. Impact profiles of the supply chain identified that the greatest shares of impacts resulted freezing and then air-cabinet, both the two most energy intensive processes of the supply chain, followed by the cultivation infrastructure, highlighting the need to optimise these processes from an environmental point of view. Hatchery processes, harvesting and the low energy preservation methods of ensilage and hang drying outdoors were found to have small shares of impacts relative to the worst performing supply chain pathway. The study also found
that, as a result of bioremediation taking place as seaweed is harvested, the supply chain mitigated between 1.1 and 2.9 times more CO₂ equivalent and between 11 and 36 times more PO₄ equivalent than was emitted, depending on preservation methods undertaken. These findings substantiate the environmentally friendliness of seaweed-based products by documenting their potential to be carbon negative or carbon neutral, and that seaweed cultivations can mitigate eutrophication even when taking a life cycle perspective.

**Keywords:** Life cycle assessment; environmental impacts; aquaculture; kelp preservation; blue bioeconomy
1 Introduction

Virgil couldn’t have been farther from the truth when proclaiming “nihil vilior alga”, which roughly translates as “nothing is more worthless than seaweed” (Virgil, 1922). Seaweed extracts are used in a range of different industries including the food processing, pharmaceutics, and textiles industries (van Hal et al., 2014). In one form or another seaweed pervades everyday life, concealed in toothpastes, cosmetic creams, ready-meals and a host of other household goods, owing to the valuable proteins, lipids, carbohydrates and other compounds they contain. Seaweeds are also more directly used as food and feed, as well as fertiliser (McHugh, 2003).

Of the estimated 28.5 million tons of seaweed cultivated or harvested wild in 2014 (FAO, 2016), the vast majority was cultivated in just four countries: China, South Korea, Japan and Indonesia. In Europe, present production comes mainly from the harvest of wild biomass (NetAlgae, 2012), though interest in cultivation has been gaining momentum over the past few years, notably following communications for the development of the bioeconomy (European Commission, 2012b) and blue growth strategies (European Commission, 2012a). Seaweed is seen as a potentially valuable future contributor to the European bioeconomy, and research is ongoing to explore their potential to produce bioplastics (Maguire, 2016), biofuels (Pechsiri et al., 2016) and a range of other materials and chemicals (Pangestuti and Kim, 2015).

Seaweeds are valuable not just in terms of their end uses, but also are recognised as an environmentally friendly biomass that doesn’t use typical agricultural inputs such as fresh water, fertilisers and pesticides (Dhargalkar and Pereira, 2005), with potential to be carbon neutral or even to sequester carbon (Seghetta et al., 2017), as a means to address eutrophication (Xiao et al., 2017), to help manage nutrient balances in finfish aquaculture (Chopin et al., 1999, Troell et al., 1999), all while providing other ecosystem services possibly including habitat provision (Phillips, 1990). Indeed, to resolve some of the societal challenges that we face in the coming decades, one might argue that little has more worth than seaweed.

Seaweed cultivation sites have been emerging along the European Atlantic coast over the past few years to supply fresh food and existing industries, and there is ongoing research into marine-biomass specialised biorefineries, including as a part of the Seafarm project in Sweden. The Seafarm project is also exploring environmental optimisation strategies for seaweed cultivation and preservation: van Oirschot et al. (2017) conducted an explorative environmental life cycle assessment (LCA) in view of identifying those parts of a dried seaweed production
system responsible for the largest shares of impacts, so that these may be highlighted as in need of optimisation from an environmental point of view. The production system was limited to seaweed cultivation, harvest and drying, omitting hatchery processes due to a lack of data. The study found that by far the largest share of impacts originated from the preservation process, which was assumed to be a drying process, thus emphasising the need to optimise drying techniques and to explore alternative biomass preservation processes such as freezing or ensiling. Little research has yet been conducted to compare such alternative preservation methods (Milledge et al., 2014).

Building on the explorative van Oirschot et al. (2017) with robust new case data from the Seafarm project, this article reports on an LCA that explores a seaweed cultivation and preservation supply chain, including the hatchery processes which are not included in van Oirschot et al. (2017). For the cultivation process, the LCA of Van Oirschot et al. (2017) compared two infrastructure configurations optimised for sites exposed to rough water conditions. These configurations, referred to as strips, consist of four parallel longlines anchored to the same points and interspaced with access corridors, the whole resulting in a more intensive production per unit of occupied sea space than classic longline infrastructures. The Seafarm project focuses on cultivation in a sheltered bay. Therefore, the LCA here uses a longline cultivation infrastructure configured for a sheltered bay as opposed to the more exposed site configuration in van Oirschot et al. (2017).

This article also compares (1) two alternative hatchery approaches referred to as submersion and spray seeding, and (2) four alternative biomass preservation methods referred to as drying by hanging longlines outdoors, drying with a heated air-cabinet, ensilage and freezing in a shipping container. These comparisons serve to identify supply chain pathways of least environmental impact or greatest impact mitigation potential for the production and preservation of *Saccharina latissima*. This is particularly valuable for decision makers and in the design, development or management of seaweed-based supply chains.
2 Methodology

Life Cycle Assessment (LCA) has become a well-established method for gaining an overview of the environmental impacts resulting a (partial) product system. A short summary of LCA methodology is provided by van Oirschot et al. (2017):

“LCA consists of four methodological phases. The first phase, goal and scope definition, specifies why and how a given LCA is performed. The second phase, life cycle inventory, quantifies all environmental inputs and outputs of the production system under consideration. The environmental inputs and outputs are translated in the third phase, life cycle impact assessment, into their contribution to a range of environmental impacts. The results of life cycle inventory and impact assessment are evaluated in the fourth phase, interpretation, in relation to the defined goal and scope in order to draw conclusions (ISO, 2006, Baumann and Tillmann, 2004, Guinée, 2002).”

The goal and scope establish the context and boundaries of the three other LCA stages. The goal of this study is to make an environmental impact-based comparison of possible optimisation strategies and alternative supply chain pathways in industrial seaweed production systems. The LCA will build on van Oirschot et al. (2017), but for the life cycle inventory of the additional alternatives and the seaweed cultivation system, takes its basis in the designs and processes as developed and tested in the Seafarm project. The methodological approach is detailed in the following sub-sections.

2.1 Functional unit

The choice of functional unit, that is the unit in terms of which all impacts are expressed, should typically be based on the function of the studied system (Guinée, 2002). The primary function of the supply chain in this study is to produce preserved *Saccharina latissima*, albeit following four alternative preservation treatments – drying (outdoors and in an air-cabinet), freezing and ensilage – each of which have an effect on the properties and composition of the biomass, i.e. it will produce biomass with different functions. The function of the system studied here is not to produce preserved biomass complying with certain specifications. The studied function is to preserve harvested seaweed. Rather than focusing thus on the four distinctive and non-
comparable outputs of the supply chain, the emphasis of system function is placed on the fresh biomass that is input to alternative preservation processes, enabling light to be shed on the impacts of preserving a given quantity of biomass in four different ways. The functional unit selected for this study is therefore one ton of freshly harvested, cultivated *Saccharina latissima*, before it undergoes preservation treatment.

Defining the functional unit of a study based on a process *input* is common for LCA’s comparing e.g. waste treatment methods, i.e. LCAs focusing on identifying the environmentally optimal *downstream* system. However, the LCA here is rather interested to find the most environmentally *upstream* system. LCAs for *upstream* systems typically employ an *output* based functional unit as they are typically interested in alternative ways to produce something with equivalent specification. Using an input-based functional unit for comparing purposes of an upstream system has not been done before to our knowledge.

The study consists of two sub-systems for which alternatives are compared: (1) an initial cradle to gate study including hatchery processes, cultivation and harvest, and whose functional unit is the sub-system product and *output* (fresh harvested biomass); and (2) a gate to gate sub-system comparing alternative ways of preserving biomass, using the same functional unit, which is the preservation’s *input* material. Selecting the fresh biomass as the functional unit will also facilitate comparisons with literature, notably the earlier van Oirschot et al. (2017) upon which this study is built.

### 2.2 Description of supply chain and life cycle inventory analysis

The supply chain considered in the present study consists of five consecutive steps (figure 1), beginning after the selection of healthy parent specimen: the hatchery processes, i.e. the spore preparation and two alternative seeding methods to attach the spores or juveniles onto string that can be deployed to sea, the cultivation period at sea, the harvest of the biomass, and finally, biomass preservation and storage. The supply chain is in principle similar to that studied by van Oirschot et al. (2017), though it is extended to include hatchery processes and different preservation alternatives. This study also features a longline cultivation system designed for use in a sheltered area (as relevant for the Seafarm-project) rather than the robust strip infrastructure designed for more exposed conditions studied in van Oirschot et al. (2017). The Seafarm air-cabinet drying process is furthermore based on the use of a blower and heat-exchanger rather than a light oil fuelled maize drying system as in van Oirschot et al. (2017).
This study also compares two conventional methods for the seeding step referred to as submersion seeding and spray seeding, as well as four alternative scenarios for the biomass preservation referred to as drying by hanging on a structure outdoors, drying by means of a heated air-cabinet, ensiling and freezing the biomass at -18 °C in a mobile shipping container. Sensitivity analysis was also conducted to handle the uncertainties associated with these processes, but also with the main parametric inputs of the model as a whole. All of the supply chain steps, their processes, materials and energy inputs are listed as inventory items in Table 1, along with the required input of each item to produce and preserve 1 ton of fresh biomass, i.e. input per functional unit.

Figure 1: the Seafarm supply chain alternatives, including all necessary steps for the production and preservation of seaweed biomass (grey boxes) with the exception of the selection of parent specimen (white box). The boxes framed with dotted lines are the supply chain steps studied by van Oirschot et al. (2017), upon which the current system has been expanded.
2.2.1 Spore preparation

First and prior to the preparation of macroalgae spores for reproduction, parent specimen should be selected. This selection process can be continuous and is not definite; it may require a variety of approaches to handle a range of parameters, from monitoring genetics of the specimens and tolerance to local conditions to identification of resistance to specific diseases and high biomass yields. For the purpose of this study, these selection processes are excluded as they are so context depended and variable; the supply chain begins with selected parent specimen.

The spore preparation (step 1) includes all the processes involved in obtaining a concentrated solution of healthy spores from parent specimen. First, the blades of parent specimen must be encouraged to develop spores; they are cleaned, then left in an artificially lit and temperature-controlled flow-through bucket, containing a medium of filtered, aerated and stirred seawater for a period of six to ten weeks. By the end of this period fertile sorus tissue has developed and the spores are collected in a beaker of sterilised water. For confidentiality reasons, it is not possible to further detail spore preparation conditions here, for instance specifying temperature requirements or lighting regimes. Table 1 therefore contains aggregate inventory data for this step. Due to a lack of fluorescent lighting systems in EcoInvent 3.2, a customised lighting system was built in SimaPro based on the material components of a 38 Watt T8 fluorescent light tube from Sangwan et al. (2014) and adjusted to the mass of the 58 Watt XLR T8 fluorescent light tubes used in the Seafarm hatchery.

2.2.2 Seeded lines

Next comes the seeding (step 2), involving all the processes to obtain a spool of string covered in juvenile seaweed (henceforth seeded line or collector), ready to be deployed to Sea. Two alternative methods are examined in this study as scenarios; they are referred to as submersion seeding (2A) and spray seeding (2B). Both methods, like the previous spore preparation step, take place in a laboratory, providing the right conditions for the spores or gametophytes to settle on collectors and grow into juveniles that are large enough to thrive at sea. The medium in which the seeding takes place, referred to as the nutrient mix in table 1, is made in the laboratory and follows the Provasoli enriched seawater formula (McLachlan, 1973). The two methods differ in terms of how the settling on the collector takes place: the submersion seeding involves submersing the collector in a concentrated spore solution and then transferring it to tanks for juvenile maturation, while the spray seeding involves an extra step which allows for the spores
to develop into gametophytes before they are sprayed onto the collectors. In practice, these methods can differ in terms the time required to produce the seeded collectors, density of settled spores on the collectors and associated subsequent yields, however in the present study, the comparison between the methods is made with the assumption that they produce the same quality seeded collectors (no difference in subsequent yields, only in the process). After the spores have settled onto the collectors, they are transferred into aquaria and mature into juveniles over a period of 3 to 5 weeks until they reach a few centimetres in length from the holdfast to the tip of the frond; only then are they finally ready to be deployed to Sea. Similarly as for the spore preparation step, for confidentiality reasons, it is not possible to provide details with regards to specific conditions of the seeding methods. Table 1 therefore also contains aggregate inventory data for this step.

Figure 2: the Seafarm cultivation infrastructure, as seen from above and from two cross-sections. The infrastructure consists of anchoring buoys (a), longline buoys (b), longline ropes
(c₁ and c₂), anchoring ropes (d₁, d₂ and d₃), chains (e), shackles (f) and concrete anchors (g). Quantities of each input are listed in terms of the functional unit in table 1, and specifications of the materials are provided in section 2.2.3.

2.2.3 Cultivation

The next step in the Seafarm supply chain is the cultivation (step 3), which includes the seaweed cultivation infrastructure, deployment of the collectors to sea and regular monitoring while the seaweed mature. Figure 2 represents the Seafarm cultivation infrastructure currently installed over 2 hectares in a sheltered part of the Koster Archipelago. It consists of a series of longlines (c₁: polyester silk, 16 mm ø, 0.17 kg/m) measuring 190 m in length and kept at a depth of 2 m by buoys (b: polyvinyl chloride, 6.1 L, 0.6 kg each) and connecting ropes (d₃: polypropylene, 8 mm ø, 0.03 kg/m) every 10 m down their whole length. At the extremity of each longline, an anchoring buoy (a: polyethylene, 120 L, 6 kg each) maintains strong buoyancy and is connected to an anchor (g: concrete, 600 kg) on the seafloor by a series of thick and strong ropes (d₁ and d₂: polypropylene, 24 mm ø, 0.26 kg/m) as well as chains (e: low-alloy steel, 19 mm ø, 7.5 kg/m) and a shackle (f: low-alloy steel, 22 mm ø, 1.3 kg each). A total of 26 longlines run parallel to one another separated by a 4 m access corridor, covering 2 hectares of sea space and providing a total of nearly 5 km of longline upon which juvenile seaweed can mature safely at sea. Additional structural reinforcement is provided by an additional longline (c₂: polyester silk, 24 mm ø, 0.39 kg/m) running laterally across the midpoints of each longline, also held in place by anchoring buoys (a) linked to concrete anchors (g) by means of thick ropes (d₁ and d₂), chains (e) and shackles (f).

2.2.4 Harvesting

Between early winter and early summer, the seaweeds mature until they reach 1-2 m in length, at which time they are harvested from the infrastructure (step 4). The uptake of nutrients and elements from the water at the moment of harvest, commonly referred to as bioremediation or bioextraction in literature, is based on compositional data from (Schiener et al., 2015) with the exception of phosphorus content which is based on author measurements. The uptake of compounds by the seaweed is included in this study by means of systems expansion, following the same method as Seghetta et al. (2017). The harvest is currently a very labour and time intensive process, limited by the loading capacity of the research vessel used for this purpose; this process is the one most in need of optimisation to enable upscaling of operations. The
current practice involves lifting the longline above the vessel’s deck, from where it is torn off and packed into harvest bags (polypropylene) ready for transport back to shore. Alternatively, the longlines can be coiled up on deck with the biomass still attached. Located approximately 10 km away from the quay, a total of 17 return trips are needed to complete the harvest. During transport back to shore, offloading at the quay and prior to the next step in the supply chain (preservation), it is assumed that 20% of the water content of the biomass is lost from drippage (Konda et al., 2015, van Oirschot et al., 2017). Once delivered to shore, the bags are offloaded from the vessel and transported a short distance to a hypothetical preservation facility. In the Seafarm case the alternative preservation processes are undertaken in several different locations, some less than 50 m from the quay where they are offloaded, others several hours drive away; however, for the sake of comparison in the present study, they are all assumed to be located in a preservation facility 1 km from the quay. The biomass is transported there by tractor and this transportation is included as a part of the harvest.

2.2.5 Preservation

Four alternative preservation methods are compared in the present study – hang drying outdoors (5A), drying in a heated air-cabinet (5B), ensiling (5C) and freezing (5D) - each of which was designed with the capacity of handling the entire harvest from the 2 hectares cultivation. Of these four alternative preservation methods, only the freezing is yet applied at full scale as a part of the Seafarm project, both for practical reasons and because of a local demand for frozen biomass, however exploring the potential of alternative preservation methods is a key part of Seafarm and other follow-up projects. The three other preservation methods have been designed for this study; they are scaled-up processes based on literature and on the experience gathered by the authors when conducting small to medium scale experiments (more than 10 kg fresh weight).

The hang drying method takes place outdoors and involves hanging the longlines with the biomass still attached directly onto a series of wooden A-frames (cleft timber and low-alloy steel screws), leaving gaps between the longlines of approximately 50 cm to ensure aeration. With this approach the biomass takes a few days to dry, then it is removed from the ropes, put into bags (polyethylene packaging film) and vacuum packed for storage. Unlike the outdoor drying method that requires the biomass to still be attached to the longlines so that it can be suspended from the wooden structures, the three other methods are more effective at preserving shredded biomass. As such, the other methods all begin by shredding the biomass using a
garden shredder, breaking up the long blades into smaller pieces to facilitate preservation. For the air cabinet drying, the shredded biomass is spread out evenly across the shelves of mobile racks (steel), which are moved into a heated and aerated room fitted with a blower and heat exchanger unit with a specific moisture extraction rate of 3 MJ per kg of water, after which it too is vacuum packed for storage. For the ensilage, each ton of shredded biomass is mixed with 2 L of ensilage chemicals (85 % formic acid and 15 % tap water), and are transferred into a silo (concrete blocks on a concrete foundation) using a tractor, covered with plastic sheeting (polyethylene packaging film) and weighted down by gravel to maintain a seal and avoid oxygen contamination. A by-product of liquid ensilage effluent is collected and used as a substrate for the production of biogas, as suggested by Herrmann et al. (2015), in which it is reported that 1m³ of biogas requires approximately 14.9 kg of ensilage effluent. A biogas substrate was identified as a part of a biogas production process in EcoInvent, which uses 0.66 kg of grass (DM) to produce 1m³ of biogas, thus it was assumed that for each 22.4 kg of effluent used to produce biogas, there would be a resultant avoided production of 1 kg of grass (DM) substrate. Unlike the three other methods, the ensiled biomass is not vacuum packed, rather it is assumed it remains in silo ready for subsequent use. The fourth and final preservation method is the freezing: the shredded biomass is packed into vacuum sealed plastic bags (polyethylene packaging film) and placed in cold storage at -18 °C (40 foot cold storage shipping container). Each preservation method includes 3 months (90 days) of storage time, an estimate considered to be reasonable, based on average storage duration of the Seafarm biomass. Unlike fisheries products which can be caught at any time of year, longer storage time is highly relevant for seaweed biomass so that it can be readily available year-round, beyond species-specific harvest seasons. The number of vacuum bags used in each preservation method is estimated as a function of the vacuum bags’ weight limit (2.5 kg per bag) and the mass of biomass being packed into the bags. The Seafarm supply chain, subject of this study, thus ends after the preservation of biomass in these four alternative ways.

2.3 Life Cycle Impact Assessment (LCIA)

The impact assessment of the kelp cultivation and preservation system, following van Oirschot et al. (2017), was conducted using the CML 2 baseline 2000 (v2.05), a commonly used method that produces impacts across ten categories: abiotic depletion (AD), acidification (A), eutrophication (E), climate change (GWP100), ozone layer depletion (OLD), human toxicity (Ht), freshwater aquatic ecotoxicity (FWet), marine aquatic ecotoxicity (Met), terrestrial...
ecotoxicity (Tet) and photochemical oxidation (PO). In complement and for additional perspective on energy use, Cumulative Energy Demand or CED (v1.09) was also used (Frischknecht et al., 2007), the six categories of CED being combined into two clusters: renewable (rCED) and non-renewable (nrCED) cumulative energy demand.

2.4 Software and databases

The life cycle inventory data was collected and processed in Microsoft Excel, wherein all calculations were made to quantify inputs in terms of the functional unit. SimaPro 8 was used to match inventory items with processes from the EcoInvent database (version 3.2), the impacts of which were exported back to Excel for further analysis.

2.5 Sensitivity analysis

There are numerous variables and uncertainties that affect a seaweed cultivation and preservation supply chain in practice, notably variations of harvest yield due to seasonal variation, all of which may have varying degrees of effects on the outcomes of a life cycle environmental analysis. Sensitivity analysis was therefore undertaken on a series of variable inputs by varying their values by 10 % increments, from 50 % to 150 % from the modelled case. Similar as in Van Oirschot et al. (2017), inputs were selected for analysis based on (1) whether they were subject to variability or uncertainty of data, and (2) if that input have a relatively large contribution to total impacts in one or several categories.

The first input selected for sensitivity analysis was the biomass yield of 10 kg per meter of longline, a number selected based on experienced yields at the Seafarm cultivation site though also likely to vary significantly from year to year, depending on the weather experienced during the growth season and a range of other parameters. The second input selected for sensitivity was the 90-day duration of the storage of preserved biomass, both because in practice this can vary significantly depending on the market and demand, but also because, unlike the drying or ensilage preservations, the freezing has a daily energy requirement for cold storage and thus is expected to vary significantly. The third input selected for sensitivity was the specific moisture extraction rate (SMER) of 3 MJ per kg of water for the air cabinet drying system, a number that can vary significantly in practice according to ambient conditions and the efficiency of the drying system in use, but also the most numerically sensitive parameter of the air cabinet drying scenario. Given the high level of uncertainty regarding the life expectancies of different
cultivation infrastructure materials, anticipated as either 5 years (for longline ropes) or 10 years (for all other components: anchors, buoys, shackles and chains), these became the fourth and fifth parameters subjected to sensitivity by shortening or extending life expectancies of all components with 5-year and 10-year life expectancies. Finally, a failure rate of up to 50% was introduced for the hatchery as an additional sensitivity parameter, to represent the need to re-run spore preparation and seeding steps when the production of seeded collectors fails.
3 Results and discussion

3.1 Comparison of seeding methods

Figure 3 presents a comparison of the impacts of the two seeding methods of the hatchery, normalised to the method with the highest impacts: the submersion seeding method. On the whole, the two methods perform similarly though submersion seeding performs slightly worse, accounting for 5 to 10% higher impacts in all categories, with the exceptions of Tet and nrCED for which impacts are around 20% greater, and for OLD and rCED where impacts are approximately 30 to 35% greater. The main differences that emerge between the two seeding methods seem to be a direct result of differences in the time that both methods take, and consequently, on the energy consumption of processes such as the aeration, temperature control and the lighting. Across most impact categories, with the exceptions of AD, A GWP100 and PO, the energy consuming processes therefore dominate. Of these energy consuming processes, on average across all impact categories, the highest shares of impacts are a result of the temperature control mainly, with the exceptions of OLDP where lighting contributes approximately the same share as cooling does, and in the two CED categories where the lighting exceeds contributions of the cooling.
Figure 3: normalised comparison of impacts of the submersion seeding (2A) and spray seeding (2B) methods employed at the Seafarm hatchery

In spite of differing in their practice and the time taken for each method, leading to above discussed energy-related differences, the spray and submersion seeding methods’ other inputs remain fairly similar, leading to similar input inventories. Both methods require the same items and amounts of material, notably the collectors, seeding lines, aquaria, filters, and other basic laboratory equipment, each of which contribute equally to the impacts of both methods. Of these material inputs, on average across all impact categories, the highest shares of impacts come from the life cycle of the aquaria (Acrylic Perspex) and then the collectors (PVC), though the contribution of the seeding line are comparable to that of the collectors in GWP100 and AD. Material inputs contribute more than energy inputs to certain impact categories, notably in AD, A, GWP100 and PO, however the energy inputs clearly dominate other impact categories, particularly OLD, rCED and the toxicity categories. It should also be considered that the laboratory scale processes portrayed in this study also represent a worst case, and the authors anticipate that efficiency savings in material and energy use would take place at larger scale operations.

The comparison of the two seeding methods, based on the assumption that they perform equally well in their provision of seeded collectors, showed that there is little difference between them in terms of their environmental impacts from a life-cycle perspective. In practice, however, these two methods do not necessarily produce seeded lines of the same quality every time. Adjusting for unequal performance in the task of delivering healthy seeded lines may have yielded slightly different results to those in the present study, however the sensitivity analysis (Figure 5) of the parameter capturing hatchery failure shows that the impact contributions of the seeding methods relative to the rest of the supply chain do not vary to a great extent. The hatchery processes (spore preparation and seeding steps combined) on average contribute between 5 and 10 % of total impacts relative to the worst case, though these contributions more than double relative to the hang-drying scenario, the total impacts of which are less than half those of the worst case. Given these relatively small contributions, that the production of seeded lines with the correct density of healthy juveniles is the ultimate function of the hatchery, and that in practice an effective hatchery will have a significant impact on the eventual yield of fresh biomass per meter of longline (the most sensitive parameter of the modelled supply chain),
it is suggested that supply chain designers should select those hatchery processes that maximise yields, first and foremost, as this will offset impacts of the entire supply chain.

Other seeding methods exist besides the two compared in the present study - some are more labour intensive, others employing patented glue-like substances to attach juvenile seaweeds directly to long-lines at sea - however, the spray and submersion methods remain the only methods employed within the Seafarm project, and thus are the only ones for which reliable data could be acquired. Future studies should review additional methods too, and optimisation strategies could be pursued to improve the energy efficiency of hatcheries. The results further highlight that due to the share of impacts from the nutrient mix used to fertilise the juveniles during their maturation, experimental work should take place on the use of alternative nutrient sources such as waste-water or slurry. This would improve the impact profile of the seeding methods, particularly in the eutrophication and toxicity categories.

3.2 Comparison of preservation methods

The relative shares of impacts from each step in the supply chain – including the four preservation methods – are presented in figure 4 and normalised to the scenario with the highest contributions, the reference scenario ending with the freezing of biomass. Since the only difference between the four supply chains originate from the preservation method, Figure 4 therefore also shows the relatively different magnitudes of contribution to impacts resulting from the different approaches to preserving 1 ton of biomass. On average across all impact categories, the preservation method with the best environmental performance is hanging the biomass outdoors, followed closely by ensiling which also has low impacts which are principally due to the concrete silos and the formic acid used to lower the pH. The ensilage effluent that leaks out of the silo during preservation is used as a biogas substrate as recommended by Herrmann et al. (2015), thus replacing grass as a substrate and resulting in the avoided production of grass. Hence that the credit for this, i.e. the negative impact for ensiling in the E and A impacts notably, helps to improve the performance of the ensilage alternative.

The worst performing preservation method was found to be the energy intensive freezing process, particularly in the CED categories due to the high energy requirements and in OLD due to refrigerants in the freezing equipment. It is also the only preservation method whose impacts are affected by the passing of time: once ensiled or dried and vacuum packed, the biomass can be stored at room temperature for months with no additional energy expenditure,
however, the frozen biomass requires constant energy expenditure to maintain a safe cold storage temperature over 90 days. The impacts of seaweed preservation by freezing could therefore be reduced by decreasing storage time to a minimum, by utilising energy efficient freezing systems, and if longer storage periods are required, by using a better insulated storage space to reduce daily energy consumption. The impacts of the other preservation methods are normalised to those of the freezing method for comparison.

The air-cabinet drying was also found to perform relatively poorly, principally owing to high energy consumption, though in this case the energy expenditure is initial - to dewater the biomass - and there are no cumulative energy requirements over time. To minimise this energy consumption and associated impacts, it would be advisable for such drying methods to employ as efficient a system as possible. Further research is needed to determine optimal conditions and practices for the effective drying of seaweed biomass. On average, impacts were found to be between 40 and 60 % lower for the air-cabinet drying than for the freezing, with the exception of estimated E and A impacts which were around 20 % lower for the freezing as a result of the high impacts of the steel drying racks in these categories, and with the exception of OLD where the particularly high impacts of the freezing method dwarf those of the air-cabinet drying. The ensilage method performed third best across all impact categories. Contributions were relatively more elevated in AD, A, E and GWP100 than in the other categories, owing to the contributions of the concrete silos, though the impacts in A and E were largely offset by the ensilage effluent, which may result in the avoided production of grass as a biogas substrate. Finally, the best performing preservation method by a significant margin was the hang drying method, whose main impact contributions originated from the wooden supports and storage bags.

3.3 Supply chain impacts

Figure 4, as as mentioned, presents the relative shares of impacts from each step in the supply chain (spore preparation, seeding, cultivation, harvesting and preservation methods), normalised to the scenario with the highest contributions, the reference scenario ending with the freezing of biomass. Positive environmental impacts can be seen for all steps, except for bioremediation that mitigates environmental impact and therefore is credited with a negative contribution, as well as the avoided production of grass as a biogas substrate. The contribution of all steps, except for the preservation methods, remains the same in absolute terms across the
supply chains. The relative shares of impacts in the supply chain differ across the preservation methods, depending on their impact contributions as discussed in detail in section 3.2. The freezing step, which includes 90 days of cold storage, a reasonable average duration of storage based on case data, resulted in a greater share of environmental impacts than the rest of the supply chain (steps 1 to 4) combined. The freezing process averages a share of between 60 and 70 % of total impacts across the impact categories, with the exceptions of OLD and rCED for which the share is even greater, above 90 %, and Tet and nrCED for which the share is between 80 and 90 %. The next greatest shares of contributions across the supply chain are those of the air-cabinet drying, which is also relatively energy intensive, contributing between 30 and 50 % of total impacts, though with particularly high shares in E and A categories. Both ensilage and outdoor hang-drying performed very well relative to the energy intensive alternatives of air-cabinet drying and freezing.

Figure 4: normalised comparison of the impacts resulting from the Seafarm supply chain, including four alternative preservation methods.

The cultivation step, which includes and represents the infrastructure, its installation ad monitoring, is also significant across all categories, taking an average of between 20 and 30 %
of contributions in the reference scenario with freezing as preservation method, except in Tet and nrCED where it contributes to around 10 % of impacts, and rCED and OLD where it contributes to less than 5 % of impacts. Those steps of the supply chain with the smallest shares of impacts were found to be the harvest, spore preparation and the seeding methods, of which the combined contribution to the impacts for the freezing scenario did not exceed 10 % in any impact category. Nevertheless and given that to the authors’ knowledge seeding processes have not been included in LCAs of seaweed production systems to date, thus the higher resolution analysis of the impacts of the seeding steps provided in section 3.1.

On the whole, the energy intensive preservation methods are responsible for the greatest shares of impacts followed by the contributions of the cultivation infrastructure, as was the case in van Oirschot et al. (2017). The relative shares of preservation and cultivation impacts, however differ between the two studies, due to a range of differences in infrastructures and supply chain configurations. The considerable shares of toxicity impacts due to the stainless steel chains in van Oirschot et al. (2017) have been reduced in Seafarm-project and thus in the present study owing to the use of a low-alloy steel in the Seafarm infrastructure. Furthermore, the infrastructure studied in van Oirschot et al. (2017) was developed for more exposed conditions than the Seafarm infrastructure, resulting in more robust infrastructure needed and thus more materials used for infrastructure in the case of Van Oirschot (2017) than here (based on differences in how the two infrastructure designs are configured). Another key difference is the air-cabinet drying process of the present study involves the use of an electrically powered blower and heat exchange unit, whose impacts appear to be reduced relative to the light oil fuelled maize drying process utilised in van Oirschot et al. (2017).

In terms of the impact contributions of each material component in the cultivation infrastructure, the results are nevertheless similar to those in van Oirschot et al. (2017), with the exception of the chains which have a much reduced impact in the present study because they are made from a different type of steel. In particular, the plastic longline ropes are still relatively high contributors to AD impacts as well as the nrCED due to the crude oil used to manufacture them, suggesting that alternative non-toxic rope materials, e.g. hemp or manila, should be explored as lower-impact alternatives particularly as these would biodegrade and not contribute to microplastic pollution.
3.4 Impact mitigation by bioremediation

Mitigation of impacts occurs in E and GWP100 categories and to a lesser extent in the Ht and Met categories, as a result of the removal of nitrogen, carbon, phosphorus and the other compounds that have been fixed in the biomass when it is harvested. Given an yearly average content in dry matter *Saccharina latissima* of 26.6 % carbon, 1.45 % nitrogen (Schiener et al., 2015) and 0.24 % phosphorus (author measurements), it is estimated that every ton of fresh harvested biomass will contain 40.2 kg of carbon corresponding to a GWP100 mitigation of 147.4 kg of CO$_2$ equivalent, and 2.2 kg and 0.4 kg of nitrogen and phosphorus, respectively, corresponding to a eutrophication mitigation of 2.03 kg of PO$_4$ equivalents. However, supply chain emissions amount to 43.5 kg of CO$_2$ equivalent and 0.05 kg of PO$_4$ equivalent to cultivate and harvest one ton of biomass (steps 1-4), with preservation resulting in an additional 7.7, 40.8, 18.2 and 92.5 kg of CO$_2$ equivalent and 0.006, 0.1, 0.02 and 0.1 kg of PO$_4$ equivalent for steps 5A-D, respectively. Thus, depending on which preservation method is undertaken, the production of preserved biomass is carbon negative, mitigating between 1.1 and 2.9 times more CO2 equivalent than is emitted by the supply chain. Furthermore, the production of preserved biomass results in a eutrophication mitigation of between 11 and 36 times more PO4 equivalent than is emitted by the supply chain. Bioremediation was also found to be responsible for partial mitigation of Ht and Met impacts, respectively only amounting to 21 % and 9 % of total impacts resulting from the freezing scenario, though respectively amounting to a much larger proportion of 74 % and 27 % of total impacts resulting from the outdoor hang-drying scenario.

This case-based validation - that as a result of the removal of the biomass from the sea, bioremediation results in a net mitigation of eutrophication and climate change impacts and partial mitigation of other impacts, *even* when taking a life cycle perspective of the entire seaweed cultivation and preservation supply chain – is perhaps the most important finding of this study. Such significant mitigation of eutrophication impacts suggests that commercial seaweed cultivation and supply chains should be recognised and promoted as powerful tools for eutrophication management in coastal areas. Furthermore, there is a need to map downstream usage of the nitrogen and phosphorus fixed by seaweed biomass, to determine the potential role of seaweed-based products in closing the loop on nitrogen, but especially the more finite phosphorus.
Bioremediation was not yet covered by van Oirschot et al. (2017), but these findings are in line with other studies in literature, notably Seghetta et al. (2017) which reports net negative impacts in climate change and both nitrogen and phosphorus limited eutrophication impact categories. It is important to emphasise the importance of this additional life cycle perspective which accounts for the impacts of material inputs required to gain impact mitigation benefits, thus providing a more complete picture than studies which do not include life cycle inputs, e.g. Xiao et al. (2017), in which the focus remains solely on bioremediation potential, disregarding the impacts resulting from the operations that enable the bioremediation. Finally, as the product of a proof-of-concept research project, the Seafarm supply chain was not optimised to minimise impacts; this highlights that with further supply chain optimisation, there is potential for even greater return on investments to be achieved with regards to environmental impact mitigation.
3.5 Sensitivity analysis

Figure 5: Sensitivity analysis of key parametric inputs of the air drying (green line only) and freezing (all other lines) scenarios of the modelled Seafarm supply chain, varying numerical inputs to the model at 10 % increments from 50 % to 150 % of the base case (100 %) across the x-axis: biomass yield (dark blue squares), duration of storage (red squares), SMER value of the air cabinet dryer (green triangles), 5-year (light blue crosses) and 10-year (purple crosses) infrastructural life expectancies, and hatchery failure (orange circle).
The results of the sensitivity analysis of six key parameters of the model in the freezing scenario are presented in figure 5. The input of 10 kg fresh weight per meter of longline is a slightly conservative estimation based on case data from the Seafarm cultivation site over several years, while also being comparable to typical yields in literature, for instance the 9.1 kg fresh weight per meter of longline reported by Seghetta et al. (2017). Nevertheless, it is considered to be highly uncertain, mostly due to seasonal variations, but also due to risk factors such as disease or storms, and variability resulting from slight changes in technical protocols, for instance in the hatchery. The sensitivity analysis revealed, in accordance with Van Oirschot et al. (2017), that biomass yield was the one of the most sensitive parameters across most impact categories, due to the fact that it is wholly tied to the functional unit of the study (the same applies for the other preservation methods). From figure 5, it can also be seen that the biomass yield’s sensitivity forms a curve, representing that the net magnitude of change in impacts is greater for reduced yields than for increased yields: decreasing yields by 50 % resulted in an increase of approximately 41 kg of CO\textsubscript{2} equivalent per ton of fresh biomass, whereas increasing yields by 150 % resulted in a much smaller decrease of approximately 14 kg of CO\textsubscript{2} equivalent per ton of fresh biomass. As an element beyond human control, natural variability in yields from year to year will therefore have a large effect on impacts resulting per ton of produced and preserved fresh biomass. However, there are also technical measures that lie within human control that can significantly affect yields, for instance the density of juveniles on the seeded line produced in the hatchery or whether a farm is positioned in sheltered or exposed waters, amongst many others; measures whose optimisation will ultimately improve biomass yields and thus reduce impacts. Similarly, the use of preventative measures to avoid significant yield losses, such as the use of more robust, storm-resistant infrastructure, should be a strategic priority even when these measures may increase impacts.

The most sensitive parameter in the freezing model was found to be the duration of storage. As aforementioned, the impacts resulting from preserving biomass by drying or ensiling biomass are not affected by the passing of time in the present model; however every additional or subtracted day of maintaining the biomass frozen requires additional energy and results in increased impacts. Conversely, shortening the duration of storage also significantly reduces the impacts of the freezing method. Another variable affecting energy consumption was also identified as highly sensitive, though with regards to the air-cabinet drying: the SMER of the drying cabinet. Varying both SMER and duration of storage resulted in linear patterns of sensitivity owing to these parameters having a direct multiplying or dividing effect on
preservation energy consumption. The high sensitivity of each of these parameters can be explained by the large impact contributions of the freezing and drying processes relative to their scenarios, suggesting that small improvements to the efficiency of these processes may have significant potential to reduce impacts, particularly in categories where those processes had particularly large shares of impacts. For instance, the air-cabinet drying step only contributes to approximately 23% of OLD impacts relative to worst scenario, in contrast to the 97% contribution of the freezing step; correspondingly, it can be seen from the OLD chart in figure 5 that these differences result in a reduced sloping gradient (and thus reduced sensitivity) of the SMER value relative to the greater sloping gradient (and thus increased sensitivity) of the duration of storage. This difference in gradient and corresponding sensitivity is repeated across all impact categories, with the plotted line of the SMER value consistently having a slightly lower gradient than that of the storage duration.

Sensitivity analysis was also conducted on the life expectancy of cultivation infrastructure components estimated to last for 5 years and 10 years. The sensitivity of both the 5-year and 10-year materials have similar results, whereby a decrease in life expectancy would result in the need for more frequent replacements, increased material inputs, and consequently, greater corresponding impacts across all categories. Like for the SMER and storage duration parameters, the magnitude of effects on specific impact categories is a function of relative contributions to that impact. Illustrating with extreme opposites, the 5-year materials have a greater contribution (56% of step 3) to AD impacts than the 10-year materials (40% of step 3), and thus the 5-year materials are correspondingly more sensitive with regards to AD impacts; whereas in the Ht category the reverse is the case, with a much greater contribution to impacts resulting from the 10-year materials (89% of step 3) than from the 5-year materials (8% of step 3), and thus the 10-year materials are correspondingly more sensitive with regards to Ht impacts. The final parameter subjected to sensitivity analysis was the productivity of the hatchery (steps 1 and 2A). Though a total of 52 collectors are deployed across the 2 ha Seafarm cultivation infrastructure, in practice, the reality is that some seeded collectors may not have developed the necessary density of healthy juveniles to be effective at sea. As such, an error margin was introduced in the sensitivity by incrementally increasing total production of seeded collectors to a maximum of 150% (approximately 75 collectors); a decrease to a minimum of 50% was seen as irrelevant. This increase in productivity also results in a slight increase in impacts across all categories, owing to the additional material and energy used in the increased production.
The relative magnitude of sensitivity of the 5-year, 10-year and hatchery productivity parameters, which is visually represented in figure 5 by the gradient of each respective plotted curve, is much lower (flatter) than those of the SMER value, storage time and biomass yields. This is principally due to the fact that, while 5-year, 10-year and hatchery productivity parameters are important potential variables of their respective supply chain steps, their shares of total impacts are diluted in the context of the whole supply chain.

One final parameter was subjected to sensitivity analysis but is not included in figure 5: the assumed distance from the port to the cultivation site. The step of the supply chain most affected by changing the assumed distance between the cultivation and the port is the harvesting step, due to the numerous return trips needed to complete the harvest. Only very small changes in overall supply chain impacts are detected with variations of 50 to 150 % from the 10 km assumption. At 100 km distance (1000 % increase), the AD, A, E and GWP categories experience small increases of around 10 % in their shares of total impacts, and PO and nrCED experience an increase of around 5 % in their shares of impacts. While these represent relatively important contributions, it should also be noted that these increases could be mitigated by improving the load limit of the vessel to reduce the number of return trips needed to complete the harvest. The present model suggests that distance of travel from port to cultivation is not a significantly important factor in terms of environmental impacts, however, given the lack of adequate sea-worthy, small-scale transport vessels (less than 100 tons) in the EcoInvent database, it is recommended that a more detailed analysis of the potential impacts of transport at sea be conducted in future.

3.6 Limitations

While the life cycle perspectives gained from this study do shed light on a broad spectrum of impacts resulting from the life cycle of the inputs of the Seafarm supply chain, LCA does not account for the direct and local environmental impacts from the presence of seaweed cultivation systems. Studies have been conducted as a part of the Seafarm project to investigate local environmental impacts notably on the benthic environment and on the provision of ecosystem services (Hasselström et al., In Press). At current scales of operation of the Seafarm cultivation, studies suggest local environmental impacts are minimal or negligible. Larger scale seaweed industries such as those in Asia are also not reportedly cause of significant environmental
impacts, quite the contrary in fact, they are seen as a way of capturing waterborne emissions of nitrogen, phosphorus and other substances (Xiao et al., 2017).

Though valuable in its provision of a broad spectrum of impacts, the CML baseline method in principle does not differentiate between phosphorus- or nitrogen-limited eutrophication, which tend to relate to freshwaters and marine waters, respectively (Hauschild and Potting, 2005). The SimaPro-software on the other hand facilitates looking into the separate contributions from both nutrients, showing order of magnitude similar contributions from all processes except bioremediation. Similar LCA studies of seaweed supply chains, for instance Seghetta et al. (2017), do differentiate between the two providing a valuable perspective lacking in the present study.

It is recommended that future studies could more explicitly distinguish between the eutrophication impact of both nutrients, or contribute to the development of relevant and novel impact categories, particularly those that may add valuable perspectives relevant to marine-based production systems and supply chains. One example of a highly pertinent environmental issue to which seaweed farms may be contributing but that was not covered by the scope of the present methodology, is the contribution to micro-plastic pollution as result of the degradation of plastic components of the cultivation infrastructure such as ropes and buoys. Similarly, the net uptake of CO$_2$ and production of O$_2$ by the biomass during photosynthesis may have other impacts or benefits, for instance related to ocean acidification, which are unaccounted by the presently employed CML baseline method.

The model of this supply chain includes an inventory of the known and quantifiable inputs and outputs of the system; it is possible, however, that some inputs and outputs may have been omitted out of error. One emission, however, was intentionally excluded from the present study, both due to a lack of available data and as a result of uncertainty in literature on the issue: the emission of bromide substances by kelp metabolic processes. Bromide gases are known to negatively affect the O-zone layer and may contribute to OLD, and they are also known to be metabolised by kelps, though little is known with certainty about the effects of these bromides in the long term, particularly those produced from kelps which are known to be short-lived. Further studies are needed to specifically determine a suitable way of incorporating these short-life bromide emissions into life cycle analyses of kelp supply chains.
Finally, it should also be noted that this study only covers part of the life-cycle of seaweed-based products: it is a cradle to gate study that begins with the hatchery, ends with preserved biomass, and is limited to the data available as a result of the Seafarm project. Future studies should aim to explore downstream processing of preserved biomass into market-ready products as well as relevant subsequent steps of these products’ life cycles, and draw comparisons with other equivalent products or materials that these may seek to replace.
4 Highlights

The results presented in this study are the outcome of a model specifically representative of the practices of the Seafarm supply chain, which has been developed for proof-of-concept following recommended practices as established in literature. The study is therefore considered to be representative of small to medium scale supply chains being developed for the cultivation and preservation of seaweed in a European context, and relevant in terms of common practices and similar supply chain activities. In the details, however, and as hereafter exemplified with three examples of minor differences in supply chain configurations, some results are not generalizable as they are a result of case-specific design choices that translate into exceptional items in life cycle inventories and specific associated impacts. In van Oirschot et al. (2017), for instance, stainless steel chains are used in the cultivation infrastructure, a material which has particularly high toxicity impacts; in the Seafarm infrastructure, however, low-alloy steel chains which have considerably lower impacts are used, resulting in one of the most important differences in impacts between van Oirschot et al. (2017) and the present study. Similarly, to facilitate the handling of large volumes of biomass arriving from the cultivation site, the ensilage method portrayed in this study employs large concrete silos, whereas other supply chains may use smaller plastic barrel silos for different reasons, which might result in a different contribution to impacts for the ensilage step. Finally, the impact of the freezing method portrayed in this study are based on the energy consumption of a cold-storage shipping container used by the Seafarm project, however alternative configurations could feature more efficient freezing methods and a better insulated storage space that may reduce total energy consumption. While these variations in supply chain designs are to be expected when comparing different studies and supply chains configurations, understanding the differences in associated impacts can reveal valuable lessons that are generalizable and have highlighted opportunities to optimise industrial activities from an environmental point of view.

In terms of overall results that are relevant to the development of seaweed farming in Europe, this study highlights that the choice of preservation method is the major factor affecting total impacts in a seaweed biomass cultivation and preservation supply chain, and that these supply chains can contribute to the European bioeconomy with valuable biomaterial for that may be carbon neutral or even carbon negative, all while also providing considerable eutrophication mitigation, even when taking a life cycle perspective of supply chain activities. The preservation method with the greatest contribution to environmental impacts was found to be
the freezing process followed closely by the air-cabinet drying, both due to their high energy requirements and for the freezing process, also because of the long duration of storage, whereas the ensiling and outdoor drying processes were found to have comparably low impacts primarily as a result of their much lower energy consumption. Effectively, this means that the environmental performance of seaweed-based products is, to a large extent, determined by the manner in which that the fresh seaweed is preserved. However, preservation methods too, in turn, will affect potential end-uses of the biomass. Drying the biomass above certain temperatures or in direct sunlight, for instance, could result in the denaturing of proteins which may be desirable compounds in seaweed-based food products; as such, these methods may not be suitable for the production of seaweed as food for human consumption, whereas other alternatives that would preserve proteins (e.g. drying at lower temperatures or freezing) might be better suited. While this study presents a comparison of the impacts of four alternative preservation pathways to inform relevant decision makers, notably that energy intensive processes such as biomass freezing and drying in an air-cabinet will result in much greater impacts than low energy alternatives such as drying outdoors or ensilage, these results will be most useful in complement to forthcoming studies that will be exploring the effects of preservation methods on biomass composition and properties, and associated costs of biomass processing alternatives.
Acknowledgments

The authors gratefully acknowledge insightful comments provided by the reviewers of this article, from Seafarm project partners and from colleagues at the Department of Sustainable Development, Environmental Science and Engineering (SEED, KTH). The study was funded by the Swedish Research Council Formas and conducted within the Formas Project ‘Seafarm’ (Grant Number 2013-92). The authors would also like to acknowledge Brazilian Science Without Borders (BEX 9714-13-8) and the Swedish Foundation for Strategic Environmental Research (MISTRA) within the AquaAgri program (DIA 2013/75) for their financial contributions.
References


Identifying suitable sites for macroalgae cultivation on the Swedish West Coast

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ABSTRACT

Special attention has been paid to sustainable macroalgae cultivation in Europe. The question on where suitable cultivation areas lie, without conflicting with current marine socio-economic activities and respecting the environment, remains a great challenge. Considering thirteen criteria critical to seaweed farming such as depth, shipping traffic and distance to ports, this paper aimed to identify suitable and sustainable offshore areas on the West Coast of Sweden for the cultivation of the Sugar Kelp, *Saccharina latissima*. An integrated approach with the tools Geographic Information Systems (GIS) and Multi-criteria Analysis (MCA) was used to aggregate the criteria by means of Boolean and Weighted Linear Combination (WLC) techniques. The Boolean method singled out 544 km² as suitable whereas the WLC method indicated 475 km² as highly suitable. Both techniques complement each other in finding optimal sites. Furthermore, the integrated models excelled in providing an overview for effective spatial decision-making that fosters sustainable development of macroalgae cultivations within marine and coastal systems.

Key words: Aquaculture, Boolean, macroalgae cultivation, site selection, weighted linear combination.
INTRODUCTION

Macroalgae, also known as seaweeds, are primary producers of food and oxygen, essential to the food chains in aquatic environments (Pereira 2015). Sugar kelps (*Saccharina latissima*) thrive attached to reefs and rocks occupying the photic zone, from temperate to polar regions (Hurd et al. 2014), in the North and Northeast Atlantic, from Portugal to Greenland including North and Baltic seas, Northwest Atlantic and Northeast Pacific (Pereira 2015). As one of the feedstocks of a valuable global industry, sugar kelps are utilized as human food, feed for fish aquaculture and in animal husbandry, to produce bioenergy and fertilisers (Peteiro, Sánchez, and Martínez 2016), and they contain a variety of compounds useful in the cosmetic, pharmaceutical and food industries (Pereira 2015). Furthermore, macroalgae cultivation presents distinct advantages compared to terrestrial biomass production: seaweed cultivation uses coastal areas thus it does not add to the competition for arable land, nor does it require fertilizers, fresh water or other agricultural inputs such as pesticides (Hughes et al. 2012). It does, however, have to compete with recreational, commercial and other marine activities for coastal and off-shore space. Research suggests that seaweed cultivations affect ecosystem services (Hasselström et al. In Press) and play important local ecological roles for instance by providing habitats (Phillips 1990), by acting as agents of nutrient bioremediation (Chung et al. 2002; Xiao et al. 2017), and may even protect against local acidification by capturing carbon dioxide (Zacharia, Kaladharan, and Rohith 2015; Mongin et al. 2016).

Global seaweed aquaculture production more than tripled from 1995 to 2012 to the order of 23.8 million tons per year and is mostly concentrated in Asia, with 81% of global production coming from China and Indonesia alone (FAO 2014). European seaweed production comes almost entirely from the harvesting of natural stocks and has decreased by approximately a third from 2000 to 2012, to around 230 000 tons per annum, primarily due to concerns over environmental impacts (NetAlgae 2012). It is thought that cultivation will have an important role in filling the growing gap between supply and demand in the coming years. Most recently, macroalgae cultivation has rapidly been gaining momentum as research initiatives and businesses develop the capacity for the cultivation and refining of seaweed biomass (Kraan 2013; Peteiro, Sánchez, and Martínez 2016). A number of economic, legislative and practical challenges, often location specific, remain to be overcome, not least of which is to identify suitable areas of coastline that could host effective cultivations without interfering with existing marine activities.

Determining the suitability of sites for the cultivation of kelps is a complex puzzle involving myriad factors of varying importance, ranging from the consideration of the numerous human activities and geophysical aspects of the local area, to the biological requirements for effective kelp cultivation. It is also necessary to closely consider these factors in light of their contributions to viability, sustainability and potential conflicts of interest (Longdill, Healy, and Black 2008; Radiarta, Saitoh, and Yasui 2011). All the factors presented hereafter are considered to be crucial for planning the development, management and operation of an offshore cultivation. First factors relating to the productivity and serviceability of a seaweed cultivation are considered, then additional factors are brought to light such as adherence to legislation, obtaining licences and considerations to the other pre-existing uses (and
users) of the coast. Given the location specific nature of these factors, they will pertain to the Swedish West Coast where the Seafarm project pilot cultivation is located. Seafarm is a Swedish Research Council (Formas) project aiming to lay the foundations for the development of a seaweed industry to support and grow a sustainable bioeconomy; the pilot cultivation sites are located in the Koster national park, the northern-most archipelago in Figure 1, South-West of Strömstad.

The importance of each factor is likely to vary from place to place, but in geophysical terms in the Baltic region, salinity is seen as the most important factor affecting kelp growth (Schultz-Zehden and Matczak 2012). Most macroalgae species need high salinity levels around 30 PSU, tolerating slight fluctuations, but locating sites in brackish waters and in estuaries with large amounts of fresh water inflow might prevent their growth to optimal levels (Kerrison et al. 2015). The optimal temperature range is highly species dependent (Werner, Clarke, and Kraan 2004), though areas with high fluctuations of sea surface temperatures should be avoided when it comes to kelps; low temperatures are usually preferable unless there is chance of seawater turning into ice (MMO 2013). Levels of both nutrients (e.g. nitrogen) and pollution (e.g. heavy metals and oils) in the water, which the algae are able to absorb, are important concerns, particularly the latter if the macroalgae is intended for human consumption. Additional physical environmental factors such as the slope of the seabed, water currents, wave action, shelter from storms, tidal exposure and water depth should also be taken into account as they are not only determining factors for macroalgae growth but impact the design and engineering of the cultivation system’s installation (MMO 2013). For each of these factors, it can be a real challenge to establish the ideal range defined as suitable. The suitability range for depth, for instance, is a delicate balance between potential impacts, costs and practicalities. Installations in relatively shallow areas, below around 10 meters, can impact negatively on the benthic habitat (MMO 2013; Rebours et al. 2014), whereas in deeper waters, costs and challenges can be amplified (MMO 2013); for instance at depths greater than 100 meters, it may no longer be feasible for monitoring and maintenance to be performed by divers. In summary, a myriad different factors can affect macroalgae growth rates and viability of cultivation – but on the West Coast, conditions are good on the whole and kelps are naturally found ubiquitously along the coastline (Karlsson 2007; Havsmiljöinstitutet 2011).

On the West Coast, perhaps more importantly than considerations affecting growth rates and the serviceability of a cultivation infrastructure, the seaweed farms and their associated activities should, as far as possible, be developed to be cost effective, to adhere to regulations, to synergise with established activities and to minimise conflicts of interest along a busy coastline. The National Resources Act, an umbrella-like piece of legislation that established proper use of land and water resources in Sweden, states that “In the case of conflicting interests, priority shall be given, as far as possible, to the activity which is most important from the public point of view and with a long term perspective” (Johansson 1997); however, it is not necessarily that simple to determine best outcomes and long-term perspectives from young industries, and Swedish regulation and planning of coastal areas did not anticipate the potential of seaweed cultivation at the time that this act was developed. As a result, it has been simultaneously challenging for Seafarm to adhere to non-specific regulations and for municipalities to grant cultivation licences.
Following the European Parliament’s directive on the development of marine spatial plans (MSPs) in Europe (Directive 2014/89/EU), MSPs have begun to take shape in Sweden. The organisation of MSP overlaps between municipalities, specifically responsible for sea space extending 12nm from the coast, and the Swedish Agency for Marine and Water Management (Havs och vattenmyndigheten), specifically responsible for the sea space extending between 1nm from the coast up to the edge of the EEZ (Havochvatten 2017). The latest MSP for the Skagerrak and Kattegat - currently undergoing public consultations and due in 2019 – includes visions for the future and highlights the important contribution that seaweed aquaculture will make, however in its current form it lacks detail regarding overlapping marine uses, especially for aquaculture, and neither the areas available nor the process for their selection have yet been made public (Havochvatten 2016). In effect the MSPs are still in their infancy, a work-in-progress, and as such, one of the contributions of the present study is to provide insights for marine spatial planners on site suitability for seaweed aquaculture in the Skagerrak region.

In the present, however, the reluctance to issue licences for seaweed aquaculture may be due not only to the on-going development of marine planning strategies and regulations, but also resulting from an underlying suspicion of negative impacts from seaweed farming and other thus far unidentified conflicts of interest, for instance the possibility of public aversion to aquaculture (Thomas et al. 2017) which could interfere with leisure boating or the aesthetic beauty of coastal areas. In terms of environmental, social and economic impacts from the cultivation of seaweed, recent studies (Aldridge, van der Molen, and Forster 2012; Schultz-Zehden and Matczak 2012; Rebours et al. 2014) suggest that the positive impacts outweigh the negative ones; however, it is difficult to make such generalisations given the large uncertainties from geographical variability. Of particular note to the Swedish case, a recent report identifies seaweed farming as a measure by which local areas may move toward a good environmental status. In addition, conflicts or synergies may also emerge from overlaps with the other uses (or users) of coastal zones, such as commercial shipping lanes, fishermen, restricted military and navy areas, wind farms, pipelines, recreational activities and nature reserves (Buchholz, Krause, and Buck 2012). To exemplify a possible synergy, it has been suggested that the new economic opportunities from blue industries could provide new, alternative incomes and livelihoods to the traditional fishing industry that has almost disappeared from the West Coast (Hasselström et al. Submitted). In summary, when based on incorrect and insufficient information, spatial decision-making can result in delays, higher costs, environmental degradation, low productivity, additional regulatory processes, conflicts of interest with other marine activities and potentially, project failure (Kapetsky and Aguilar-Manjarrez 2007).

Decision-making entails the assessment of a series of complex subjects (Wrisberg et al. 2012). The ultimate purpose of Geographic Information Systems (GIS) is to provide support for making decisions (Bonham-Carter 1994; DeMers 2009; Malczewski 2010). The GIS software is comprised of a set of functional capabilities for input, retrieval, visualization, storage, manipulation, combination, query, analysis, modelling and output of spatial data (or mapped data) (Bonham-Carter 1994; Malczewski 2010). The integration of these functions enables one to simulate or predict natural and anthropogenic activities and, therefore, to explore the various consequences and outcomes of making a set of
assumptions by analysing performances of models (Bonham-Carter 1994; DeMers 2009). GIS modelling is, as a result, indisputably useful to solve spatial decision problems (Malczewski 2010). Additionally, GIS, mapping and remote sensing, are important tools to assess site suitability for aquaculture development and to organize a framework for management of marine aquaculture (Kapetsky and Aguilar-Manjarrez 2007). Decision-making can be a complicated process when it encompasses a variety of criteria, and it may involve the consultation of diverse stakeholders and experts. To make sense of the complexity of such situations, the Multi Criteria Analysis (MCA) tool was developed to help to find the best solution by identifying trade-offs between several criteria or parts of the decision problem (Werner, Clarke, and Kraan 2004). This is carried out by a thorough analysis of the parts of these criteria and then by integrating them in a rational way (Malczewski 1999). It is for these reasons that MCA is considered well suited to analyse complex situations, particularly the many dimensions that characterise sustainability issues (Werner, Clarke, and Kraan 2004).

Conventional MCA methods are not designed to specifically consider geographical data. To include spatial data in an MCA strengthens spatial decision-making (Malczewski and Rinner 2015). GIS and MCA tools used in conjunction are referred to as Geographic Information Systems based Multi Criteria Decision Analysis (GIS-MCDA) and together they combine the best of both worlds by handling numerous decision criteria and large spatial data sets. GIS-MCDA is a very convenient tool that provides a structured and perceptible analysis about complex spatial problems (Wood and Dragicevic 2007), and is already well established as a method for aquaculture site selection (Ross, Mendoza Q.M, and Beveridge 1993; Arnold et al. 2000; Pérez, Telfer, and Ross 2005; Longdill, Healy, and Black 2008; Radiarta, Saitoh, and Miyazono 2008; Silva et al. 2011; Micael et al. 2015; Stelzenmüller et al. 2017). The most common decision rules are the weighted summation type, e.g. weighted liner combination (WLC) and the related Boolean overlay. These are seen as appropriate to implement by using GIS software as they are simple to follow and easy to comprehend by decision-makers (Malczewski 2006). While several studies have applied these methods to the site selection of generic aquaculture, only a few papers have applied them to inform site selection specifically for macroalgae cultivation (Radiarta, Saitoh, and Yasui 2011; Sousa, Moura, and Marinho-Soriano 2012; Capuzzo 2014). All of these cited papers differ on many points (e.g. macroalgae species, type and number of criteria, study area, and applied method and sensitivity analysis) given the large possible combinations to assess and geographical variability to consider. However, all the authors refer to the method GIS-MCDA as an effective instrument for identifying areas for aquaculture in offshore regions. The differences between Boolean and WLC methods are well established (Jiang and Eastman 2000), however to the authors’ knowledge, no studies have compared the WLC and Boolean overlay techniques in studies at sea or offshore, e.g. macroalgae cultivation site selection, despite their differences in practice and in terms of outputed results. WLC is considered more detailed and time consuming yet provides high-resolution results, whereas the Boolean overlay technique can be applied more quickly and simply yet it provides more binary and low-resolution results (Eastman 2001; Riad et al. 2011).

In the early stages of the Seafarm project, it was confirmed that the conditions for cultivating macroalgae on the West Coast are favourable; the large number of islands provide sheltered areas,
water salinities, water temperatures and light availability have been proven suitable, and the first few seaweed harvests have been a success, producing many tons of high quality biomass. The technical knowledge for cultivation is therefore robust and the environmental conditions for biological productivity of these locally sourced species are considered to be suitable. One of the important challenges remaining in laying the foundations of a seaweed industry in Sweden is to identify suitable and sustainable farming areas that fit into the complex puzzle of interacting, overlapping socio-technical factors and limitations at play on the West Coast, e.g. commercial and leisure use of the sea, sea depth, shipping traffic and other risk factors. This study aimed to contribute to overcoming this particular challenge and supports ongoing efforts in developing the marine spatial plan for the Skagerrak/Kattegat, by conducting a GIS-MCDA of kelp cultivation site suitability on the Swedish West Coast, with a focus on finding the gaps in the MSP puzzle which are technically suitable to seaweed farming.

STUDY AREA

This study focuses on the West Coast of Sweden: from the Norwegian border to Gothenburg, covering approximately 150 kilometres in a straight line. The study area extends to include the Swedish exclusive economic zone (EEZ) and territorial seas between 57°60' and 59°13' North and between 10°00' and 12°10' East, making up a total area of around 7702 km² (see Figure 1). The term offshore is used henceforth when referring to all zones in the study area, including those defined as coastal, off the coast or offshore mariculture zones as stated by FAO (2013).

Like most Swedish coastal zones, the West Coast is primarily an area for recreation and tourism though it has a long and rich history of maritime activity. The rocky, arid landscapes of the coast are densely covered in typical wooden houses which remain empty except in summer (Hammarström 2007). There is also an important industrial presence on the West Coast: the study area includes two of the busiest ports in the Nordic countries, Gothenburg and Lysekil, and the refineries in Gothenburg and Brofjorden, which handle 80% of the Sweden’s refinery capacity, have large impacts on both land and sea areas (Preem 2017). Havochvatten, the Swedish Agency for Marine and Water Management, reporting on the distinctive features of the Skagerrak and Kattegat, notably remark that “nearly half of Sweden’s maritime sector employees are located here”, that “intensive shipping is expected to grow” and that there are “major risks for oil leaks that quickly reach land” (Havochvatten 2014).

The Skagerrak and the Kattegat seas that border on the West Coast comprise characteristics different from any other coastal Swedish marine environment, notably, a dynamic stratification of the water column by salinity with a brackish Baltic surface layer (between 12 and 30 PSU) and high salinity Skagerrak waters (up to 32 PSU) at depth (Hernroth and Gröndahl 1985). The salinity and temperatures of these waters are unique for Swedish waters and provide very good conditions, not only for kelps, but also for intrinsic ecosystems to thrive (Garpe 2008). Kelps are ubiquitously found on the seabed along the Swedish West Coast (Karlsson 2007; Havsmiljöinstitutet 2011) and play an important role in the local ecosystems, evidence that the area has favourable conditions for kelps to thrive. The key then will
be to identify spaces along the coast that both cater to the practicalities of seaweed cultivation (positive factor) and minimises potential conflicts of interest (conflicting factor).

**MATERIALS AND METHODS**

First, the aim of identifying suitable offshore areas for macroalgae cultivation on the Swedish West Coast was set. Objectives were broken down in a (general) sequence of operations as illustrated in Figure 2 and described hereafter. Data was introduced to the study as they were gradually acquired, resulting in the models being constantly improved in a continuous iterative process.

The acquisition of data was based on availability, quality and relevance to limitations of seaweed cultivation according to environmental, social and economic perspectives (see Figure 3). With this it is proposed that the aggregated criteria represent a suitability map that considers some key sustainability challenges. Thirteen criteria ended up being selected for use in this study: Chlorophyll-a concentration (CHL-a), Oil discharges, Risk of Oil Spillages, Depth, Territorial seas and Exclusive Economic Zone (EEZ), Shipping Lanes, Shipping Traffic Density, Shore Protection, Fishing Areas, Fishing Ports, Marinas, Military Areas and Marine Protected Areas (MPAs). Motivations for the use of each criterion (relevance to sustainable site selection) are provided in Table 1. Descriptions of metadata are provided in the supplementary material.

Data organisation is a key phase in preparation for data analysis. It involved the assessment, adaptation, and preparation (massaging) of criteria (or layers), by means of the GIS tools in Idrisi (Andes) and ArcGIS (10.4) software. Thereafter, Idrisi software was used to build two different GIS-MCDA models for the analysis: a Boolean overlay and a WLC. Additional information about the criteria preparation is available in the supplementary material.

Table 2 shows the booleanization’s parameters to convert all criteria to Boolean format. Suitable areas, where macroalgae cultivation is considered most feasible or sustainable, are assigned values of 1, while unsuitable areas, where macroalgae cultivation is prohibited or impeded, are assigned values of 0. Each criterion thus contributed an (enabling/supporting) factor or constraint layer to the final combined Boolean overlay.

Just like for the Boolean model, in the WLC model each criterion was defined as either factor or constraint, with the constraints acting as Boolean criteria to mask out unsuitable areas. For the factors, however, it was necessary to rationally define suitability relative to the other factors using fuzzy logic (Jiang and Eastman 2000) based on literature review and expert opinions. Table 3 illustrates the fuzzy parameters and the weights that were specified to each factor. For more information about fuzzy logic weighting and the definition of constraints and factors, see supplementary material. The fuzzy parameters enabled the production of maps for each criterion, so that in turn, each map could be used
as a layer in the final WLC using the Multi Criteria Evaluation module in Idrisi. The weights assigned to each factor layer are motivated in the supplementary material.

RESULTS

The criteria of site suitability were selected based on data availability and social or technical relevance to sustainable site selection, either acting as factors that enable or support cultivation sites or as constraints that impede or restrain them. Together the criteria contribute to painting a picture viability- and sustainability-related factors and constraints that support or impede the suitability of macroalgae cultivation sites. Table 1 lists the criteria considered in the models, including a short motivation of their relevance and application. For more information on the metadata of each criterion, see supplementary material.

In the Boolean overlay model, individual Boolean layers (available in the supplementary material) were created from the booleanization of all the criteria, which were then overlaid using the multiplication operator to derive the Boolean areas of the Boolean suitability map. The parameters and results of the booleanization of the suitability criteria are presented in Table 2. Figure 4 shows the Boolean Suitability Map. Boolean areas show the regions where the assigned values of 1 are shared among all the criteria. In other words, common areas to all the criteria are visualised. Boolean areas comprise a total area of 544 km², 7.1% of the study area, and are spatially distributed across the coastal municipalities.

The suitability map was reclassified in order to derive the WLC suitability map shown in Figure 5. In this model, rather than booleanizing the value of each criterion, weights were assigned indices from 0 (no suitability or interdicted areas) to 10 (maximum suitability areas) to illustrate the degree of suitability of areas that could be assigned for seaweed cultivation. A weighted map of each criterion is available in the supplementary material.

A general pattern is discernible from the combined WLC suitability map where areas nearer the shore present a higher suitability degree than the more distant ones. The best suitability area (index 10) represents 6 km² of area in total, and that corresponds to 0.1% of the total study area. The suitability indices 9 and 8 cover 182 km² and 287 km², respectively. The constraints, which impede cultivation in these areas, cover 40.5% of the study area. From a planning perspective, the suitability indices 8, 9 and 10 are worthy of closer scrutiny. They seem the most appropriate to further consider as highly suitable areas to cultivate macroalgae based on the criteria and weighting applied in this study. The sum of these indices is 475 km² (6.2% of the study area). In compliment to the Boolean and WLC overlay maps, both were superimposed, the outcome of which is illustrated in Figure 6. The outcome of this superimposition is a slight reduction in suitable areas compared to the Boolean and WLC methods, as the discrepancies between the methods, e.g. areas identified as suitable by one method but as non- or less-suitable by the other, have been removed.
DISCUSSION

The site suitability assessment methods submit that approximately 475 to 544 km$^2$ of sea space may be suitable for seaweed cultivation on the Swedish West Coast, based on selected and available data. The suitability maps can also be improved with more data, used as input for further suitability studies and may help to inform decision makers and marine spatial planners. But what is the significance of these numbers and what can we learn from them? Assuming the analysis is robust enough to make extrapolations, one option may be to use these numbers as a factor when estimating the development potential for the industry on the West Coast. Depending on the specific site, seasonal fluctuations of growth-related parameters (e.g. weather), the configuration of the seaweed cultivation infrastructure and the selected species, productivity per hectare can lie anywhere in the order of 20 to 150 tons of biomass per year (wet weight) (Kerrison et al. 2015). Now, assuming that only half (approximately 250 km$^2$) of the suitable areas identified in this study were to be cultivating biomass, the West Coast may be able to contribute anywhere in the order of 50 000 to 375 000 tons (wet weight) of biomass every year to be refined or used as feed, food, energy, fertilizers and a variety of other products. In comparative terms, this remains only a small proportion, at around 1%, of the global seaweed industry (FAO 2014), but it would represent a significant contribution to European seaweed production (NetAlgae 2012) contributing an increase of more than 100% from production in 2012. In terms of economic potential, assuming that the 50 000 tons of wet weight production were sold at a (conservatively estimated) market value of 5 SEK per kg wet weight (0.5 USD), this would still represent a turnover of 25 million USD, thus showing much potential as the foundation of a new generation of maritime activity in a region which has suffered from the decline of its traditional fishing industry. More research is needed to shed light on the potential of the industry to generate livelihoods and incomes to the region, but it should also further investigate what the ramifications of such developments might be, including environmental impacts and ecosystem services.

Robustness Assessment

The present study is limited in terms of the precision of the results, as a result of the scale of the study area, the resolution and reliability of input data and the relevance and weighting of different criteria. For instance, the study is confined to the scale, spatial resolution of the intermediary and final (raster) maps (pixel size of 250 meters), and to the inherent limitations and potential errors in the original data sets (input data). The accuracy of the outputs is also directly dependent on the accuracy of input data, which in some cases is questionable. For instance, some of the older oil discharge data points may be outdated, may not reflect current reality and they could not be removed from the data sets. Similarly, it was necessary to perform some alterations of the maps’ projections together with the utilized GIS tools in the layers, which may affect the accuracy of the results. The projections of CHL-a concentration and Shipping Traffic layers were changed, for example, and a set of tools including interpolation and alteration of the coordinate system were applied to the Depth layer. Some data were also simplified to
facilitate some of the modelling processes. For more information on how the data was massaged prior to analysis, please refer to the supplementary material.

The relevance of each selected criterion was primary in affecting the results of the analysis. Some criteria that may also affect site suitability have been left out of the models, either as a result of poor-quality or absent data, for instance the slope of the seabed, concentration of nutrients (nitrogen and phosphorous) in the water, speed of water currents, and meteorological information including storm frequency and wave height. In further analyses of site suitability, such aspects may be tackled to some extent: assessments could be performed in a more localized and specific approach in the areas identified in the present study as the most suitable, new data could be collected and the pixel resolution could be increased. On the whole, however, though the number of criteria is limited and perhaps over simplifying the complex reality of the MSP puzzle on the West Coast, they remain the most important aspects identified by the authors for which data was available. It is important to acknowledge, however, that important criteria may be missing and could be added to the models, particularly in view of the ongoing development of marine spatial plans for the Skagerrak and Kattegat seas (Havochvatten 2016).

In addition to the importance of relevance of each layer, uncertainties also lie in the assumptions made when rationalizing all the chosen criteria and in setting all the parameters to conduct the GIS-MCDA models. These uncertainties imply “some risks that the decision made will be wrong” (Eastman 2005). In the present study, these uncertainties were managed by basing the rationalizations of each layer on the accumulated knowledge of piloting the seaweed farms in the Koster national park. This knowledge/opinion basis has and shall evolve over time, and thus the rationalization and weighting of the criteria as well as the identification of new criteria in the future may all influence the repeatability of the study. Recent research also suggests that the ecosystem services delivered by a seaweed farm may help to improve local environmental status according to the EU Marine Strategy Framework Directive, (Directive 2008/56/EC) particularly by helping to minimise eutrophication (SwAM 2015). This is not considered in the present study however future studies may add layers related to the environmental status of different areas and weight them as such to render more suitable the areas in need of improvements that could be enhanced by seaweed farms. In summary, it should be acknowledged that had a different set of experts, literature studies been consulted or should this study have been conducted with different priorities, the results of the models might have diverged significantly.

Though the number of criteria is limited and perhaps over simplifying the complex reality of the MSP puzzle on the West Coast, their weighting is considered robust, based as it is on the accumulated knowledge of piloting the seaweed farms in the Koster national park. In spite of a number of limitations, uncertainties and potential for accuracies, the chosen approach yielded results in line with the purpose of this study, to make some first steps towards planning for the likely increase of seaweed farming sites on the West Coast in the coming years.
Comparing Boolean & WLC

The Boolean overlay technique uses a risk-averse (AND or multiplication) operator so that there is no trade-off. Therefore, only the common areas amongst all the Booleanized criteria (or layers) are visualized in Figure 4, and all these identified areas are considered equally suitable. There are neither social, economic nor environmental conflicts in the identified areas; besides, the non-appropriate areas for the purpose are clearly delineated. Boolean overlay was found to be less resource consuming, cheaper and quicker than WLC technique and provides no areas of low or high suitability, as also remarked by Jiang and Eastman (2000). Thus, Boolean black and white outcome can oversimplify the representation of reality; however, a decision-maker can take advantage of Boolean approach as initial assessment for good or bad locations. It is believed thus that it is risky to choose cultivation sites based only on the Boolean overlay approach and without considering other assessment parameters such as in other evaluation strategies (e.g. WLC technique).

The WLC technique was subsequently applied in order to overcome the aforementioned limitations of Boolean overlay. Weights were assigned to factors to manage the degree of compensation amongst them (trade-off). The subjective rationale, applied to originate parameters for fuzzy logic and weighting to run the model, is crucial to the outcomes. The coloured outcome is a weighted representation of reality. Though an average level of risk is existent it is a more expensive and time-consuming technique than the Boolean method. Nevertheless, both GIS techniques using thirteen criteria save considerable amounts of time, labour and costs if compared to actual explorations in situ.

In combining both WLC and Boolean methods by superimposing the results, as shown in Figure 6, the differences in the results of each method are highlighted. This superimposition shows some WLC areas of the highest indices falling outside Boolean areas, and conversely, some Boolean areas fall outside of the highest indices of WLC Suitability Map. These are due to differences in the selected parameters and the purposes of each model, including the fuzzy and weighting processes of the WLC and the binary (constraint/factor) approach of the Boolean model. Specifically, this is caused by criteria that act as constraints in the Boolean but as factors in WLC technique. These criteria are: distances from ports and marinas greater than 30 km, high shipping traffic density areas, fishing areas, oil discharges, risk of oil spillages and depths greater than 100 meters but shallower than 10 meters. By superimposing the results of both methods, the overlapping areas (found to be suitable by both methods) validate one another and produce the most robust recommended suitable areas, most likely to be free of competing uses while fully taking into account the social, economic and environmental criteria defined by each method.

**CONCLUSION**

The alarming growth of world population and the subsequent increase production of food, feed and energy are great sustainability challenges. To provide populations a just and sustainable lifestyle,
decision-makers must have an important say regarding these challenges. Macroalgae production provides wealth all over the globe and their sustainable offshore production in Europe is believed to be a driving force to reduce competition for arable land, freshwater for agriculture and husbandry and chemical fertilisers and pesticides, all while producing environmentally friendly products e.g. third-generation biofuels (Pechsiri et al. 2016). Consequently, imports of kelps from Asia will decrease, saving carbon emissions from transportation and boosting European economy. As such, the increasing macroalgae production must be planned in a reasoned and in the most sustainable way possible by planners, developers, engineers and by high-level decision-makers. The present study identified, analysed and discussed offshore areas suitable for cultivating macroalgae. This paper was planned to assist Seafarm and its stakeholders and to contribute to a sustainable implementation of kelp offshore farms in the Skagerrak and part of the Kattegat seas on the West Coast of Sweden, though the methods and lessons learnt can be valuable for similar projects anywhere.

The GIS-MCDA techniques of Boolean overlay and of WLC were applied. In total, thirteen criteria were analysed in detail and were selected based on sustainability aspects: EEZ, Shipping Lanes, Shore Protection, Fishing Areas, Fishing Ports, Military Areas, Marine Protected Areas, Marinas, Shipping Traffic, Depth, CHL-a concentration, Oil Discharges and Risk of Oil Spillages. Potential areas for cultivating macroalgae were successfully delineated. Boolean suitable areas encompass 544 km$^2$ (7.1% of the study area). As for the WLC technique, the best areas that scored the highest, with suitability indices 8, 9 and 10, encompass a total of 475 km$^2$ (6.2% of the study area).

Boolean overlay alone does not seem to be appropriate to a study of this calibre because decision-makers would want to measure criteria and gain insights of higher resolution that better represent the complex reality. The results are, hence, more personalized and tailored to the idea and perspective of the planner once the criteria are fuzzy standardized and weighted. The results further indicated that both GIS-MCDA techniques excelled in providing an overview for effective spatial decision-making while saving high costs in field studies, a remark that is also in similar studies. Even though Boolean overlay proved to be a simpler and faster method to perform, it lacks the increased accuracy and flexibility of the WLC.

A layer-by-layer analysis may additionally help to identify and help to decide on a real suitable cultivation site. It is subsequently recommended that a thorough field verification of the sites be conducted – a validation of sorts. This is to quality control certain data such as by analysing the areas on environmental and socio-economic factors, e.g. monitor local shipping density, confirm water depth, analyse water quality, check seabed slopes, and acquire historic data of storms and wind speeds and other external relevant local data about the site. Furthermore, the input data of this study and the models themselves should be refreshed in light of the new marine spatial plans being developed for this coastline. Future studies could also extend the study area to include the Kattegat or other marine regions, and the methodology could be adjusted to consider suitability criteria for the cultivation of species other than *Saccharina latissima*. 
Main highlights

• To the authors’ knowledge no study on seaweed aquaculture site selection has been conducted using such a range of criteria with the purpose of including sustainability aspects within a comparative GIS-MCDA.

• The large areas identified on the West Coast of Sweden as suitable highlight the potential of this new industry and the complexity of associated marine spatial planning.

• Boolean and Weighted Linear Combination methods were applied and compared, providing valuable insights in the selection of methods for spatial decision-making support. These insights should support a more sustainable development of macroalgae cultivation in the region, as well as a more resilient marine spatial planning process for blue growth strategies.
Figure 1 – Study area, located on part of the West Coast of Sweden, including seas and communes names.
Aim: Identify Suitable Offshore Areas for Macroalgae Cultivation on the Swedish West Coast

Sustainability Aspects

Identification of Environmental and Socio-economic Criteria

Data Acquisition

Data Organisation

Data Analyses and Modelling

Non-Boolean Model

Factors

Constraints

Fuzzy-logic

Weighted Linear Combination

Non-Boolean Suitability Map

Boolean Model

Booleanization of Criteria

Boolean Overlay

Boolean Suitability Map

Figure 2 – Simplified working procedure.
Figure 3 – Criteria imbedded in the sustainability aspects and the proposed sustainable Suitability Map.
Table 1 – Acquired criteria, their decision roles and interpretation to the study and respective sources.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Decision Role</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEZ</td>
<td>Constraint1</td>
<td>(Lantmäteriet 2017)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Helcom 2017)</td>
</tr>
<tr>
<td>Exclusive Economic Zone and Territorial Seas, referred as EEZ, delimit the study area and constrain cultivation within these areas.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shipping Lanes</strong></td>
<td>Constraint</td>
<td>(Trafiksverket 2017)</td>
</tr>
<tr>
<td>Prohibit cultivations within commercial and recreational shipping lanes.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shore Protection</strong></td>
<td>Constraint</td>
<td>(Länstyrelserna 2017)</td>
</tr>
<tr>
<td>Prohibit cultivations in the protected marine areas near the shore.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Military Areas</strong></td>
<td>Constraint</td>
<td>(Lantmäteriet 2017)</td>
</tr>
<tr>
<td>Prohibit cultivations inside military areas.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Marine Protected Areas</strong></td>
<td>Constraint</td>
<td>(Lantmäteriet 2017)</td>
</tr>
<tr>
<td>(Helcom 2017)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prohibit cultivation inside marine protected areas.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fishing Areas</strong></td>
<td>Factor2</td>
<td>(Thörnqvist 2006)</td>
</tr>
<tr>
<td>Restrain cultivation within fishing defined boundaries.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fishing Ports</strong></td>
<td>Factor</td>
<td>(Thörnqvist 2006)</td>
</tr>
<tr>
<td>Serve cultivations as loading and unloading stations in the vicinities; restrain cultivations in longer distances from the site to the ports.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Marinas</strong></td>
<td>Factor</td>
<td>(Naturvårdsverket 2010)</td>
</tr>
<tr>
<td>Serve cultivations as monitoring auxiliary stations in the vicinities; restrain cultivations in longer distances from the site to the marinas.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shipping Traffic</strong></td>
<td>Factor</td>
<td>(Helcom 2017)</td>
</tr>
<tr>
<td>Restrain cultivations in the considered higher traffic areas.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Chlorophyll-a concentration</strong></td>
<td>Factor</td>
<td>(SEDAC 2009)</td>
</tr>
<tr>
<td>Indicates levels of marine productivity; restrains cultivations in regions with considered poorer productivity levels.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td>Factor</td>
<td>(BSHC 2013)</td>
</tr>
<tr>
<td>Indicates water depths, a decisive factor for cultivations structure's anchorage; restrains cultivations in regions with considered lesser appropriate depths.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Oil Discharges</strong></td>
<td>Factor</td>
<td>(Helcom 2017)</td>
</tr>
<tr>
<td>Restrain cultivation these zones, avoiding these potential polluted areas.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Risk of Oil Spillages</strong></td>
<td>Factor</td>
<td>(Helcom 2017)</td>
</tr>
<tr>
<td>Restrain cultivations in these zones, avoiding these potential future polluted areas.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Constraints impede or restrain macroalgae cultivations from taking place.

2 Factors encourage or support macroalgae cultivations to take place.
Table 2 – Selected parameters for the Booleanization of the criteria.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Assigned values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inside¹</td>
</tr>
<tr>
<td>EEZ</td>
<td>1</td>
</tr>
<tr>
<td>Shipping Lanes</td>
<td>0</td>
</tr>
<tr>
<td>Shore Protection</td>
<td>0</td>
</tr>
<tr>
<td>Fishing Areas</td>
<td>0</td>
</tr>
<tr>
<td>Distance to Fishing Ports</td>
<td>1</td>
</tr>
<tr>
<td>(meters)</td>
<td>≥ 1000 &lt; 25 000</td>
</tr>
<tr>
<td>Military Areas</td>
<td>0</td>
</tr>
<tr>
<td>Marine Protected Areas</td>
<td>0</td>
</tr>
<tr>
<td>Distance to Marinas (meters)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>≥ 1000 &lt; 25 000</td>
</tr>
<tr>
<td>Shipping Traffic (density)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>≥ 1 &lt; 60</td>
</tr>
<tr>
<td>CHL-a concentration</td>
<td>≥ 1 &lt; 12.5</td>
</tr>
<tr>
<td>(mg/m³)</td>
<td></td>
</tr>
<tr>
<td>Depth (meters)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>≥ -100 &lt; -10</td>
</tr>
<tr>
<td>Distance to Oil discharges</td>
<td>0</td>
</tr>
<tr>
<td>(meters)</td>
<td>≥ 1000</td>
</tr>
<tr>
<td>Risk of Oil Spillages</td>
<td>0</td>
</tr>
</tbody>
</table>

1 Refers to geographic areas within the boundaries of the representation of each criterion.
2 Refers to geographic areas beyond the boundaries of the representation of each criterion.
Table 3 – Selected parameters for fuzzy configuration and weights given to each factor.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Fuzzy logic</th>
<th>Membership Function</th>
<th>Control Points</th>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Type / Shape</td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>Depth (meters)</td>
<td>Sigmoidal</td>
<td>/ Symmetric</td>
<td>-100</td>
<td>-30</td>
</tr>
<tr>
<td>Shipping Traffic (density)</td>
<td>Linear</td>
<td>/ Monotonically Decreasing</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>Distance to Fishing Ports (meters)</td>
<td>Linear</td>
<td>/ Monotonically Decreasing</td>
<td>1000</td>
<td>25 000</td>
</tr>
<tr>
<td>Distance to Marinas (meters)</td>
<td>Linear</td>
<td>/ Monotonically Decreasing</td>
<td>1000</td>
<td>25 000</td>
</tr>
<tr>
<td>Fishing Areas (meters)</td>
<td>J-Shaped</td>
<td>/ Monotonically Increasing</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>Risk of Oil Spills (meters)</td>
<td>J-Shaped</td>
<td>/ Monotonically Increasing</td>
<td>50</td>
<td>1000</td>
</tr>
<tr>
<td>Oil Discharges (meters)</td>
<td>J-Shaped</td>
<td>Increasing</td>
<td>0</td>
<td>1000</td>
</tr>
<tr>
<td>CHL-a concentration (mg/m³)</td>
<td>Sigmoidal</td>
<td>/ Symmetric</td>
<td>2.5</td>
<td>6.0</td>
</tr>
</tbody>
</table>

1 By applying a fuzzy (or logic) set the factors are standardized in a continuous common suitability scale, in contrast with the crisp Boolean logic;
2 Types of set membership mathematical functions typically define the fuzzy set, Sigmoidal, J-shaped, Linear and User-defined; each display different possibilities of shapes (forms) and control (inflection) points.
3 Parameter weights define the relative importance of each factor.
Figure 4 – Boolean Suitability Map.
Figure 5 – WLC Suitability Map.
Figure 6 – WLC Suitability Map’s indices 8, 9 and 10 superimposed with Boolean suitable areas to highlight overlaps.
References


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Is it time for a seaweed goldrush? The economic potential of seaweed farming in Sweden

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ABSTRACT

Seaweed cultivation is a large industry worldwide, but production in Europe is small compared to production in Asian countries. In the EU, seaweed farming may be seen from two perspectives, one being as a possible contributor to economic growth through biomass production, and the other being as a way of providing ecosystem services through positive externalities, such as eutrophication mitigation. In this paper, we assess the economic potential of large-scale cultivation of kelp, \textit{Saccharina latissima}, along the Swedish west coast. The findings suggest that seaweed farming has the potential of becoming a profitable industry in Sweden. Concerning externalities, positive values generated from sequestration of nitrogen and phosphorus are potentially counteracted by negative values from interference with recreational values. Additionally, although large-scale seaweed farming may sequester a significant share of annual nitrogen and phosphorus inflows to the basins on the Swedish west coast, the socioeconomic value of this sequestration is only a minor share of the potential financial value from biomass production. This suggests that e.g. subsidies for nutrient uptake based on the socioeconomic values generated is not likely to be a tipping point for the industry.

Key words: Aquaculture, Seaweeds, Kelp, \textit{Saccharina latissima}, Cost-Benefit Analysis, Externalities
INTRODUCTION

Seaweed has been called the “promising plant of the millennium” (Dhargalkar & Pereira, 2005) due to its comparative advantages vis-à-vis land-based biomass production. It does not need land, fresh water, fertilisers, or pest-insect- or fungicides to grow, and the biomass can be used for many purposes, such as food (Mouritsen, 2017), feed (Fleurence, 1999), materials (Maguire, 2016), biofuels (Pechsiri et al., 2016), or as gelling or stabilising substance in a range of applications (Pangestuti & Kim, 2015). Additionally, seaweed farming provides positive externalities in terms of ecosystem services such as generating habitats for fish and crayfish species, and nutrient sequestration (Hasselström et al., 2018).

In a recent study, it is suggested that phosphorus uptake from large-scale seaweed cultivation in China can significantly contribute to mitigating coastal eutrophication (Xiao et al., 2017), and it has also been suggested as a potential carbon sink (Chung et al., 2011, 2013; Duarte et al., 2017). Moreover, the sequestering of carbon may mitigate ocean acidification (Krause-Jensen et al., 2015).

Globally, most seaweed aquaculture is currently located to Asian countries, mainly China and Indonesia, who together produce 91 % of the world market production (FAO, 2016). The European production is still small-scale, but several drivers point towards a possible expansion. The European Commission highlights seaweed aquaculture as having strategic potential for the development of the European bioeconomy and as a driver of blue growth (EC, 2012). Additionally, the Swedish Agency for Marine and Water Management identifies seaweed cultivation as a possible contributing vector for achieving Good Environmental Status with respect to eutrophication according to the Marine Strategy Framework Directive (Directive 2008/56/EC) (SwAM, 2015). A large number of research projects and networks are now developing to study this industry from a range of perspectives (e.g. Seabioplas1, BioMara2, MAB43, EnAlgae4, Seafarm5, etc.).

The discussion on development of seaweed farming has had two major foci in the literature – one being its environmental impacts such as provisioning of ecosystem services, nitrogen and phosphorus recovery, and possible substitution of fossil-based raw material; and the other being its potential contribution to economic growth through biomass production. These different foci have implications for how seaweed farming should be understood (Hasselström et al., 2018). If framed as an ‘environmental measure’, e.g. eutrophication mitigation, seaweed farming competes with other mitigating measures in terms of cost-effectiveness. If framed as an ‘industrial project’, it competes with other means of providing biomass. For industrial development in Europe, risk-factors are associated with e.g. high labour costs, yearly variation in biomass growth, the lack of mature supply chains, and permissions for allocating space. Hence, while seaweed farming may have a double dividend, it has to

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1 https://cordis.europa.eu/project/rcn/110672_en.html
2 http://www.biomara.org/
3 https://mab4.org/
4 http://www.enalgae.eu/
5 http://www.seafarm.se/
compete on its own within one of these two sub-regimes (environmental measure or business) unless the governing system succeeds in bridging the two by e.g. payments for ecosystem services structures.

In this paper, we examine the economic potential of large-scale farming of kelp (*Saccharina latissima*) along the Swedish west coast, to a) provide perspective on the potential balance between financial viability and externalities, and b) generate knowledge on potential profitability and tipping points in price and production costs. Our analysis shows that seaweed cultivation has the potential to become a highly profitable industry in Sweden and that the monetary values of externalities are rather small compared to the financial values generated. Additionally, values forgone due to interference with recreation may be substantial. The analysis signals that seaweed cultivation is not dependent on subsidies, e.g. based on environmental performance, to survive. However, large-scale seaweed cultivation along the Swedish west coast is an imaginable tool in future eutrophication combating. Our analysis suggests that large-scale seaweed cultivation may sequester 14 percent of annual anthropogenic net nitrogen and 100 percent of annual anthropogenic net phosphorus inflows to the basins on the Swedish West coast.

**METHOD**

**General assessment method**

The assessment is made in two main steps. First, a single-firm case with 2 ha cultivation over 10 years is studied. Cost data are acquired from invoices and interviews for estimations of labour-hours in a presently operating test cultivation for research purposes in the Koster archipelago. Assumptions for market price along with cost data enable a financial analysis. We assume a supply chain which enables access to the world market for dried seaweed for human consumption. Externalities in terms of the most substantial positive (eutrophication mitigation) and negative (impact on recreational values) external impacts, according to Hasselström et al. (2018) are monetized based on literature data. Financial and external net values are then combined to provide an overview of the overall economic balance. This overall methodology is in line with cost-benefit analysis (Johansson & Kriström, 2016). Second, the analysis is repeated for a scenario with scale-up to the maximum potential cultivation area on the Swedish West coast over 40 years.

Thomas et al. (submitted) study suitable locations for cultivation of *Saccharina latissima* along the Swedish west coast, including coastal, off-the-coast and offshore zones from the Norwegian border to Gothenburg (see Figure 1). The area covers approximately 150 kilometres in a straight line and is limited to the Swedish exclusive economic zone (EEZ) and territorial seas. Thirteen criteria (GIS layers) for suitability are included: Chlorophyll-a concentration, Oil discharges, Risk of Oil Spillages, Depth, Territorial seas and EEZ, Shipping lanes, Shipping Traffic Density, Shore Protection, Fishing Areas, Fishing Ports, Marinas, Military Areas and Natural and Preserved Areas. Some of these criteria are binary constraints (such as military areas) whereas other criteria represent variables with different degrees of suitability (such as depth). Two models for suitability were used: a Boolean approach based on binary suitability sorting (suitable or not suitable for each respective criterion) and a Weighted Linear Combination approach resulting in a suitability index for sites from 0-10, with 0 and 10 defined
as least and most suitable, respectively. Here, we use the combination of the two models, selecting areas with the highest suitability scores (index 8-10) found inside of the Boolean areas. This results in an assumption for max potential according to Figure 1 amounting to 338 km$^2$ of suitable potential cultivation areas. Reaching such a scenario within 40 years would require 28 % growth in cultivation area annually, which is significantly higher than the current annual growth of farmed aquatic plants globally (around 9 % average growth between 1990 and 2014; with the highest growth in Indonesia around 21 %; calculated from FAO, 2014; FAO 2016).

![Figure 1](image1.png)

**Figure 1.** Suitable locations for cultivation of *Saccharina latissima* along the Swedish west coast. Max potential scenario. 338 km$^2$ of cultivation area, i.e. areas scoring 8, 9 and 10 on the suitability index, restricted to Boolean areas.

From an economic perspective, a project should be undertaken if benefits exceed costs on a societal level (Johansson & Kriström, 2016). Technically, this is the case if the net present value (NPV; eq.1) is greater than zero. This implies an aggregation of costs ($C$) and benefits ($B$) over a given time period ($T$). Future costs and benefits are discounted using a discount rate ($r$).

$$NPV = \sum_{t=0}^{T} \frac{1}{(1+r)^t} (B_t - C_t)$$  \hspace{1cm} \text{(eq.1)}$$

where $t$ denotes the time when the respective cost or benefit item occurs.
Indata: Financial flows and ecosystem services

Table 1 shows the cost and benefit values for the variables that are included in the analysis. Details on the assumptions can be found in the supplementary material. Min and max values are presented for all variables, except for km long line per hectare and costs for material, which are based on case data. In the following analysis, the midpoint values have been used for all variables. In the sensitivity analysis we use the min and max values for each variable to evaluate the robustness of our results.
Table 1: Summary table for the variables used in the analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Midpoint value</th>
<th>Min value</th>
<th>Max value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production/output biomass</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long line</td>
<td>km per hectare</td>
<td>2.47</td>
<td></td>
<td></td>
<td>Case data.</td>
</tr>
<tr>
<td>Production: wet weight</td>
<td>Tons per km long line per year</td>
<td>12.5</td>
<td>11.25</td>
<td>13.75</td>
<td>Pechsiri et al. (2016).</td>
</tr>
<tr>
<td>Dried seaweed as share of wet weight</td>
<td></td>
<td>0.1936</td>
<td></td>
<td></td>
<td>(based on 22% moisture content in dried seaweed (Scoggan, Zhimeng, and Feijiu 1989) and dry weight/wetweight ratio as below.</td>
</tr>
<tr>
<td>Dry weight share of wet weight (i.e. no water at all left)</td>
<td></td>
<td>0.151</td>
<td></td>
<td></td>
<td>(Schiener et al. 2015)</td>
</tr>
<tr>
<td>Production: dried seaweed</td>
<td>Tons per hectare</td>
<td>5.9774</td>
<td></td>
<td></td>
<td>Calculations from above.</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material every year</td>
<td>EUR/2 ha</td>
<td>21647</td>
<td></td>
<td></td>
<td>Case data.</td>
</tr>
<tr>
<td>every 5th year</td>
<td>EUR/2 ha</td>
<td>8180</td>
<td></td>
<td></td>
<td>Case data.</td>
</tr>
<tr>
<td>every 10th year</td>
<td>EUR/2 ha</td>
<td>34969</td>
<td></td>
<td></td>
<td>Case data.</td>
</tr>
<tr>
<td>Labour</td>
<td>EUR/2 ha</td>
<td>10225</td>
<td>7669</td>
<td>12782</td>
<td>Case data.</td>
</tr>
<tr>
<td>every year</td>
<td>EUR/2 ha</td>
<td>84</td>
<td>63</td>
<td>105</td>
<td>Case data.</td>
</tr>
<tr>
<td>every 5th year</td>
<td>EUR/2 ha</td>
<td>8196</td>
<td>6147</td>
<td>10245</td>
<td>Case data.</td>
</tr>
<tr>
<td>every 10th year</td>
<td>EUR/2 ha</td>
<td>81</td>
<td></td>
<td></td>
<td>Case data.</td>
</tr>
<tr>
<td>Energy</td>
<td>EUR/2 ha</td>
<td>81</td>
<td></td>
<td></td>
<td>Case data.</td>
</tr>
<tr>
<td>Productivity growth a</td>
<td></td>
<td>2.4%</td>
<td></td>
<td></td>
<td>See supplementary material for details.</td>
</tr>
<tr>
<td>Nitrogen uptake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N content, kilo/ton dry weight</td>
<td>EUR/kg N</td>
<td>7,568</td>
<td>3,647</td>
<td>11,489</td>
<td>Ahlroth (2009), Kinell et al. (2009), Noring et al. (2014), Czajkowski et al. (2015), Ahltainen et al. (2014).</td>
</tr>
<tr>
<td>Phosphorus uptake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P content, kilo/ton dry weight</td>
<td>EUR/kg P</td>
<td>86,458</td>
<td>0</td>
<td>172,916</td>
<td>Ahlroth (2009), Kinell et al. (2009).</td>
</tr>
<tr>
<td>Recreation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total recreational values west coast</td>
<td>Thousand EUR</td>
<td>1805800</td>
<td></td>
<td></td>
<td>Calculations based on Czajkowski et al. (2015) and SwAM (2012)</td>
</tr>
<tr>
<td>(&quot;Consumer Surplus&quot;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Assumption.</td>
</tr>
<tr>
<td>Share of Consumer Surplus loss at max potential scale</td>
<td></td>
<td>6%</td>
<td>2%</td>
<td>10%</td>
<td>Assumption.</td>
</tr>
<tr>
<td>Financial discount rate</td>
<td>Discount rates</td>
<td>4%</td>
<td>6%</td>
<td>6%</td>
<td>Assumption. (Evans 2007)</td>
</tr>
<tr>
<td>Social discount rate</td>
<td></td>
<td>4%</td>
<td>2%</td>
<td>2%</td>
<td>(Evans 2007)</td>
</tr>
</tbody>
</table>
RESULTS

We begin our analysis by studying the single-firm case to see what drives the results in the short run. We then turn to the scale-up scenario where 338 km² (the max potential) are used for seaweed cultivation. Figure 2 shows the results of the CBA based on a single-firm that cultivates two hectares over ten years. In the CBA, the values are discounted to net present values in thousand euro. As Figure 2 shows, both the financial net (€1966 thousand) and socioeconomic net (€1938 thousand) are strongly positive. The variables that have the largest impact on both the financial and socioeconomic net are the production costs (€303 thousand) and revenues (€2269 thousand), while the externalities have a minor impact. The positive externalities, N and P uptake, amount to €10 thousand and €16 thousand respectively, while the negative externality (loss of recreation possibilities) amounts to minus €54 thousand. This suggests that the values of positive and negative externalities partially cancel one another out, resulting in a net externality estimated to minus €28 thousand.

Figure 2: Net present values for a single firm cultivating two hectares over ten years (thousand Euros).

The break-even sales price in the single-firm case is 3 €/kg dried seaweed. This is well below the midpoint sales value and also below the predicted min sales value (see Table 1). Figure 3 shows the results for the scale-up scenario where the total area of 338 km² is used for seaweed cultivation. The figure shows the same pattern as Figure 2, with large financial and socioeconomic net values (€4.6 billions).
The large-scale scenario implies production during year 40 of approximately 1 000 000 tons of biomass (wet weight). Such volume still remains a rather small share (4 %) relative to current global production of farmed aquatic plants (FAO, 2014). Concerning N and P uptake, this level of production in year 40 would sequester 2521 tons N and 378 tons P. The yearly anthropogenic net load to these basins is 18 400 tons of N and 380 tons of P (SwAM, 2016; data year 2014), which implies that this cultivation size would enable sequestration of 14 % (N) and 100 % (P) of the annual anthropogenic net load to these basins.

At this level of seaweed cultivation, the net present value of the N and P uptake amounts to €22 million and €37 million respectively. The recreational impact is estimated to minus €123.6 million, resulting in a negative socioeconomic net of €64.6 million. Compared to the revenues the N and P values amounts to 0.4 and 0.7 percent respectively, while the negative externality amounts to 2.4%.
**Sensitivity analysis**

A sensitivity analysis was conducted for robustness by changing the midpoint value of the variables to either the min or max value that are presented in Table 1. The analysis is done for each variable separately. For all cases, both the financial and socioeconomic net turns out to be positive.

For both the single-firm and the scale-up scenario the results are most sensitive to changes in the sales value. If the min value 5 €/kg dried seaweed is used, the socioeconomic net for the single-firm scenario will fall to €173 thousand and for the scale-up scenario to €566 million. For the max value 50 €/kg dried seaweed, the socioeconomic net increases with 143% for the single-firm scenario and with 138% for the scaled-up scenario. The reason that the percentage change is lower for the scale-up scenario is due to the fact that the values are discounted over a longer time period. 40 years compared to 10 years for the single-firm scenario.

For the single-firm scenario the variable that have the second largest impact is the production of seaweed per km long line per year. The socioeconomic net varies with ± 12% if the min and max values are used. The financial discount rate have the third largest effect, where the max value lower the socioeconomic net with 7.8%. Applying the min and max values for recreational loss implies that the socioeconomic net varies with ± 1.9%. Increases in hourly wage costs with 25% lower the socioeconomic net with 1.1%. Finally, using the max values for both N and P increases the socioeconomic net with 1.1%.

For the scale-up scenario, with a longer time horizon than the single-firm scenario, the financial discount rate have the second largest impact. An increase of the financial discount rate to 6%, lower the socioeconomic net with 49% to €2.4 billion. However, the financial discount rate can be increased to 19% before the socioeconomic net becomes negative. Production of seaweed per km long line has the third largest impact, and varies the socioeconomic net with ± 11.4%. For recreation, the socioeconomic net varies with ± 1.8% compared to the midpoint scenario. If the max values for N and P uptake are used, the socioeconomic net increases with 1.1%. Increases in the hourly wage cost, also has a minor impact on the results for the scale-up scenario. An increase in the hourly wage costs with 25%, lower the socioeconomic net with 0.7%. One reason that the effect of wage increases is fairly small, is that the underlying model assume that there is a productivity growth of 2.4% per year (see Table 1), which lower the labour costs. The result of the robustness check is shown in the supplementary material.

**DISCUSSION**

Although the sensitivity analysis suggests that our results are robust, our data have some limitations. The largest uncertainty is for the externalities. Due to lack of lack of case specific studies for recreational loss due to seaweed cultivation, a share of the CS for recreation have been applied to measure the loss. The true value can be both larger and smaller than the values that we have used, and the extent to which recreational values are lost depends on locations and design of the cultivation sites. Given that seaweed is harvested in May and a new cultivation cycle begins in the fall (Hasselström et al., 2018), it is possible that recreational losses here have been overestimated since the main recreational season in Sweden is during the summer months.
The economic values of N and P uptake are based on WTP studies. Although the assessment shows that substantial amounts of these nutrients can be sequestered, the value of this sequestration is still low compared to the financial turnover. Even when the maximum values are used for N and P sequestration, production costs are higher than the value of reduced eutrophication, suggesting that seaweed cultivation is not an economically profitable measure for eutrophication mitigation per se.

While eutrophication mitigation and recreational impacts are identified as the most significant externalities (Hasselström et al., 2018), there are other positive and negative externalities as well, not being monetized in this study; positive effects such as habitat generation for fish and crayfish, reduction of ocean acidification, carbon sequestration and possibly negative effects from e.g. shading effects on bottom fauna. Concerning carbon sequestration, the net result requires a life-cycle perspective, where total impact from seaweed cultivation on the CO2 balance in the atmosphere is dependent on a) temporary storage in growing biomass, b) life-length of storage in products generated by the biomass, c) the energy requirement in different production stages, and d) substitution of other products (Hasselström et al., 2018). Concerning other externalities, these are likely to be dependent on the specific case setup and location choice. Additional study is needed to conclude on the magnitude of these externalities in monetary terms.

The use of biomass may affect biomass price. It is here assumed that dried biomass is sold to the world food market. Given other applications, price may be lower or higher which may influence the overall profitability. However, our analysis shows that a price as low as 3 €/kg dried seaweed generates financial break-even. This suggests that even low-value products would have the potential for financial break-even.
REFERENCES


