Environmental assessment of an upscaled production of macroalgae

A prospective Life Cycle Assessment of the Swedish production of *Ulva fenestrata*

Master's thesis in Industrial Ecology

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Cover: *Ulva fenestrata*. Photography by Oscar Gustavsson, Nordic Seafarm.

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Abstract

Aquaculture, including macroalgae production, is one of the most rapidly growing economies worldwide. Off-shore cultivation of macroalgae, also known as seaweed, is a biomass production recognized to have significant potential as a sustainable food source and is also considered a suitable option for up-scaled production. Despite the acknowledged environmental and profitable benefits and potential of macroalgae production in Europe, there are still many existing knowledge gaps and challenges regarding the topic and mapping the environmental impacts of new potential blue foods is necessary. Therefore, this study investigates the environmental impacts of coastal (off-shore) seaweed production by conducting a prospective life cycle assessment (pLCA) on an initiated Swedish cultivation of the green macroalgae, *Ulva fenestrata.* The study also includes an upscaled future scenario to point out the potential environmental impacts and give insight into how the upcoming Swedish aquaculture practitioners could decrease the environmental impact of their systems. Additionally, life cycle assessment (LCA) lacks clear possibilities for including local marine environmental impacts. By conducting an exploratory literature search of the current state of knowledge regarding local impacts of seaweed cultivation, the thesis strives to holistically review the environmental impacts of the studied seaweed cultivation. Additionally, to find tools and methods for evaluating local environmental impacts and increase the knowledge about how to assess the environmental impacts both within and outside the scope of LCA.

The study was divided into three main parts: The base scenario (using pLCA), future upscaled scenario (using pLCA) and local environmental impacts (using exploratory literature search). The data for the pLCA was mainly gathered from interviews, a study visit and contact with researchers and personnel at Nordic Seafarm, KTH and RISE. The pLCA was performed with Excel in combination with the LCA software SimaPro v.9.3.0.3 and information mostly from the databases EcoInvent v.3.8, Agribalyse 3.0.1 and Agrifootprint 5.0. For the future upscaled scenario information was based on the result of the base scenario, academic papers, and grey literature. Information for the exploratory research was collected from academic papers using databases Google Scholar and Scopus.

The pLCA results show that dominant factors contributing to environmental impacts proved to be mainly the processes of spore preparation and cultivation, where the components: carrying line, screw anchors, anchor buoys and longlines were dominant. Additionally, diesel and gasoline had high impacts in most impact categories. The sensitivity analysis showed significant changes when investigating e.g., different seeding line options, weight of screw anchors and amount of biomass yield. Factors that contributed to a higher impact were the use of plastics and fossil fuels and the lifetime, volume and duration of the components used in the system. The future upscaled scenario yielded decreases in environmental impacts compared to the base scenario in most impact categories. From the exploratory literature search, several local impacts of upscaled aquaculture and seaweed farming, both positive and negative, that could affect local marine ecosystems were identified—for instance, carbon and nutrient uptake, shading, animal entanglement and seabed damage. Several ways of including local impacts into environmental evaluation exist, including specifically developed characterization factors, ecological risk assessments and specific methodological recommendations. However, further research is needed to find suitable ways to holistically include a broad spectrum of possible local impacts of upscaled seaweed cultivation.

Keywords: Macroalgae, *Ulva fenestrata*, Life Cycle Assessment (LCA), Prospective Life Cycle Assessment (pLCA), local marine environmental impacts, upscaled production

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Abbreviations

LCA - Life Cycle Assessment
LCI - Life Cycle Inventory
LCIA - Life Cycle Impact Assessment
pLCA - Prospective life cycle assessment
ES - Ecosystem Services
FU - Functional Unit
PE - Polyethylene
PP - Polypropylene
PS - Polystyrene
PES - Polyester
PVC - Polyvinylidenchloride
PLA - Polylactic acid
CO_2 - Carbon dioxide
SEA - Strategic Environmental Assessment
EIA - Environmental Impact Assessment
EBA - Environmental Benefits Assessment
EAA - Ecosystem Approaches to Aquaculture
FAO - Food and Agriculture Organisation
CF - Characterizations factor
NPP - Net primary production
GHG - Greenhouse gases
SO_x - Sulphur oxides
NO_x - Nitrogen oxides
CED - Cumulative energy demand
GWP100 - Global warming potential 100
RER - Europe
GLO - Globally
TRL - Technology readiness level
MRL - Manufacturing readiness level
SO_2 - Sulphur Dioxide
PO_4 - Phosphate
DB - Dichlorobenzene
Sb - Antimony
Eq - Equivalents
MJ - Megajoule
ISO - International Organisation for Standardisation
IMTA - Integrated Multi-Trophic Aquaculture
ADP - Abiotic Depletion Potential
RISE - Research Institutes of Sweden

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Introduction

With an increasing human population, overuse of finite resources and a decrease in the amount of available land, the world is facing tremendous challenges in finding sustainable ways of meeting the worlds' needs. The worlds' oceans are suffering from human exploitation; however, they also possess a tremendous amount of unlocked potential (FAO, 2020). Offshore cultivation of macroalgae, also known as seaweed, is a biomass production that has been recognized to have major potential regarding both sustainability and profitability (EC, 2021; EC, 2015, EC, 2012). Seaweeds have the potential to, for instance, capture carbon, take up nitrogen and phosphorus to address local eutrophication, and provide different ecosystem services (FAO, 2020; Corrigan et al., 2022). In addition, seaweeds are fast grown and nutritious marine plants that can be used for a variety of applications and can be suited as a sustainable plant-based food source for both humans and animals (Tiwari & Troy, 2015). Aquaculture, including seaweeds, is one of the most rapidly growing economies worldwide (FAO, 2020). Despite the acknowledged environmental and profitable benefits and potential of algae production in Europe, there are still lots of existing knowledge gaps and challenges regarding the topic (Araújo et al., 2021).

However, an important part of the European Union's priority towards a green transition is investments in the blue economy that aims to support, e.g., the circular economy, climate change mitigation, biodiversity preservation and food security regarding industries, production and actors related to oceans and coasts (EC, 2021). In Sweden, there are multiple initiatives to support a sustainable transition and national food security. The Swedish national food strategy aims to unlock the potential of sustainable national food production and promotes green, biobased, and circular growth (Livsmedelsverket, 2016). The strategy also notes the potential of marine resources and articulates the importance of prioritising the development of Swedish aquaculture (Livsmedelsverket, 2016; Svenska Lantbruksuniversitetet [SLU], 2020).

One necessity mentioned by researchers in connection to this development of usage of the oceans, is the need to quantify, map and environmentally assess new potential blue foods and production systems that could support the sustainability goals (Blue Food, 2022) In Sweden, various seaweeds are domestically occurring and suitable to cultivate in cold waters with a northern climate (Steinhagen et al., 2021; Uppsala Universitet, 2020) and thus, have the potential to contribute to national self-sufficiency (Riksdagen, 2020). This is not the least true for the green macroalgae *Ulva fenestrata* (Steinhagen et al., 2021). However, much focus in research has been on a few seaweed types such as *Saccharina latissima* ("sugar kelp"). Additionally, the European production of seaweed has also mainly been focused on brown algae, prominently the sugar kelp (Araújo et al., 2021). Depending on what type of seaweed is grown, the production systems need to be adapted and the production process can look very different depending on the type of algae (Nakhate & van der Meer, 2021). To assess the environmental impacts of the different algae production systems, it is important to map and evaluate the different production systems and acknowledge the differences to highlight benefits, drawbacks and suggest improvements.

Even though algae aquaculture has an environmental advantage over, for instance, land-based animal production (EC, 2020), aquaculture has also related to several environmental impacts (Bohnes & Laurent, 2019). Therefore, it is highly important to environmentally assess the emerging technologies in an early stage to be able to include improvements and ensure sustainable aquaculture production (Thonemann et al., 2020; Bohnes & Laurent, 2019).

Life Cycle Assessment (LCA) is a widely used tool that can be used to assess the environmental impacts of various products and systems, including different seaweed production processes (Baumann & Tillmann, 2004; Thomas et al., 2021). Even though LCA is a widely used tool, beneficial in many ways, there are several issues regarding the environmental analysis of aquacultural upscaling systems with LCA (Bohnes & Laurent, 2019). Seaweed aquaculture in Sweden is a new and underdeveloped technology. Environmental assessment of a technology not yet fully realised makes the demand for the evaluation method high since the data will be of high uncertainty (Arvidsson et al., 2018). According to Woods et al. (2016), LCA was initially elaborated to analyse and evaluate the impacts of industries based on land in terrestrial and freshwater ecosystems and knowledge is lacking regarding executing LCA on aquaculture systems. Moreover, even though research has been going on for over two decades, there is yet no clear ways of effectively and accurately including impacts on the local marine ecosystems and biodiversity in LCA (Winter et al., 2017). Apart from general emissions assessed with an LCA, it is important to identify potential trade-offs that a potential future up-scaling of algae production in Sweden might entail regarding local environmental impacts.

1.1 Aim and research questions

The thesis aims to perform a prospective LCA of an initiated implementation of a Swedish *Ulva fenestrata* cultivation to evaluate the system's environmental impacts. The purpose of the thesis is also to include an upscaled future scenario to point out the potential environmental impacts of an upscaled production and give insight into how the upcoming Swedish aquaculture practitioners could decrease the environmental impact of their systems. Additionally, LCA lacks clear possibilities for including local marine environmental impacts. By conducting an exploratory literature search of the current state of knowledge regarding tools and methods for evaluating local environmental impacts, the thesis strives to increase the knowledge about how to assess the environmental impacts both within and outside the scope of LCA.

The thesis aims to answer the following research question:

- What are the hotspots of the studied production system of *Ulva fenestrata* in terms of contributions to environmental impacts?
- What could an upscaling of a Swedish off-shore *Ulva fenestrata* production system entail regarding future environmental impacts?
- What improvement proposals could an assessment of an upscaling of a Swedish off-shore *Ulva fenestrata* production system give regarding future environmental impacts?
- What are the potential environmental impacts on the local marine ecosystems of a Swedish offshore *Ulva fenestrata* production system and how can they be environmentally assessed both within and outside the scope of LCA?

1.2 Limitations

The study was solely focused on the environmental impacts and thus excluded social and economic dimensions of sustainability. Geographically, the LCA study focused on Swedish algae cultivation and the assessment was made on a specific seaweed production located on the Swedish west coast. There were no standardised production methods for seaweed cultivation and since this LCA study was performed based on a specific case, the study was somewhat limited to this case or similar cases and not directly applicable for other seaweed production systems. In addition, the LCA study was based on the production system of the specific algae type *Ulva fenestrata.* The study was therefore also not directly applicable to other types of macroalgae. Furthermore, the study was focused on off-shore seaweed cultivation systems and was thus limited to this type of cultivation. More detailed limitations and assumptions regarding specific parts of the study will be further addressed in *chapter 3: Methodology of the study*.

2

Background

This chapter will give an overview of macroalgae, followed by a description of the methodological framework used in this thesis. The overview of macroalgae includes descriptions of the current spread of seaweed aquaculture, production methods, the studied green macroalgae *Ulva fenestrata*, and earlier LCA studies on macroalgae. The second part consists of a description of LCA in general and prospective LCA.

2.1 Macroalgae - an overview

Macroalgae, also called seaweeds, are multicellular plant organisms living in aquatic environments. Unlike microalgae, macroalgae are large enough to see with the naked eye (SLU, 2022; Lei, 2021). Macroalgae are often categorised into three groups: Chlorophyta, Phaeophyta and Rhodophyta, commonly known as green, brown, and red macroalgae (Lei, 2021). Seaweeds grow naturally across the globe and only in Sweden, there are over 1100 known species of macroalgae (SLU, 2022).

Seaweed has a lot of eminent characteristics and benefits making it suitable for a wide range of implementations (FAO, 2020). In Europe, there are several initiatives currently investigating sustainable production, safe consumption and new creative applications of algae that can help support the transition to a sustainable blue biobased economy (EC, 2020). Due to their valuable nutritional composition often rich in protein, carbohydrates, vitamins and minerals, seaweeds are well established as a food source (mainly in Asia) for both humans and animals (FAO, 2020; Tiwari & Troy, 2015). However, the nutritional content such as protein can vary a lot with regard to seaweed (Fleurence, 1999). The use of macroalgae as a food and protein source for human, fish and animals is on the rise in Europe and it is exploratively researched on many fronts (Winter et al., 2017; Araújo et al., 2021). Furthermore, compared to other types of biomasses it is relatively fast grown and can be harvested annually (Forster & Radulovich, 2015). Other applications currently being explored are macroalgae as biofuel, fertilizers, components in cosmetics and medicine and for making new biomaterials (EC, 2020; Lei, 2021).

Algae have also been recognized for their contributions of beneficial environmental services. Just like bivalves, macroalgae are so called extractive species which means that they take up nutrients from the surrounding waters (Cai et al., 2021; Corrigan et al., 2022). By extracting nutrient deposits such as nitrogen and phosphorus that has reached the oceans from land-based activities and absorbing carbon dioxide, extractive species can help decrease the risk of marine eutrophication and marine acidification as well as mitigate climate change (FAO, 2020; Corrigan et al., 2022). Furthermore, due to the uptake of dissolved nutrients from the surrounding environment, there is no need for adding feed, fertilizers or pesticides which is beneficial compared to many other food production systems (Cai et al., 2021; Jones et al., 2022; Parodi et al. 2018). Additionally, seaweed has an important role in the global primary production and as creation of habitats for other species (Jones et al., 2022; Corrigan et al., 2022; Cai et al., 2021).

2.1.1 Current spread of macroalgae production

Cultivation of seaweed has become more and more popular in the last decades (FAO, 2020). Asian and Pacific countries such as China, Japan, Indonesia, Philippines, and South Korea have a long history of seaweed cultivation and a large share of the market (Araújo et al., 2021; Lei, 2020) but recently, interest has started to grow both in Europe and North America (Kim et al., 2017; Araújo et al., 2021). Currently, there is development of macroalgae production in 13 countries in Europe with Spain, France and Ireland standing for the majority. Norway, Denmark, and the United Kingdom are countries with productions well on the rise (Araújo et al., 2021). However, Norway is the largest developer of the aquaculture production of macroalgae (Araújo et al., 2021; Buschmann et al., 2017).

Norway, comparable in climate to Sweden, is currently the second biggest exporter of seaweed in Europe (Stévant et al., 2017). In several countries such as Norway and the United States, the production has mostly been focusing on kelp seaweed species, such as *Saccharina latissima*, due to their possibility of producing high yield, easy growing attributes, and the high nutritional content (Stévant et al., 2017; Kim et al., 2019). However, the inquiry and interest for other seaweed species have increased and more permits are starting to apply for other species such as *Ulva species (spp)* (Grebe et al., 2019; Kim et al., 2019; Eriksson et al., 2017). In Norway, however, *Ulva spp* are not yet cultivated at sea (Stévant et al., 2017; Araújo et al., 2021).

In Sweden, on the west coast, initiatives on seaweed cultivation are also starting to arise. Nordic Seafarm (NSF) is today one of the most prominent producers of cultivated seaweed in Europe and the production system that this LCA study will be based on. They are mainly focused on cultivation of sugar kelp (Nordic Seafarm, n.d,a), however, recently they have started a new project with cultivation of *Ulva fenestrata*. NSF has developed a method for cultivation of *Ulva fenestrata* where the cultivation can be done directly in the ocean. In that way, there can be a high-quality cultivation with low costs (Nordic Seafarm, n.d, b). However, to enable cultivation in the ocean, some preparatory processes are needed on land. The processes conducted on land are today based at Tjärnö on the Swedish west coast, meanwhile, the cultivation in the ocean is deployed in different places in the northern archipelago of the Swedish west coast (personal communication, 2022).

2.1.2 Production methods and their challenges

Seaweed can be produced both in aquaculture and from wild harvesting of coastal ecosystems (Araújo et al., 2021). Globally, aquaculture production dominates production volumes. Currently, wild harvesting is still dominating production volumes in Europe, however, cultivation is increasing (Araújo et al., 2021). Harvesting of wild stocks has been widely debated and questioned regarding environmental sustainability (Callaway, 2015; Monagail et al., 2017; Yeo., 2021). Wild harvesting can be made mechanically (with the help of machines and cranes), by hand (manually with tools) or sometimes by trawling. Mechanical harvesting provides larger volumes more time effectively which generates more income than manual harvesting (Araújo et al., 2021; Yeo, 2021). Wild harvesting by hand takes more time but does not jeopardize the wild stocks as much as the mechanical since risk of over-exploitation can increase if not managed and regulated properly (Yeo, 2021; Monagail et al., 2017).

Cultivation of seaweed can be performed both on land and in the sea (Araújo et al., 2021). Land-based cultivation takes place either indoors or outdoors in tanks, ponds or basins filled with seawater adjusted to the right conditions depending on the species (Titlyanov & Titlyanova, 2010; Brockmann et al., 2015; Araújo et al., 2021). Compared to sea-based cultivation, land-based cultivation of seaweed can provide benefits such as simplified harvesting and higher yields and entails total control over the cultivation, which enables tampering with parameters (Steinhagen et al., 2021; Titlyanov & Titlyanova, 2010). In addition, it can simplify measures to decrease epiphytes (Lüning & Pang, 2003). However, land-based systems often entail higher costs in terms of construction, materials, and equipment requirements and higher maintenance and operational costs, which tends to make mass production challenging. In addition, land-based systems require a large amount of seawater and additional nutrients (Sebök et al., 2019; Titlyanov & Titlyanova, 2010; Lüning & Pang, 2003).

The most used cultivation production method in Europe is currently sea-based, mainly located close to coastlines (Araújo et al., 2021). Contrary to land-based systems, sea-based systems do not require as much additional seawater and nutrients. Additionally, it does not entail any land occupation and does not compete with other land-based production that matters (Seghetta et al., 2017). However, sea-based cultivation also implies challenges such as vulnerability to storms and the great demand for infrastructure (Kim et al., 2019; Bak et al., 2020). Depending on water depth and distance from shore, the benefits of sea-based and off-shore cultivation make a promising and feasible alternative for larger-scale productions (Bak et al., 2020). Most of the current sea-based seaweed cultivation systems are limited in the suitable time for the cultivation. Normally, the growth period for seaweed cultivation is between autumn and spring, when there is sufficient sunlight and nutrients to induce good growth (Campbell et al., 2019; Steinhagen et al., 2021). Even though summertime entails sun and nutrients, there can often be high levels of fouling which can limit the seaweed quality (Campbell et al., 2019).

2.1.3 The green macroalga *Ulva fenestrata*

Ulva fenestrata is a green macroalgae which can be found in the waters in the northern hemisphere (Steinhagen et al., 2021). It grows an attaches on rocks in shallow subtidal and in rocky shores. Its key characteristics is that its thallus (the "body" of the algae) is see-through, light green, broad and crumpled. Furthermore, the thallus can be around 25 centimetres long and can be found in the ocean all year (The Seaweed Site, n.d; Pizzolla, 2008). *Ulva spp* is seen as a promising seaweed as it has a high environmental tolerance and can resist changing abiotic factors. Additionally, it has a fast growth rate and can thrive even under high stocking densities (Bolton et al., 2016; Steinhagen et al., 2021). *Ulva spp* is also seen as a seaweed with a multipurpose use. For example, it has several beneficial nutritional properties and can be used both as feed to animals and as food for humans (Bikker et al., 2016). Even though the protein content of seaweeds can vary (Fleurence, 1999), Ulva spp has been seen to consist of a high crude protein content of up to 44 % of dry matter (Holdt & Kraan, 2011). Moreover, it can function in other applications such as cosmeceuticals, pharmaceuticals, and nutraceuticals (Steinhagen et al., 2021).

Currently, there are some ambiguities regarding the terminology and taxonomy of the different species within the genus of *Ulva Linnaeus 1753* (ITIS, 2022; Hughey et al., 2019; Bolton et al., 2016). The most common and well-known species name is the generitype *Ulva lactuca*, also commonly called "sea lettuce" (ITIS, 2022; Hughey et al., 2019). The name *Ulva lactuca* and sea lettuce have been widely used as the name to describe various green sea lettuce-like plants in oceans across the globe. There has been previous belief that the *Ulva lactuca* is the species found in tropical waters as well as cold north waters (Hughey et al., 2019). However, genetically speaking, this is not the case. With genetic analysis of different collected samples of *Ulva spp* it has been identified that there are genetic differences between *Ulva* found in different geographical locations. The *Ulva lactuca* has been shown to be more genetically sequentially similar to tropical types of *Ulva* found in warm waters rather than *Ulva* species found in cold waters in the Northern Hemisphere. The species found in colder waters have instead been more correctly identified as the holotype *Ulva fenestrata,* close to identical with the lectotype *Ulva stipitata* (Hughey et al., 2019).

2.1.4 Earlier LCA studies on macroalgae

There have been several LCA studies performed on macroalgae of which the majority are from the last decade. Various studies are of the brown kelp seaweed, *Saccharina latissima*. Thomas et al. (2021) for instance, performed a comparative environmental LCA of hatchery, cultivation, and preservation of the *Saccharina latissima* in the Koster archipelago on the Swedish west coast, where three different preservation methods and two different hatchery processes were compared. Another LCA study was made by Seghetta et al. (2017), where the environmental impacts of seaweed as an innovative feedstock for energy and feed were evaluated. In the article, different scenarios for future industrial-scale production processes were compared. Even here, the *Saccharina latissima*, in addition to another macroalgae type, *Laminaria digitata* (Oarweed), was assessed. Taelman et al. (2015), and Langlois et al. (2012) have also performed LCAs on *Saccharina latissima*. Taelman et al. (2015) performed a comparative environmental LCA of two seaweed cultivation systems in North West Europe with a focus on quantifying sea surface occupation. Langlois et al. (2012), assessed biomethane from offshore-cultivated seaweed. Aitken et al. (2014) published an article of a performed LCA on biofuel made from another macroalgae called *Macrocystis pyrifera*. Little research has yet been conducted on the green macroalgae. To our knowledge, an LCA of the green macroalgae *Ulva fenestrata*, also found on the Swedish west coast, has never been done.

2.2 Life Cycle Assessment theory

This section aims at describing the theory and methodological framework of LCA. It includes a description of the framework, the four steps and different application fields.

2.2.1 Framework

According to ISO (2006a) 14040, LCA is a standardised method used in order to assess the environmental impact of the stages in a product or service life cycle. The stages include raw material acquisition, production, use, end-of-life treatment, recycling, and disposal (ISO, 2006a). Not all LCAs follow the full life cycle, an LCA that evaluates the whole life cycle has a cradle-to-grave approach meanwhile an LCA that is performed to assess the environmental impacts from manufacturing to the factory gate has a cradle-to-gate approach (Baumann & Tillman, 2004).

LCA was created as a consequence of societies increasing awareness of environmental impacts associated with products and the need for environmental protection (ISO, 2006a). An LCA can have several different purposes and the main goal is to change or improve a product system either in a more direct or indirect way (Baumann & Tillman, 2004). In addition, a distinction between two different types of LCA is usually done. One is the attributional LCA where the purpose is to describe the relevant in- and outflows from the life cycle together with its subsystems. The other one is the consequential LCA which has the purpose to give a description of how the flows could shift depending on the decisions taken (Finnveden & Potting, 2014). The framework of LCA procedure is illustrated in *Figure 1*.

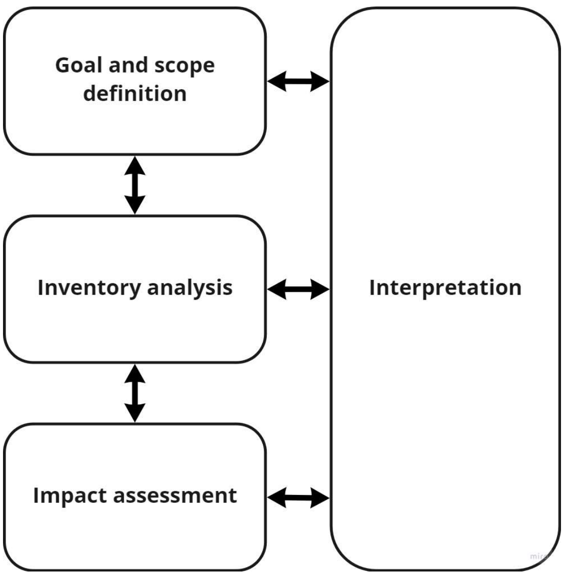

Figure 1. LCA framework

2.2.2 The four steps in LCA

The structure of an LCA according to the ISO (2006a) 14040 standard follows four steps: goal and scope definition, inventory analysis, impact assessment and interpretation. The interpretation step is an iterative process and is integrated into all other steps (ISO, 2006a).

The goal and scope definition aims to describe the purpose of the LCA and the product to be studied. In accordance with the ISO standard 14040, the goal should state whom the result is intended for, why the LCA is performed and the intended application. This is done by defining a problem formulation with specific questions. The scope of the study should state the functional unit, which describes the function served by the product system and corresponds to a reference flow. Additionally, the scope should state other important elements including system boundaries, choice of impact categories, data quality requirements and method for impact assessment (Baumann & Tillman, 2004).

The second step when conducting an LCA is to make an inventory analysis. This is the stage where the environmentally relevant material and energy flows within a product system are collected and quantitatively attributed to the functional unit. It includes both inflows and outflows and is normally presented as a flow chart (Baumann & Tillman, 2004). The life cycle inventory (LCI) involves the collection of relevant data needed in order to meet the defined goals (ISO, 2006a). Data collection is one of the most time-consuming activities when performing an LCA. Firstly, there is a need to find relevant data. This includes both quantitative data such as amount and types of inputs and outputs to and from the system regarding raw materials, products, emissions, and energy. It also includes qualitative data such as geographical boundaries, the function of the system, description of the process etc. Secondly, when all data is collected, it needs to be validated according to the ISO 14041 standard. This implies a check of the data to confirm that valid data is used. These checks could for example be in comparison with other sources or if the data collected is relevant for the intended use of the LCA (Baumann & Tillman, 2004).

The next step of an LCA is the impact assessment which aims to translate the result from the LCI into environmental impacts, such as eutrophication, acidification, and global warming. Reasons for performing the impact assessment are manifold, e.g., to make the result more environmentally relevant, and to improve readability and ease of comparison of results. According to the ISO standard 14042 for life cycle impact assessment (LCIA), there is a structure of sub-phases that should be followed. The structure consists of the mandatory steps impact category definition, classification, and characterisation followed by the optional steps normalisation, grouping, weighting, and data quality analysis. It is in the impact category definition step that the impact categories to be included are defined. When the impact categories have been defined, a classification of the LCI result is done by assigning the different LCI result parameters into the selected impact categories. When the classification has been done a characterization is performed. The characterization is a quantitative step and aims to calculate each inventory flow and its relative contribution to the selected categories (Baumann & Tillman, 2004).

To make sense of all the data from the calculations and to reach conclusions and recommendations, the LCA consists of an interpretation step. In this step, the raw results from the inventory calculations are refined into a selection of the most important results and presented in different types of diagrams (Baumann & Tillman, 2004). Furthermore, by doing an interpretation of the results, a conclusion can be drawn on if the aspiration of the goal and scope has been met (Muralikrishna & Manickam, 2017). In addition, the robustness of the drawn conclusions is evaluated, for example, through sensitivity analysis or uncertainty analysis. Conducting a sensitivity analysis does not require further data collection, instead a change of input parameters is done to identify the critical parameters. The critical parameters are those where a small change could lead to a large change in the result. Other analyses that can be conducted in the interpretation phase are, for example, a dominance analysis, contribution analysis and break-even analysis where, for example, the dominance analysis aims to investigate the parts in the life cycle which contributes the most to environmental impact (Baumann & Tillman, 2004).

2.2.3 Application fields

There are four main application fields according to the ISO standard (ISO, 2006a). The four application fields of LCA and their purposes is to identify possible improvements in products' environmental performance, act as a basis for support for decision-makers, be used when choosing environmental performance indicators, and for implementation of marketing strategies. Within the field of identification of improvement possibilities are the area of product design and development which is one of the areas that have received the most attention. There are several ways in which an LCA based approach can be used to affect the design of a product. The advantage is that it can deliver a perspective that is holistic and environmentally based which can be used in the deliberations of design options. Another application area is to improve production processes' environmental performance. The aim of LCA applications in this field could for example be process optimisation in the process industry or optimisation of the whole supply chain (Baumann & Tillman, 2004).

2.3 Prospective LCA theory

This chapter describes the framework of a prospective LCA (pLCA) and possible challenges that can occur. In addition, there is a description of the scenarios and different approaches used to develop future scenarios.

2.3.1 Framework and challenges

A pLCA is performed to assess the environmental impacts of emerging technologies and provide environmental guidance in those contexts. It can, for example, be used to support upscaling of emerging technologies where the technology is modelled in a future world and for a more mature stage (Thonemann et al. 2020). The methodology and framework for a pLCA is similar to a regular LCA, however there are some important differences and challenges that differs.

Regarding a pLCA, it is of importance to decide on an emerging technology's maturity level to provide insight into risks, readiness, and performance. Two tools used to evaluate a technology's maturity level are technology readiness level (TRL) and manufacturing readiness level (MRL). MRL is used to define technology manufacturing maturity, which means the readiness of a technology to be manufactured and in which scale (Fernandez, 2010). For example, low values on MRL indicate that the technology is early in the manufacturing process, for example, laboratory-scale production or pilot-scale. Contrarily, high MRL indicates levels comparable to mass production. TRL is used to define the current level of technology readiness and in contrast to MRL that defines the readiness for manufacturing it defines how much the technology has developed in the formative phase before production. A low TRL level indicates that the technology has not been demonstrated in real applications; meanwhile, a high-level means that the technology has been demonstrated in real applications. A pLCA is often used to assess technologies in an early laboratory stage with the purpose of upscaling to mass production (Arvidsson et al. 2017).

There are three main challenges in conducting a pLCA since it evaluates scenarios still not realised. The first challenge is regarding comparability between emerging and mature technologies. This includes stating the aim, functionality, system boundary and choice of impact assessment. The second challenge is about data issues that consider the availability of data, data quality and scaling issues connected to the inventory. The third challenge, uncertainty, implies the challenge of providing correct information when using scenario modelling and the situation of imperfect information in general (Thonemann et al., 2020).

2.3.2 Scenarios in pLCA

There are several approaches that can be used to develop future scenarios for an upscaling of a product system in LCA. Predictive scenarios are one approach, and it aims to develop scenarios that are likely to happen in the future. There are several ways in which data can be obtained in order to build predictive scenarios. Examples of sources that can be used for obtaining scale-up data are input from experts, assumptions, simulation results, initial base cases, technology learning curves, literature etc. (Thonemann et al. 2020). Another approach that can be used is "What-if" scenarios which are used to compare different options for situations that are well-known. In this approach, hypotheses of the future are based on existing data where the system is tested depending on different choices that can be made and their environmental impact. The result is often quantitative and gives indications of which scenario that should be chosen. In general, independently of the choice of scenario approach, a pLCA contains at least a base scenario and one or several alternative scenarios (Pesonen et al. 2000).

Scenarios built to fit the scope of LCA can illustrate possible future states and each scenario can involve different material and product alternatives. The use of scenario development in LCA affects all parts of the LCA although it is in the goal and scope definition that the scenarios are framed. The scenarios based on the conditions set in the goal and scope are then modelled in the LCI and LCIA. The framework should include a short description of the scenario followed by specific assumptions made for the scenario. The inventory analysis should describe the choice of data that have been collected with the data needed for modelling the scenarios. In addition, data on estimations need to be clear and methods for how to handle uncertainties in the data need to be included. It is important to discuss and analyse each scenario and its uncertainties separately and present the results in such a way that comparison is easy to do. Examples of sources that can generate uncertainties are parameter uncertainties, choices, variability between objects/sources, spatial variability, and model uncertainties. Another aspect important to take into consideration is that if the scenarios have an important role in the results of the LCA, strengths and limitations of the scenarios should be considered and expressed in the conclusion (Pesonen et al. 2000).

3

Methodology of the study

In this chapter, the methodology of this study is presented. The chapter starts with general methodology and decisions, followed by LCA modelling, LCA data collection, sensitivity analysis and future upscaled scenario. Lastly, the exploratory literature search is described. After the general methodology, the chapter will describe in more detail, the execution of the pLCA, including data needed for both the base scenario and the future upscaled scenario. Secondly, the conduction of the future upscaled scenario will be described. Lastly, the conduction of the exploratory literature search will be described to display how data related to local environmental impacts were found and used.

3.1 General methodology and decisions

In order to investigate and map the environmental impacts of the *Ulva fenestrata* production system, the thesis was done and divided into three parts.

Firstly, a pLCA was done of the base scenario which, in his study, means the current *Ulva fenestrata* production system. The base scenario and current production system was the next step after lab-scale tests and represented a "demonstration-scaled" production system, not small as the lab-scale but not yet large and industrialized. This base scenario aimed at investigating and quantifying the environmental impacts of the currently implemented *Ulva fenestrata* production system on the Swedish west coast. The lab-scale was based on research and initial test farming, resulted in the development of a demonstration-scaled production system which the base scenario in this project was based on. The construction of the production system of the base scenario had been initiated, however, some steps in the processes were still not fully realised and were therefore based on assumptions made by the production manager at Nordic Seafarm (G. Nylund, personal communication, 23, 24 February, 2022). During the execution of pLCA, site-specific data was collected through interviews and a study visit to quantify and identify environmental impacts related to the planned production system of *Ulva fenestrata*. In addition, other relevant literature was used together with background data from the databases Agrifootprint 5.0, Agribalyse 3.0.1 and EcoInvent 3.8. When all data was collected, the modelling was done in Excel. A sensitivity analysis was also performed for critical parameters that could have significantly affected the result.

Secondly, when the pLCA was executed on the base scenario, the pLCA was extended by investigating and calculating a larger future industrial-scale cultivation, which was referred to as the future upscaled scenario. This was done to identify possible and probable future environmental impacts connected to *Ulva fenestrata* production systems at a larger scale to support the upcoming development of macroalgae cultivation. The same FU was used when calculating the future upscaled scenario. The future upscaled scenario was performed by gathering data on possible future scenarios and factors that will probably change in the future for the *Ulva fenestrata* production and then calculate how the FU will change compared to the base scenario.

Since the FU remained the same, only factors which may have changed in the future, (the future was set to the year 2040) were interesting to assess for this study. This means that factors, such as materials from the base scenario that are expected to increase linearly with an increased production, were not included and recalculated in the future upscaled scenario since this would not change the FU. However, factors such as a future change towards more renewable energy share in the Swedish electricity mix is something that would change the FU and thus, aspects like this, were included. Adding an evaluation of a future upscaled scenario enabled an assessment of what environmental impacts that could be extra relevant in the future, which could support future cultivators of *Ulva fenestrata*. Factors that were included are explained further in chapter *3.6 Future Upscaled Scenario*.

The different scales referred to in the two scenarios are based on hectares (ha) of cultivation area and tonnes of fresh weight biomass. The demonstration-scale represents a 2-ha cultivation with a fresh weight biomass capacity of 20 tonnes, while the industrial-scale represents a 10-ha cultivation with a fresh weight capacity of 100 tonnes.

Thirdly, to be able to further examine the local marine environmental impacts of a macroalgae cultivation system, an exploratory literature search was done. The literature search aimed to investigate and analyse existing information and assessment methodologies in terms of evaluating pressures on local marine ecosystems. This part was done to find relevant data on how to include the assessment of local marine environmental impact both within and outside the scope of LCA. Furthermore, the literature study aimed at investigating how environmental impacts on local marine ecosystems could be evaluated and how they were connected to the two different scale-scenarios.

A representation of the scope of the study is presented below in *figure 2*. The boxes represent the different parts of the study, and the arrows represent how data and knowledge flows between the different parts of the study. The black dashed line shows the included scope.

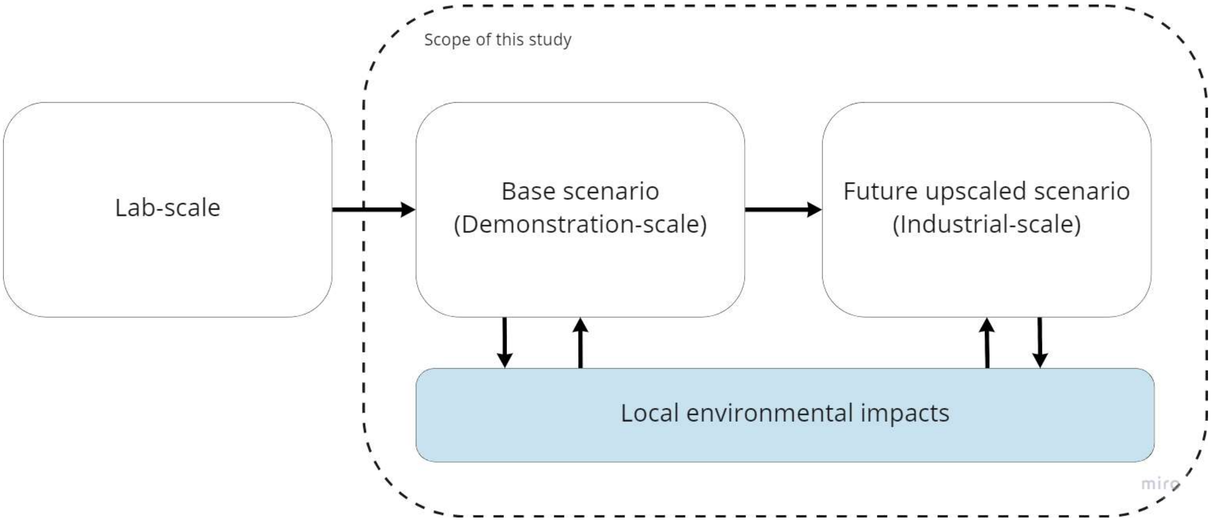

Figure 2. Representation of the three included parts of the study. The boxes represent the different parts of the study, and the arrows represent how data and knowledge flows between the different parts of the study. The black dashed line shows the included scope.

3.2 Goal and scope definition

In this section, the first step of the LCA, namely, the goal and scope definition of this study is presented. This goal and scope section presents information on the purpose of the LCA, functional unit, scope and modelling requirements, future upscaled scenario modelling, system boundary, impact categories chosen, cut-offs, data quality requirements and shows an initial flowchart.

3.2.1 Goal and purpose of the LCA

The goal of the LCA was to evaluate the environmental impacts of the *Ulva fenestrata* off-shore production system and thereby identify potential environmental strengths and weaknesses related to current Swedish *Ulva fenestrata* production. Furthermore, the LCA aimed to provide knowledge and insights that could potentially support future studies and upcoming Swedish aquaculture practitioners in the development of larger-scale *Ulva fenestrata* production systems in Sweden. In addition, the prospective LCA included a designed future upscaled scenario that identified the relevant future environmental impacts that could be important for upscaled production.

More specifically, to support the goal of the LCA, the following guiding questions were created:

- What are the most dominant and contributing activities and materials in the cradle-to-farm gate production of the *Ulva fenestrata* production system in terms of environmental impacts?
- In regards to these aspects, what could a potential industrial scale-up of a Swedish off-shore *Ulva fenestrata* production system entail regarding future environmental impacts?

3.2.2 Functional Unit

The purpose of the LCA was to evaluate environmental impacts related to the off-shore production system of *Ulva fenestrata* from a cradle-to-farm gate perspective, and the function of the system was to provide harvested fresh *Ulva fenestrata*. Hence, the functional unit was set to one tonne of harvested fresh weight (fw) biomass. The fresh weight biomass was considered to be the weight of the biomass immediately after harvest. In this study, it was assumed that the biomass had the same moisture content and weight, meaning no losses of water or biomass, when harvested and loaded onto the boat, and transported to the harbour.

3.2.3 Scope and modelling requirements - prospective modelling

There are several contextual and genetic differences between the *Ulva* species. However, in this study, the product that has been investigated and explicitly modelled was the off-shore cultivated *Ulva fenestrata* algae produced on the west coast of Sweden. More specifically, the LCA study was based on the algae production at Tjärnö where site-specific data and foreground systems were collected.

Since a purpose of the thesis was to investigate a future macroalgae cultivation system the LCA study represented a prospective approach guided by the ISO standardized LCA methodology focused on the environmentally relevant flows regarding the production system of the *Ulva fenestrata* algae. Globally, macroalgae production is not an emerging technology. However, the offshore systems are very different depending on geographical location and species that are being cultivated. In Sweden, macroalgae production has not been industrialized yet and is still in an early phase of development.

The technology readiness level (TRL) and manufacturing readiness level (MRL) was evaluated for the current system studied. Based on the technology maturity guidelines compiled by Fernandez (2010), the *Ulva fenestrata* production system has, in this study, been evaluated to be at the beginning of TRL 9, end of TRL 8 and MRL 8. The actual technology system has been successfully tested, demonstrated and is in progress to begin at a lower rate with initial production but has not yet been tried and proven at a full-scale production level.

3.2.4 Future upscaled scenario

Apart from the assessment of environmental impacts of the present base scenario, a predictive future scenario was incorporated and accounted for within the pLCA to incorporate the environmental impacts of a potential future upscaled scenario.

The factors that were included and upscaled for the foreground system were the surface area, the efficiency of harvest, energy efficiency, duration of electricity-intensive components, material use, and type of fuel used for the boats. For the background system, the factor taken into consideration for a future upscaling of the system was the electricity mix in Sweden. More data and descriptions of the different factors are found in chapters *3.6 Future Upscaled Scenario*.

3.2.5 System boundaries

The LCA had a cradle-to-farm gate approach where the last step considered was harvesting. Therefore, the study did not include the preservation-, use- and disposal phases. This was due to the large uncertainties regarding the *Ulva fenestrata* production in these phases.

The studied system was divided into a foreground and background system based on the possibilities to influence and change the system. The foreground system studied included the processes possible for practitioners to influence and are directly linked to the *Ulva fenestrata* production at Tjärnö, which were spore preparation, seeding, cultivation and harvesting. The background system includes all processes with low possibilities for the practitioners to influence and includes processes such as to the extraction, production and transport of material and products and their respective emissions. More specifically, the background system processes are processes that affects the foreground system but is harder for the practioners of the foreground system to change. A detailed flowchart of the foreground and background systems can be seen in *figure 4* in *chapter 4: Life Cycle Inventory Analysis.*

In the spore preparation and seeding processes, only the energy consumption and consumable materials have been included. For components such as air pumps, seawater pumps, autoclave machines and water only the respective energy consumption has been included and not the materials. The materials were excluded in this study due to limited access to databases and relevant processes.

Regarding the foreground system, although the seaweed cultivation system is based off-shore, out in the ocean, the production is man-made and thus, included in the technical system. Initially, motherplants have been collected from the natural system and taken into the technical system. However, the amount of mother plants needed is very small and rarely done, therefore, this aspect was considered negligible and not included in the assessment. Initially, the new raw material needed is taken from the natural system, enters the technical system and further down the system is released as emission outputs to the natural system. From the chosen impact categories, this study considered emissions produced in the technical system and released into the natural system through air and water. In addition, only transport by boat has been included in this assessment. This is partly due to assumed negligible transportation distances by car and partly due to uncertainties regarding the car transports.

The geographical boundary for the LCA was the Swedish west coast. However, the water conditions such as salinity and nutrient density can vary along the west coast and thus, could potentially limit the geographical boundary further for the different scenarios. More specifically, the geographical boundaries for the foreground system stretched from the on-shore site where the initial spore preparation and seeding processes occur, to the off-shore farm site of 2 hectares where the planned cultivation and harvest will happen. The background system data regarding extraction of raw materials, manufacturing processes and other more general information was not required to be site-specific and was not limited to any geographical boundaries.

Since this thesis included a prospective future scenario, the temporal perspective was varied depending on the scenario. For the base scenario, the temporal boundary was set to the current time (2022 or as close to this as possible). For the future upscaled scenario, the temporal perspective was instead for the year 2040. The data for the base scenario strived to represent as certain and current data as possible via expert knowledge while the future scenario was based on prospective data on forecasts and scenario planning. This will be further discussed later in the report (*Chapter 6.3 Future Upscaled Scenario*).

3.2.6 Initial flowchart and the studied system

The initial flowchart shown in *figure 3* presents the main processes of the *Ulva fenestrata* production system from a cradle-to-farm gate perspective and represents the boundaries of this LCA. The production system consists of the initial process, spore preparation, including maintenance of parental biomass, induction of fertile tissue and spore release. The subsequent processes are seeding, cultivation and harvesting. A more detailed flowchart is presented in *figure 4*.

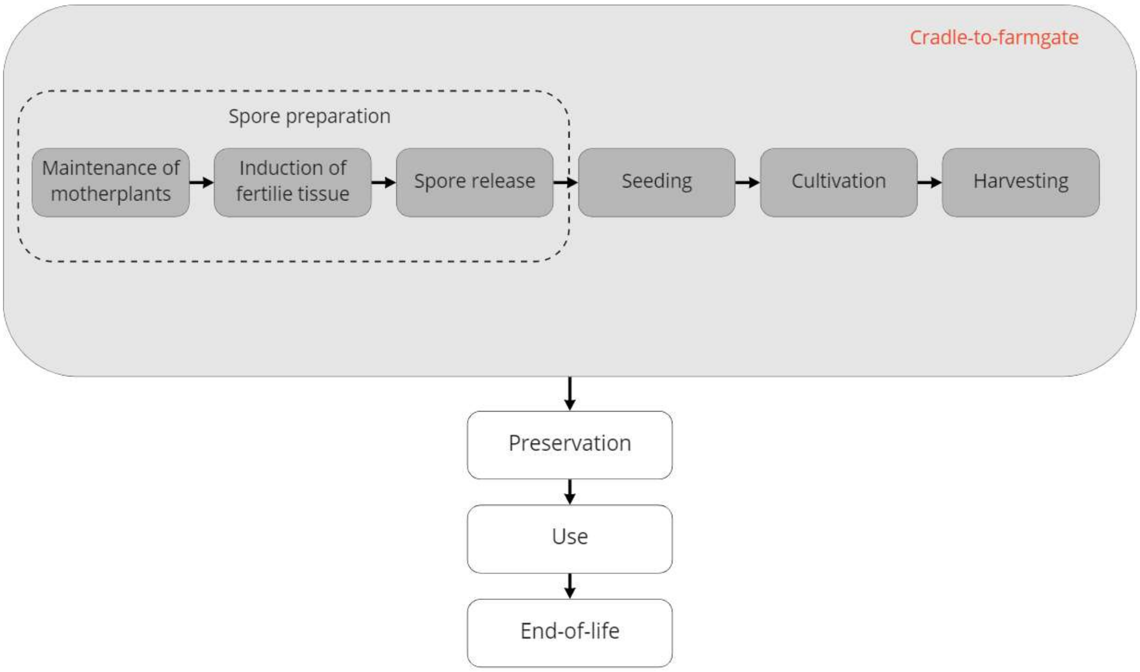

Figure 3. Initial flowchart of the production system of Ulva fenestrata

3.2.7 Cut-offs

This study had a cradle-to-farm gate perspective and thereby had a cut-off regarding the collection of parental biomass, preservation, use phase, and waste treatment. These cut-offs were made due to the low level of knowledge regarding the processes after farm-gate. In regards to other cut-offs, environmental impacts from production and maintenance of capital goods, such as machinery, buildings, vehicles, and personnel have not been considered in this study due to assumed low influence on results.

3.2.8 Relation to other systems and allocation

The foreground data gathered have been collected to specifically represent flows that influence the emission outputs of one tonne of harvested fresh weight (fw) biomass. All materials and energy inputs were only used to produce the functional unit. Thereby, the allocation has been avoided. Worth mentioning is that monitoring of the cultivation site and infrastructure during the growth period off-shore was planned to partly be executed by a fisherman on his daily or weekly fishing trips. If included, this aspect would require allocation. However, the additional environmental load that this aspect could potentially result in were considered negligible and thus, excluded from the study. Regarding the processes used from Ecoinvent for the background system, the allocation by mass was used when choosing data. Mass allocation was found more suitable in this study since economic aspects for algae are still uncertain, in addition to the LCA ISO standard recommends mass allocation over economic (ISO, 2006a, 2006b).

3.2.9 Assumptions and limitations

The planned cultivation of the *Ulva fenestrata* and its 2 hectares rig infrastructure is assumed to produce 20 tonnes of biomass after harvest. When it comes to the *Ulva fenestrata* algae, it is possible to use almost the entire plant and therefore reduce waste (G. Nylund, personal communication, 23, 24 February, 2022), thus, no significant waste was considered relevant in this study. However, the cultivation and harvesting will probably result in some biomass losses due to, for instance, hard weather. Since the data on the exact production yield was uncertain, in this study, 20 tonnes of harvested biomass were assumed to include the approximate losses of 5 % that could potentially be lost due to e.g., rough weather.

3.2.10 Data quality requirements

To strive for a result as relevant, reliable, and accessible as possible, some data quality requirements have been set. Data needed for the background system was gathered from the SimaPro 9.3.0.3 software with the databases: Agrifootprint 5.0, Agribalyse 3.0.1 and Ecoinvent version 3.8. However, primary data concerning the foreground system was specifically gathered in direct contact with the production manager at Nordic Seafarm (G. Nylund, personal communication, 23, 24 February 2022) and the researcher at Tjärnö. Since the studied system concerns a specific algae type in a specific environment with specific technology and infrastructure, site-specific data for the foreground system was a requirement in order to reach a relevant result. The data collection regarding the foreground processes strived to primarily be site-specific and collected via people within the production. Any foreground system data gaps that occurred has been searched and collected from other similar LCA studies or product specifications. Apart from geographical and technological coverage, site-specific data were also used to achieve a time-related coverage. The algae production industry is fast-growing and constantly changing. Therefore, gathering new and current data has been of importance. However, it is important to note that this study examined a production in progress, meaning that the steps from pilot trials to the actual up-scaling have not yet been fully realized. To take the uncertainties regarding data into account, a sensitivity analysis was performed *(Chapter 3.5 Sensitivity Analysis and 5.2 Sensitivity Analysis)*.

3.2.11 Choice of impact categories and method of impact assessment

The impact assessment methods that were used in this study were the CML-IA baseline version 3.07/EU25 and Cumulative Energy Demand (CED) version 1.11. The CML-IA method is divided into baseline and non-baseline where the baseline is the most used within the LCA field (Acero et al., 2016) and also the one that is used in this study. The CED method intends to quantify the primary energy usage throughout the life cycle of the studied product (Acero et al., 2016) by looking at both the direct and indirect uses of energy.

The impact categories used in this study, from the CML-IA baseline method, were acidification, eutrophication, global warming, abiotic depletion, and marine aquatic ecotoxicity. In addition, all three renewable and the three non-renewable energy categories in the CED method were used. All categories are shown below in *tables 1 and 2.*

The choice of impact categories in this study was based on expected stressors of macroalgae production found in articles and conclusions made from reading literature and LCA studies regarding aquaculture. Initially, all CML-IA baseline categories were evaluated but due to the limited time of this study, including all impact categories was not possible and not relevant in terms of results. The final choice of impact categories was thus an iterative process, where some impact categories were excluded due to a negligible result. This was the case for the terrestrial ecotoxicity that, in comparison with the other toxicity categories, were almost non-existent. The choice to exclude human toxicity was mainly as this study is focused on environmental impacts and the human toxicity category measures the chemicals with relevance to human exposure (Keller et al., 1998).

According to Ziegler et al. (2022), seaweed aquaculture systems are an example of energy-dominated systems where greenhouse gas emissions often tend to be energy driven. Therefore, important impact categories are the Global Warming Potential (GWP100) and the method CED which, as earlier stated, includes three renewable and three non-renewable energy categories.

GWP is represented by CO_2 equivalents and is important to be able to evaluate impacts from greenhouse gases, i.e., gases that absorb infrared radiation in the atmosphere which changes the energy balance of the earth and thus contribute to global warming (Forster et al. 2007; Bala et al. 2010; Baumann & Tillman, 2004). CED is measured in MJ and evaluates the direct and indirect energy use across the whole assessed product system from extraction of raw material to waste management of products (Huijbregts, 2006). When modelling the CED, the renewable categories (biomass, wind, solar, geothermal, water) and non-renewable categories (fossil, nuclear, biomass) were compiled separately to simplify the representation.

Furthermore, according to a compilation by Bohnes and Laurent (2019) of 60 articles on LCA of different aquaculture systems, including seaweed, over 50 percent of the articles included climate change, aquatic eutrophication, acidification and CED as four of their impact categories. More specifically, LCAs performed on seaweed cultivation (Thomas et al., 2021; Langlois et al., 2012) have also mentioned these impact categories as important in regard to hotspots. Woods et al. (2016) who writes about ways towards a meaningful assessment of marine ecological impacts in LCA, also highlights global warming, acidification and eutrophication as some of the major drivers of marine biodiversity loss.

Eutrophication and acidification are measured in kg PO_4 eq respectively kg SO_2 eq. Eutrophication happens due to a too large amount of fertilising nutrient emissions being released into soil and waters, which can lead to an increase in algal blooms and deficiency of oxygen (Baumann & Tillman, 2004). Acidification measures the potential to form acidic solution with moisture which can decrease the pH in soil and water causing damage to the ecosystems (Martinez-Hernandez & Ng, 2022)

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However, Bohnes and Laurent (2019) also highlights the importance of including a broader spectrum of impact categories in order to get a fair and holistic view of the environmental impacts of aquaculture. Therefore, apart from climate change, eutrophication, acidification and CED, two more impact categories were included in the study; Abiotic depletion (non-fossil) and Marine aquatic ecotoxicity.

Abiotic depletion evaluates the use of non-living, non-renewable resources such as fossil fuels, raw mineral materials, ore materials and industrial mineral materials and is measured in kilograms of Antimony (Sb) equivalents *(kg Sb eq)* (Oers & Guinée, 2016). Abiotic depletion can be separated into two different categories; abiotic depletion (fossil fuels) and abiotic depletion. The choice made for this LCA was to exclude abiotic depletion (fossil fuels) as it can be comparable with the impact categories in the CED method.

The marine aquatic ecotoxicity category was included in order to evaluate the impacts on marine ecosystems from the algae production system. The category reflects the level of harm to marine ecosystems that different substances can cause and are measured regarding the reference substance 1.4-dichlorobenzene and expressed as *kg 1.4-DB equivalents* (Baumann & Tillman, 2004).

Table 1. All the included impact categories from the CML-IA baseline method.

Impact Category (Midpoint)	Unit
Acidification	kg SO_2 eq
Eutrophication	kg PO_4 eq
Global Warming (GWP100)	kg CO_2 eq
Marine aquatic ecotoxicity	kg 1.4-DB eq
Abiotic depletion	kg Sb eq

Table 2. All the included impact categories from the Cumulative Energy Demand (CED) method.

Impact Category	Unit
Non-renewable, fossil	MJ
Non-renewable, nuclear	MJ
Non-renewable, biomass	MJ
Renewable, biomass	MJ
Renewable, wind, solar, geothermal	MJ
Renewable, water	MJ

3.3 LCA modelling

The approach used to conduct the LCA followed the standardised LCA methodology according to ISO (2006a) 14040. This implies a method carried out in four steps: goal and scope definition, inventory analysis, impact assessment and interpretation. Furthermore, the project involved several overlapping steps, resulting in an iterative process. In addition, the LCA was performed in accordance with the rules of a pLCA. This included steps to involve an assessment of environmental impacts of emerging technologies and a potential upscaling of these. Additional parts conducted for our LCA was therefore a determination of TRL and MRL level (Arvidsson et al., 2017) and modelling of scenarios (Calero et al., 2022; Thonemann et al., 2020). A dominance analysis was used to investigate which processes, components (non-electricity driven and electricity driven), and raw materials that contributed the most to environmental impacts and were presented in diagrams in the result. Additionally, a sensitivity analysis was done to find critical parameters in the system.

The modelling processes for the LCA were done mainly in Excel with some additional support using SimaPro 9.3.0.3. All data for the inventory analysis was collected and transferred to Excel where the calculations and modelling of diagrams and tables were done. The Excel document consisted of different sheets to support the final calculations and modelling. Firstly, four sheets for each process were created where calculations for components, energy and material were done. This data was mainly based on the interviews, the study visit, literature, and other relevant sources. To support this data and calculate the characterisation factor (CF) for each impact category, additional data regarding material, components and production processes was needed. This data was collected from SimaPro and the EcoInvent database. Using the chosen materials in EcoInvent, seen in *table 6*, CFs for the chosen impact categories were calculated in SimaPro. The CFs were then integrated into the Excel file together with the data of material and energy use. Lastly, diagrams could be created using the data collected. The diagrams were divided into three main categories which displayed the impacts related to processes, components, and materials.

The modelling in SimaPro and choices of processes in EcoInvent were done with the help from a research and development engineer at RISE, experienced in performing LCA. This was mainly due to the knowledge gap of modelling in SimaPro, the access to the Software and the time limit of the project. The modelling in SimaPro started with collecting and stating all materials and production processes needed for the production system of *Ulva fenestrata*. The most suitable production processes and materials were chosen in cohesion with the advice from the research and development engineer at RISE. Some of the chosen processes were already created by the research and development engineer at RISE and based on algae production in the USA. The chosen processes from SimaPro and EcoInvent can be found in *table 6* in *chapter 4*.

3.4 LCA data collection

The data collection regarding the foreground processes have strived to be site-specific and was done via people within the production in form of interviews and a study visit. Any foreground system data gaps that occurred were searched and collected from earlier LCA studies on similar systems or product specifications which were then discussed with the production people to ensure relevance. Data needed in regards to the background system were gathered from databases and from literature.

3.4.1 Interviews and study visit

The interviews were conducted with one researcher and the production manager at Nordic Seafarm, Göran Nylund (personal communication, 23, 24 February, 2022), who both are working with *Ulva fenestrata* at Tjärnö's marine biological laboratory. The interviews were carried out via Zoom on two different occasions and had a semi structured approach where both prepared and supplementary questions were allowed. The structure of the interviews started with a brief presentation about the project and methodological choices followed by prepared questions. Other questions from both the researchers and the thesis writers occurred continuously throughout the interview. The interviews were recorded to maintain a natural and smooth discussion. The recorded material was later transcribed and used as a basis for the LCA.

A study visit at the laboratory at Tjärnö was conducted to collect further data on the production system of *Ulva fenestrata*. The visit included a guided tour, followed by two supplementary interviews with the production manager (G. Nylund, personal communication, 23, 24 February, 2022). The guided tour included the steps from maintenance of motherplants to seeding. Information regarding material and energy use and the processes was collected during the tour. Additional information concerning materials and energy performance of different components were collected during the interviews.

3.4.2 SimaPro & EcoInvent

To be able to calculate the impact in each impact category, additional data was needed regarding materials and production processes and their CFs in each impact category. This data was collected from the EcoInvent database in SimaPro. Data that was collected was different materials and their production processes from EcoInvent. The choices made in EcoInvent were based on some of the following preferences. Firstly, processes that included market activities with the label "market for" were chosen to include all the activities from production to retailer, for example, product losses and the product's transportation (EcoInvent, n.d.). If the market activity was not available, "production" was chosen, which included processes for producing the material, product, or service. Secondly, geographical preferences were either in Europe (RER) or globally (GLO).

3.4.3 Additional data

Additional literature was collected for those processes where data gaps occurred in the primary sources. Examples of other data that have been collected for the LCI are weight, length, volume and capacity of different components. There was also a need for additional data from secondary sources to support assumptions and choices in the LCA and for the future upscaled scenario. The additional literature consists of both grey literature, such as documents from businesses and industry, and academic literature, such as peer reviewed articles.

3.5 Sensitivity analysis

A sensitivity analysis was performed to evaluate the effect of changes in different critical parameters found throughout the process (Baumann and Tillman, 2004). The intention was to explore both input parameters and assumptions where a change could affect the outcome of the total result. The alternative cases were first identified and then tested via a change in material input, energy input and lifetime. The chosen alternatives were components of infrastructure, duration of electricity-intensive components, tanks in polypropylene or fibreglass, yield (one or two harvest), monitoring trips and weight of screw anchors. A description of each alternative and included changes and assumptions can be found below.

3.5.1 Components of infrastructure

The variation was based on data from the production manager where two different alternatives for the seeding line were tested (G. Nylund, personal communication, 23, 24 February, 2022). The base scenario, as it is today, considers a 1.2mm seeding line together with a carrying line as support. The alternative scenario that can be used in a future implementation consists of a thicker seeding line with 4mm in diameter without a carrying line.

3.5.2 Duration of electricity-intensive components

There are some steps where the duration of electricity-intensive components has been changed from four weeks, which is the base scenario, to an alternative case of two weeks. This information was given by the production manager (G. Nylund, personal communication, 23, 24 February, 2022) on the study visit where knowledge about duration of different processes still was a bit unsure. This variation applies to the steps of induction of fertile tissue and spore release in the spore preparation process. The concerned components for this type of change are the cooler, the fridge, and the LED stripes.

3.5.3 Tanks in polypropylene or fibreglass

In the base scenario, polypropylene tanks are used for both the seeding and spore preparation process. However, according to the production manager, (G. Nylund, personal communication, 23, 24 February, 2022) the tanks in a future process could be made of fibreglass instead. Furthermore, an assumption has been made that the polypropylene tanks have a lifetime of 10 years while fibreglass tanks have a lifetime of 20 years.

3.5.4 Yield: One or two harvests

Information from the production manager (G. Nylund, personal communication, 23, 24 February, 2022) and the researcher shows that there are possibilities in the future to harvest two times instead of one time per year. The first yield is then harvested earlier to create time for a second yield on the same infrastructure. This change would affect the result regarding material and energy consumption and yield. Based on data from the production manager, (G. Nylund, personal communication, 23, 24 February, 2022) two harvests would produce 30 tonnes instead of the 20 tonnes produced in the base scenario with only one harvest.

Changes in the spore preparation process were regarding energy and material consumption. The energy connected to the first step maintenance of mother plants was not changed as this is a continuous process not affected by the yield. What changed were the consumables which were the cups and the nutrient mix. The amount used was doubled as the spore preparation process is carried through two times. Furthermore, the energy consumption for the cooler, autoclave, fridge, and LED stripes was doubled as these processes would be used two times.

Material and energy use in the seeding process was also changed. In this process, the amount of seeding line was doubled; however, the life length of the spools was halved as these can be used several times. The energy use for the lamps and air pump were doubled as these processes are needed two times. Furthermore, the tanks in this process were not changed as the use for one or two yields will probably not affect either life length or amount used. The nutrient mix in the seeding process was also doubled. The filters in spore preparation did not change regardless of the number of yields; however, the filters in the seeding stage are consumable components which means that the number of filters used in the seeding stage for two yields was doubled.

Changing from one harvest of 20 tonnes to two harvests with a total of 30 tonnes would also require some changes in the cultivation and harvesting processes. The amount of carrying line needed would remain the same since it can be reused, however, it is reasonable to believe that an additional cultivation and harvest process could decrease the lifetime of the carrying line due to more tearing. The assumption that is used in this study is a halved lifetime of the carrying line (from 5 to 2.5 years) when increasing the yield.

Furthermore, the 30 tonnes alternative would require two cultivations and two harvest processes thus, double the boat activities included in these steps. Apart from changing the carrying lines' lifetime, the boat transport of all the boats, including the barge, was also increased with two harvests. An increase in boat transport would require more fuel. The number of increased transports and the increase in fuel use was related to the amount of increased yield and what that would mean in terms of the number of extra return trips needed.

3.5.5 Monitoring trips

Another factor that was assessed in the sensitivity analysis was the number of monitoring trips that can occur due to different reasons. The number of storms during the year is one factor that determines number of monitoring boat trips. When storms occur, the infrastructure is at a higher risk of damage. The variations in data that were used in the sensitivity analysis regarding extra activity due to storms, were based on information on storms in Sweden, affecting the west coast, in previous years. Four and five storms respectively occurred in the years 2019 and 2015 in Sweden (SMHI, 2022). The number that was chosen to use in the sensitivity analysis in this study was therefore, four additional return trips a year, in addition to the base scenario where there is only one monitoring trip a month each cultivation year.

3.5.6 Weight of screw anchors

The assumed weight of the screw anchors used in the infrastructure at sea was an uncertainty point. The information regarding what type of screw anchors and the approximate measures were available, however, not the weight information. That is why this aspect was considered and included in the sensitivity analysis. Approximations made based on communication with the production manager at Nordic Seafarm and information search (G. Nylund, personal communication, 23, 24 February, 2022; Carapax, 2016; Helix Mooring, 2016; Ecputility, n.d.) led to an assumption of using 10 kg (base scenario), 30 kg and 50 kg as the different alternatives to determine whether the weight aspect would be of significance.

3.6 Future upscaled scenario

This section explains the methodology of the extension made of the pLCA to evaluate a future industrial-scale cultivation. More specifically, the section displays how the upscaling was made and the relevant factors that was chosen for the future upscaled scenario. Additionally, there is a description of each factor and its relevance for the future upscaled scenario.

3.6.1 Choice of relevant factors for the future upscaled scenario

To be able to scale up and evaluate probable effects in environmental impacts in the future, an extension was made to the executed pLCA of the base scenario. The extension means that quantitative parameters were either changed, added or excluded in order to form a probable future upscaled scenario for a more industrialised and larger *Ulva fenestrata* production system on the Swedish west coast. The future upscaled scenario was based on data from the executed pLCA of the base scenario and additional data regarding possible future changes obtained through a researcher at Tjärnö, the production manager (G. Nylund, personal communication, 23, 24 February, 2022), literature and assumptions. New processes were also collected from the databases in SimaPro 9.3.0.3. The choices of factors to change, add or exclude were mainly of a predictive approach where the scenarios were based on what is likely to happen in the future (Taelmann et al., 2020). Furthermore, some scaled up factors and parameters were also more of a “what-if” approach where the scaled-up factors were chosen from the different alternatives tested in the sensitivity analysis (Pesonen et al. 2000). The upscaled factors are presented in *table 3* and described in more detail in the following sections.

Table 3. Presentation of the upscaled items and the differences between the base scenario and the future upscaled scenario.

	Scaled up Item	Base scenario	Future upscaled scenario
Foreground	Surface area	2 ha	10 ha
	Efficiency	1 harvest	2 harvests
	Duration of electricity-intensive components	4 weeks	2 weeks
	Energy efficiency	2022 (expert data from Tjärnö)	15% less energy need for electricity-intensive components
	Single-use cups material	PS	PLA
	Fuels	Gasoline and Diesel	Natural gas
	Infrastructure	1.2mm seeding line with carrying line	4mm seeding line without carrying line
Background	Electricity mix	Based on electricity mix, 2021 - EcoInvent 3.6	Forecast Swedish electricity mix in 2040

3.6.2 Factors changed in the foreground system

Surface area

An upscaled production system will require more surface area. An assumption was made that 10 hectares of the surface area of the Swedish west coast will be occupied by infrastructure for farming of *Ulva fenestrata*. As this was assumed to be a linear increase, it will not affect the reference flow as everything else will increase linearly when the surface area is increased. However, more occupied surface area could potentially have an effect on the local environment and will thus be discussed further in *chapter 5.4*.

Efficiency: Two harvests

In the LCA of the base scenario, the performance of two harvests per year instead of one was better, both in terms of yield and from an environmental perspective. Furthermore, according to the production manager, an implementation of two harvests per year in the future is seen as promising and realisable (G. Nylund, personal communication, 23, 24 February, 2022). Therefore, a choice was made that a future upscaled production system will have two harvest per year instead of one.

Energy efficiency

One assumption made for a future upscaled scenario was that technology used in the production would be more mature as it has been used in practice, tested, and probably improved. The TRL level of the system in the base scenario was assumed to be between 8-9 and the MRL level of 8. For a future upscaled scenario, the TRL level can then be assumed to be on 9 and the MRL level on 10. This indicates a more mature technology where the system has been proven in successful operation with a full-rate production (Fernandez, 2010). Examples of improved technology used in the production system are LED stripes, lamps, and refrigerators. LEDs are already today one of the highest-performing lights and consume approximately 85 percent less energy than normal bulbs. In addition, in the next coming years, they are expected to become even more efficient and long-lasting. Moreover, a new type of refrigerator could be used in the future which uses magnets instead of vapour compression with coolants that damage the environment (Lester, 2015). According to Bohnes and Laurent (2021), mature technology could result in a decrease of 10 to 20 percent of the energy consumed. Therefore, an assumption was made that all electricity-intensive components will use 15 percent less energy by 2040.

Duration of electricity-intensive components

The sensitivity analysis showed that using some of the electricity-intensive components for two weeks instead of four weeks will decrease the energy consumption and the total impact on the environment. In discussion with the production manager (G. Nylund, personal communication, 23, 24 February, 2022) at Tjärnö, it was deemed reasonable to assume that duration of two weeks is realisable in the future and was therefore used in the upscaled scenario. The concerned components were the cooler, the fridge, and the LED stripes in the steps of induction of fertile tissue and spore release in the spore preparation process.

Material use

Trends today show that people are more aware and want to make more sustainable choices. Plastics, which are a significant part of the world's consumption, will therefore be less used. Furthermore, as the trend changes, consumers demand less plastic which affects companies to offer more sustainable alternatives in the form of, for instance, plastic-free alternatives (Renee, 2022; Smith, 2020). Therefore, in the future upscaled scenario in 2040, a choice was made to use a more sustainable option in the production system of *Ulva fenestrata*. The choice was to change the single-use cups in the spore preparation process to a more sustainable alternative, polylactic acid (PLA), in the upscaling scenario. PLA is an aliphatic polyester where starch fermentation during corn wet milling produces lactic acid which is used to create PLA. Most of the PLA is produced from corn, however, other alternatives such as wheat and sugarcane can also be used. The advantage of using PLA is that plants used to produce PLA absorb carbon dioxide during their growth. Additionally, PLA is a material that degrades fast under the right conditions (Trimarchi et al. 2021). However, this will decrease the potential usage areas for off-shore cultivation as some of the right conditions for PLA to biodegrade is exposure to UV light, temperature and mineral content in saltwater (Miller, 2021; Arceo, n.d.). In water, PLA can last only between 47 to 90 days without any sealing that protects the PLA from absorbing water. If it is exposed to direct sunlight the degradation time will be even shorter (MonoFilament DIRECT, n.d.). Therefore, only the cups were changed as these are used for a shorter period (maximum 4 weeks) and are single-use components. The density of PLA is approximately 18 percent higher than for PS, therefore, an assumption has been made that the weight of the cups in PLA will weigh 18 percent more than the cups in PS (Emiliano, 2019; Material properties, n.d).

Table 4. Differences in density, weight, and kg/FU between the different alternative materials PS (base scenario) and PLA (future upscaled scenario)

	Density (kg/m^3)	Weight of cups (kg)	kg/FU	Source
PS	1050	0.088	0.275	(Material properties, n.d)
PLA	1240	0.10384	0.3245	(Emiliano, 2019)

Fuels

In a future upscaled scenario in the year 2040, there may be a change of fuel from diesel and gasoline to other more sustainable alternatives. Reasons are, for example, higher marine fuel oil prices and the development of newer more environmentally friendly fuels (Singh, 2022). One fuel that is seen as promising for reducing local air pollution is natural gas (Thomson et al., 2015). In addition, according to Ellingsen and Aanondsen (2006), changing fuel types in mariculture systems, e.g., diesel to natural gas, has been shown to decrease the emission of nitrous oxide, thus greenhouse gas emissions, significantly. The choice in this studies' future upscaled scenario was therefore made to have boats that run on 100 percent natural gas in 2040. The choice did not include a change in motor types and boats, the change was just regarding a change of fuel.

Infrastructure

The infrastructure was changed to a structure with a 4 mm seeding line and no carrying line in the future upscaled scenario. This was mainly based on data from the production manager (G. Nylund, personal communication, 23, 24 February, 2022) as it was seen as a possible scenario to implement. It was also based on the result from the sensitivity analysis which displayed that a 4mm seeding line was preferable to use as it had overall a lower impact.

3.6.3 Factors changed in the background system

One factor was considered for the background system of the upscaling scenario; this was the Swedish electricity mix.

Swedish electricity mix

The goal in Sweden for electricity production is to have 100 percent renewable electricity production by 2040 (Naturskyddsföreningen, 2021; Regeringskansliet, n.d; Government offices of Sweden, 2018). According to Ministry of the Environment and Energy (2018) the energy mix will consist of hydropower (47%), wind power (38%), biofuels (10%), solar power (4%) and other renewable production types (1%). However, a choice was made to consider the last one percent of other renewable production types to be solar power as it was difficult to know what other types this referred to. One percent is seen as a rather small share which will not affect the total result in a vital way.

3.7 Exploratory literature search with a snowballing approach

This study contained an exploratory literature search with a snowballing approach aimed at investigating potential approaches and methodologies, both outside and within the LCA framework, that can evaluate local environmental impacts on marine ecosystems. The databases used in this study were Scopus and Google Scholar. An exploratory literature search aims to be broad to get an overview of a topic (Koseoglu & Bozkurt, 2018). In this study, the literature search started off broad, to get a grasp of what the topic seemed to include and successively narrowed down to get more focused with certain criteria as guidelines. The literature search was divided into three main parts focused on local marine impacts due to aquaculture and seaweed farming, in addition to methods within and methods outside of LCA to assess local marine impacts. The search included certain terms and keywords and Boolean operators. Keywords that were used foremost were words included in the search string examples below. In Scopus, the title, abstract, and keywords of articles were searched using the following search strings as a basis:

("environmental assessment" OR "environmental analysis" and "marine environment" OR sea OR marine OR ocean AND lca OR "life cycle assessment" OR "life cycle analysis")) AND (aquaculture OR seaweed OR algae)

("environmental assessment" OR "environmental analysis" AND "marine environment" OR sea OR marine)) AND ("local environment" OR "local change") AND aquaculture AND method OR approach**

On Google Scholar, articles were searched using the following search strings as a base:

aquaculture OR seaweed OR algae AND "environmental assessment" OR "environmental analysis" and "marine environment" AND local AND impact OR sea OR marine OR ocean AND lca OR "life cycle assessment" OR "life cycle analysis" AND tools* OR method* OR approach*

macroalgae OR seaweed AND aquaculture AND local AND impacts AND environmental OR ecological AND marine*

The search strings were also adapted by adding or removing specific method names or terms such as removing “LCA” and “life cycle assessment” to find methods outside of the LCA scope or adding “ecosystem services” or “marine biodiversity” to find further interesting articles within fields that seemed promising in regard to the criteria. Abstracts were continuously read and articles that felt relevant were chosen. The literature search included a “snowballing” approach which refers to usage of the reference list of an article of relevance or the citations to the relevant article to identify additional papers (Wholin, 2014). Snowballing was the main way of finding the chosen article. Several relevant articles were also obtained by researchers at RISE that had earlier explored the field.

For the selection of articles for the literature search, a criterion for the articles was that they included concrete approaches or recommendations for how assessments regarding local marine impacts can be performed. Regarding local effects on marine ecosystems, the criteria were broader for the chosen articles. Several of the articles found for potential assessments of local impacts also wrote about the local marine effects. Some of these articles were therefore also chosen to be included in the literature on local effects.

The chosen literature was peer reviewed articles in academic journals in the English language and published no later than 2012, or reports from relevant governments such as in Norway and Sweden. The time requirement was set to keep the information relevant and at the same time, being able to keep the relevance in content as the priority. In total, 15 articles were chosen *(see table below)*. These 15 articles were the ones that were mainly used; however, some additional literature has been used to strengthen some information which can be seen in *Chapter 5.4 Local environmental impact assessment.*

Table 5. Compilation of the 15 articles that were documented from the exploratory literature search including authors, year, title and whether it handles approaches within LCA or outside of the LCA scope and/or local marine effects.

Title	**Author**	**Scope**
Proposed Local Ecological Impact Categories and Indicators for Life Cycle Assessment of Aquaculture: A Salmon Aquaculture Case Study	Ford et al., 2012	Within LCA
Sea use impact category in life cycle assessment: characterization factors for life support functions	Langlois et al., 2015	Within LCA, local effects
Comparative Environmental Life Cycle Assessment of Two Seaweed Cultivation Systems in North West Europe with a Focus on Quantifying Sea Surface Occupation	Taelman et al., 2015	Within LCA
LCA of aquaculture systems: methodological issues and potential improvements	Bohnes and Laurent, 2019	Within LCA
An effect factor approach for quantifying the entanglement impact on T marine species of macroplastic debris within life cycle impact assessment	Woods et al., 2019	Within LCA
Ecosystem damage from anthropogenic seabed disturbance: A life cycle impact assessment characterisation model	Woods and Verones, 2019	Within LCA
Development of a life cycle impact assessment framework accounting for biodiversity in deep seafloor ecosystems: A case study on the Clarion Clipperton Fracture Zone	Préat et al., 2021	Within LCA
A methodology for the assessment of local-scale changes in marine environmental benefits and its application	Hopper et al., 2014	Outside of LCA
The impact of seaweed cultivation on ecosystem services - a case study from the west coast of Sweden	Hasselström et al., 2018	Outside of LCA, local effects
Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services	Kim et al., 2019	Outside of LCA, local effects
An ecosystem approach to kelp aquaculture in the Americas and Europe	Grebe et al., 2019	Outside of LCA
The Environmental Risks Associated With the Development of Seaweed Farming in Europe - Prioritizing Key Knowledge Gaps	Campbell et al., 2019	Outside of LCA, local effects
Development of a framework and toolbox for measuring and evaluating ecosystem interactions of seaweed aquaculture	Tonk et al., 2021	Outside of LCA
Quantifying habitat provisioning at macroalgal cultivation sites	Corrigan et al., 2022	Outside of LCA, local effects
Seaweed aquaculture in Norway: recent industrial developments and future perspectives	Stévant et al., 2017	Local effects

4

Life Cycle Inventory Analysis

The LCA results for the base scenario will be presented in this section: the reference flow, diagrams, and interpretation of the LCI. However, the amount and exact details of the different parts in the process will not be given due to data confidentiality.

Figure 4 represents the production system of *Ulva fenestrata*, including both processes within and outside the scope of the thesis. The boxes inside the blue frame represent processes in the foreground system; meanwhile, the boxes in the grey frames display the processes in the background system. The foreground system consists of four main processes: spore preparation, seeding, cultivation and harvest. Inside the processes presentation of material and energy requiring activities are presented. Supporting processes are also included in the foreground system: installation of off-shore infrastructure and maintenance. Processes displayed in the background system are, for example, the production of components and energy production. Note that the steps in the background system are a simplified representation. There are further steps, such as acquisition of raw materials and, infrastructure and maintenance which supports the production in the background system. Furthermore, the blue arrows in the flowcharts represent those flows where transport is included meanwhile the black arrows represents the flow with no transportation between the processes. Lastly, there are processes outside the scope of our LCA in the foreground system, for instance, collection of motherplants, preservation, use and disposal.

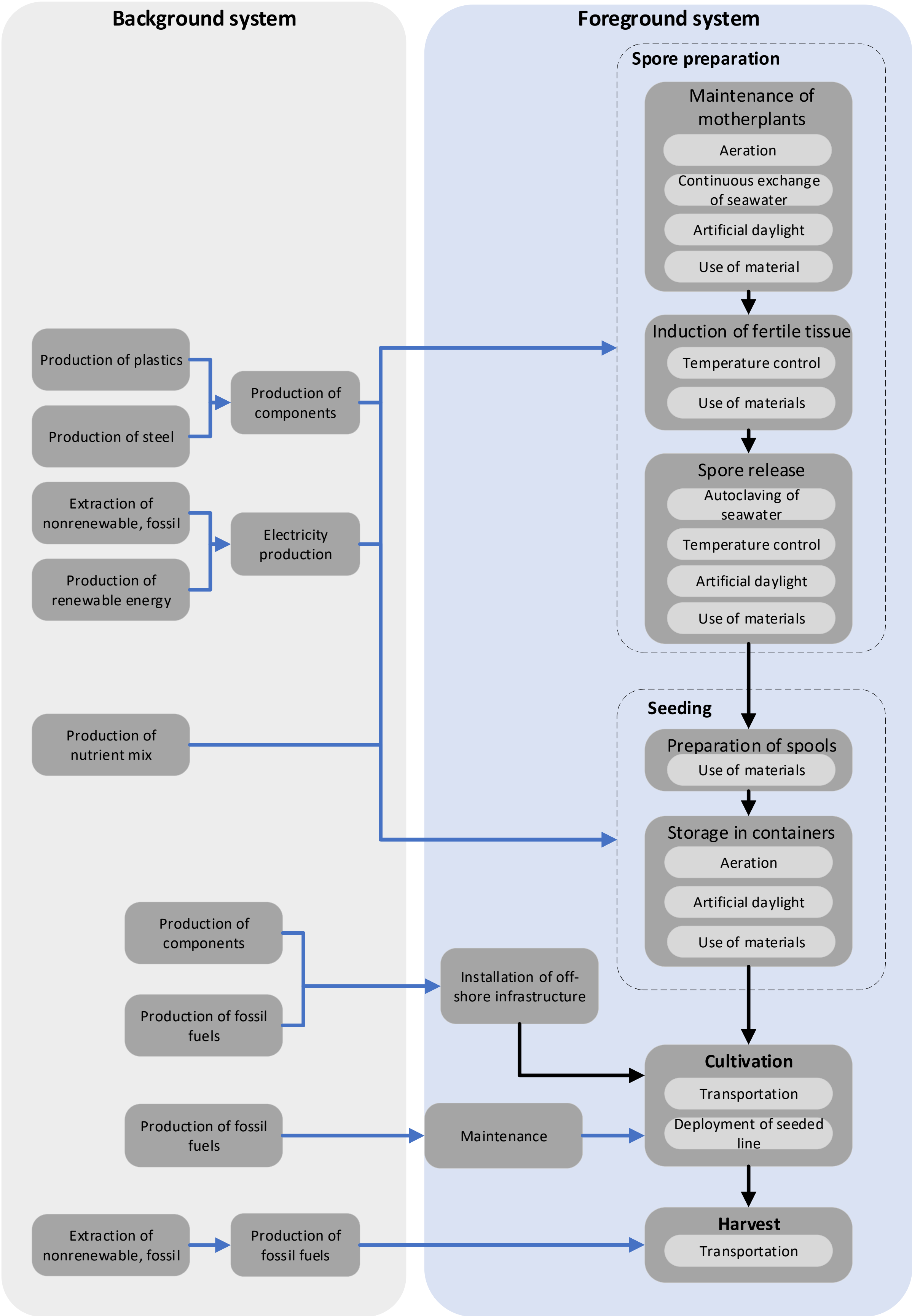

Figure 4. Flowchart of the production system of Ulva fenestrata

Presented in *table 6* below, are all the employed materials and energy sources used throughout the whole cradle-to-farm gate of the *Ulva fenestrata* production system. Additionally, the right column in the table presents the chosen processes that have been used to calculate the environmental impacts of each material and component.

Table 6. Material, energy and production inventory table for the entire system including the chosen processes from the databases Agrifootprint 5.0, Agribalyse 3.0.1 and EcoInvent 3.8.

Material/Energy	**Unit**	**Process (Ecoinvent database 3.6)**
PP	kg	Polypropylene, granulate {GLO}| market for | Cut-off, U
PE	kg	Polyethylene, high density, granulate {GLO}| market for | Cut-off, U
Plastic foam (Polyurethane)	kg	Polyurethane, rigid foam {RER}| market for polyurethane, rigid foam | Cut-off, U
Polyester PES	kg	Fibre, polyester {GLO}| market for fibre, polyester | Cut-off, U
PVC	kg	Polyvinylidenchloride, granulate {RER}| market for polyvinylidenchloride, granulate | Cut-off, U
PS (polystyrene)	kg	Polystyrene, general purpose {GLO}| market for | Cut-off, U
Galvanised steel	kg	Steel, low-alloyed {GLO}| market for | Cut-off, U
Stainless 304	kg	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U
Nylon (polyamide 6.6)	kg	Nylon 6-6 {RER}| market for nylon 6-6 | Cut-off, U
Fibreglass	kg	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for | Cut-off, U
N fert	kg	Ammonium nitrate, as N/FR U
P fert	kg	Phosphate fertiliser, as P2O5 {GLO}| market for | Cut-off, S - Copied from ecoinvent
Diesel	kg	1 kg Diesel {RER}| market group for | Cut-off, S (av projekt Ecoinvent 3 - allocation, cut-off by classification - system) + Combustion CO_2 emissions (https://drivkraftsverige.se/uppslagsverk/fakta/berakningsfaktorer/energiinnehall-densitet-och-koldioxidemission/)
Gasoline	kg	1 kg Petrol, low-sulphur {Europe without Switzerland}| market for | Cut-off, S (av projekt Ecoinvent 3 - allocation, cut-off by classification - system) + Combustion CO_2 emissions (https://drivkraftsverige.se/uppslagsverk/fakta/berakningsfaktorer/energiinnehall-densitet-och-koldioxidemission/)
Swedish energy	kWh	Electricity, medium voltage {SE}| market for | Cut-off, U
Processing	**Kg material incl. material loss**	**Process**
Injection moulding	0.994	Injection moulding {RER}| processing | Cut-off, S
Blow moulding	0.997	Blow moulding {RER}| blow moulding | Cut-off, U
Stretch blow moulding	0.978	Stretch blow moulding {RER}| stretch blow moulding | Cut-off, U
Rope production	0.95	Adjusted "Fleece, polyethylene terephthalate/RER, at plant/RER" by removing material to reflect only production and infrastructure
General metal processing	-	Metal working, average for metal product manufacturing {GLO}| market for | Cut-off, U

4.1 Spore preparation

The first step in the life cycle of *Ulva fenestrata* production is the spore preparation which includes all processes necessary to obtain a spore solution ready to be applied on seeding lines. The process consists of maintenance of mother plants, induction of fertile tissue and spore release. The components, raw material and energy inputs for the spore preparation process are presented in *tables 7-8.*

4.1.1 Maintenance of motherplants

The maintenance process of motherplants is a continuous process where parent specimens are kept in tanks all year round. The selection and collection of motherplants were not included in this study as this process can vary and are dependent on various parameters such as local conditions and genetics. Therefore, this study began with the maintenance of already collected motherplants. All the parent specimens were kept in tanks with a continuous water exchange through a seawater pump. In addition, the water coming in to the system was filtered through three different filters (10µm, 5µm, 1µm). The tanks were provided with an air pump to add aerated air. As this process is performed inside a building, artificial light from lamps is provided for 12 hours per day. The seawater is excluded in this study as it is seen as a circulation process where the same amount of seawater leaves and enters the system. The materials used for this step were mainly different kinds of plastics and steel.

The electricity-intensive components were the lamps, the air pump and the seawater pump. A choice was made to include only the energy input from these components. The reason to exclude the material was based on that all of the components had a long lifetime and could therefore be neglected as they would not contribute much per functional unit.

The filters used in this step consisted of five different materials and an approximation was made regarding the distribution of the materials. The assumption made was that the plastic parts had a share of 30 percent each and the metals had a share of five percent each.

4.1.2 Induction of fertile tissue

This step included a cooling process to stimulate the motherplants and induce fertility. To manage the cooling process, a cooler was needed. A nutrient mix was added in this step which was based on a simplified mixture consisting of only ammonium nitrate and phosphate fertiliser. The amount of the mixture needed was based on literature and calculations made by a research and development engineer at RISE *(see appendix I)*. The real mixture used at Tjärnö consisted of several other chemicals, however, a choice was made that the two chemicals could be used as a sufficient substitute to calculate and see the contribution of fertiliser on each impact category.

4.1.3 Spore release

The last step in the spore preparation is the spore release where the spores are extracted from the fertile tissue and then placed in cups to grow to a size suitable to be placed on seeding lines. The cups consist of a spore solution including seawater, spores and a nutrient mix and are replaced once per week. The nutrient mix is based on the same assumptions as made in the previous step and the use of seawater is excluded in this step with the same explanation as described before. However, the seawater is autoclaved and the energy consumption for this process is included. An assumption was made regarding the capacity of the autoclave and based on data from a company *(see appendix I)*. The spore solution in the cups is then placed in a fridge where it is kept cold and provided with artificial daylight until it is ready to be placed on the seeding lines.

Table 7. Material inventory table for spore preparation including the yearly consumption for 20 tonnes and kg per one tonne of harvested fresh weight (fw) biomass (functional unit).

Component	**Material**	**YC 20 ton**	**kg/F.U**
		kg	
Tank	PP	90.8544	0.454272
Filter (10µm)	PP+Stainless steel+Tinned steel+PES+nylon	3.24	0.162
	PP + injection moulding*0.3	0.972	0.0486
	Stainless steel+ tinned steel + metals*0.1	0.324	0.0162
	PES + rope production*0.3	0.972	0.0486
	Nylon + rope production*0.3	0.972	0.0486
Filter (5µm)	PP+Stainless steel+Tinned steel+PES+nylon	4.44	0.222
	PP + injection moulding*0.3	1.332	0.0666
	Stainless steel+ tinned steel + metals*0.1	0.444	0.0222
	PES + rope production*0.3	1.332	0.0666
	Nylon + rope production*0.3	1.332	0.0666
Filter (1µm)	PP+Stainless steel+Tinned steel+PES+nylon	2.28	0.114
	PP + injection moulding*0.3	0.684	0.0342
	Stainless steel+ tinned steel + metals*0.1	0.228	0.0114
	PES + rope production*0.3	0.684	0.0342
	Nylon + rope production*0.3	0.684	0.0342
Nutrient mix	N fert + P fert	0.244	0.0122
Single-use cups	PS	5.5	0.275

Table 8. Energy inventory table for spore preparation including the yearly consumption for 20 tonnes and kg per one tonne of harvested fresh weight (fw) biomass (functional unit).

Component		**kWh/year**	**kWh/F.U**
Lamps		2382.72	119.136
Air pump		2409	120.45
Seawater pump		24120	1206
Cooler		118.8	5.94
Autoclave		0.56	0.028
Fridge		136.8	6.84
LED stripes		62.208	3.1104

4.2 Seeding

The first step in this process was to prepare PVC spools with a seeding line which was done by wrapping the twine around the spools. The spore solution could then be applied by spraying it onto the prepared spools when they had dried. The spray bottles were excluded in this study due to negligibility. Lastly, the spools were stored in tanks in a container for approximately one month to evoke growth and prepare them for installation at the off-shore infrastructure. The container is supplied with an air pump to induce aeration, light to create artificial daylight, filters, and a solution of seawater and nutrient mix. The seawater is neglected in this process whereas the nutrient mix is included, and both have the same explanation and are based on the same assumptions as for the spore preparation. The components, raw material and energy inputs for the spore preparation process are presented in *tables 9-10*.

Table 9. Material inventory table for seeding including the yearly consumption for 20 tonnes and kg per one tonne of harvested fresh weight (fw) biomass (functional unit).

Component	**Material**	**YC 20 ton**	**kg/F.U**
		kg	
Seeding line (1.2mm)	Polyester Silk	18	0.9116
Spool	PVC	208.8	0.522
Filter (0.2µm)	PP+Stainless steel+Tinned steel+PES+nylon	0.2	0.01
	PP + injection moulding*0.3	0.06	0.003
	Stainless steel+ tinned steel + metals*0.1	0.02	0.001
	PES + rope production*0.3	0.06	0.003
	Nylon + rope production*0.3	0.06	0.003
Filter (0.5µm)	PP+Stainless steel+Tinned steel+PES+nylon	0.2	0.01
	PP + injection moulding*0.3	0.06	0.003
	Stainless steel+ tinned steel + metals*0.1	0.02	0.001
	PES + rope production*0.3	0.06	0.003
	Nylon + rope production*0.3	0.06	0.003
Filter (5µm)	PP+Stainless steel+Tinned steel+PES+nylon	0.37	0.0185
	PP + injection moulding*0.3	0.11	0.0055
	Stainless steel+ tinned steel + metals*0.1	0.04	0.002
	PES + rope production*0.3	0.11	0.0055
	Nylon + rope production*0.3	0.11	0.0055
Tank (PP)	Polypropylene	204.4224	1.022112
Nutrient mix	N fert + P fert	0.244	0.0122

Table 10. Energy inventory table for seeding including the yearly consumption for 20 tonnes and kg per one tonne of harvested fresh weight (fw) biomass (functional unit).

Component		**kWh/year**	**kWh/F.U**
Lamps		544.32	27.216
Air pump		64.8	3.24

4.3 Cultivation

There are three parts included in the cultivation process analysed in this study: Installation of the off-shore infrastructure, the cultivation of the seeded lines and monitoring.

4.3.1 The infrastructure

In order to proceed with the cultivation of the seeded lines, the off-shore infrastructure must be installed beforehand. The off-shore infrastructure is a 2 hectares large floating rig consisting of several kinds of ropes, lines, buoys, anchors and other smaller components. The rig has a capacity of 20 km of seeded lines which corresponds to a 20-tonne yield of fresh biomass and is expected to have an approximate lifetime of 10 years. Some parts of the infrastructure however have a shorter lifetime and the total lifetime can depend on several factors such as the frequency of storms.

The 2 hectares (100x200 m) large rig is outlined by 14 large anchoring buoys, attached with a total of 18 screw anchors of galvanized steel, which in turn are attached with anchoring lines at approximately 20-metre depth.

The short sides are each constituted by 100 meters of a 28 mm anchoring line divided by four of the large anchoring buoys with approximately a 25-metre distance. Additionally, 16 large inflatable buoys are attached to the anchoring lines for stabilization. In between these anchoring lines, throughout the rig, three 24 mm holding lines are attached to the rest of the anchoring buoys helping the rig to stabilize.

The long sides, and horizontally throughout, the rig is constituted by 11 units of 200-metre longlines attached with smaller inflatable buoys with a 10-metre distance. In addition, the different buoys are attached with their own buoy ropes to help hold up the rig. The seeded lines themselves will be twirled around an 8mm carrying line attached in a zig-zag pattern to the long lines. The zig-zag patterns enable more seeding lines per unit of the rig. Apart from this, galvanised steel shackles, stainless steel longline clips and thimbles are used for attachment between ropes and anchors and ropes and ropes.

4.3.2 The deployment of seeded lines

When the rig is installed, the spools with the seeded lines are transported by boat from the harbour to the cultivation site where the rig is located approximately 6.5 km off-shore. The seeded lines are deployed by being twirled around the carrying lines attached in a zig-zag pattern. Deployment of the 20 km of seeding lines, would in total require approximately 8-9 sessions of day work. At the lines, the seaweed spores are to be grown between 6-9 months until fully grown. The growth period can vary depending on how many harvests that are possible and desirable to obtain. The *Ulva fenestrata* normally grows the most during late summer and spring when there is more sun and a higher temperature. Since the number of harvests is uncertain and alternatives of both one and two harvests are relevant, the scenario of obtaining two harvests in one cultivation year will therefore be investigated.

4.4 Harvesting

Once the seaweed is fully grown it is time for the harvest. The harvest is done with a large vessel with an attached barge, mechanically pulling the carrying lines with the tangled seeded lines up from the water. Additionally, a smaller aluminum boat is used for assistance during harvesting. Knives are used to detach the seaweed which is then stored in large plastic tanks on the barge. The maximum load capacity is 6 tonnes which means it takes approximately four transports with a vessel and barge to collect the 20 tonnes of seaweed from the whole rig. Since the data on the exact production yield is still uncertain, in this study, 20 tonnes of harvested biomass are assumed to cover also the approximate losses of 5 % that could potentially perish. Due to an assumed low contribution of the boats themselves and other aspects, only the fuel consumption for the boats is included in this inventory analysis. This means that knives, plastic tanks, production of boats and other materials or components are excluded. Additionally, neither have factors related to maintenance of boats, such as coatings, been included in the inventory analysis. The boats that are used to produce the *Ulva fenestrata* are used for several other purposes as well, and the inclusion would require significant allocation calculations which were assumed to be negligible for this study.

4.5 Transportation and fuel consumption

There are two different boats used for the installation, cultivation and harvesting. One of them is a smaller six-foot-long aluminium boat with an outboard motor with 150 horsepower driven by gasoline.

According to the collected data obtained from the production manager at Tjärnö (G. Nylund, personal communication, 23 February, 2022), the estimated time for deployment of the seeded lines is estimated to be approximately 45 minutes per 400 metres of the seeded line, corresponding to around 2.4 km of seeded line per day. To deploy the 20 km of seeding lines, would in total require approximately 8-9 sessions of day work. One cultivation session is estimated to require around 5-6 hours of idle running and one return trip back and forth to the harbour located approximately 6.5 km from the cultivation site.

For simplification and approximation, some assumptions have been made regarding the calculations. The numbers used for the calculation of the energy consumption were based on the amount of deployed lines per minute which is around 8.9 m/min. For the total 20 km of seeded lines, this corresponds to around 37.5 hours of work, which in turn corresponds to approximately 7 days of sessions with an idle running of 5.5 hours and a return trip back and forth each of those days from the cultivation site to the harbour.

The other is a larger diesel-driven vessel named Nereus that is used during installation of infrastructure and harvesting. During harvesting, Nereus is also used in combination with a barge where the freshly harvested biomass is stored. The maximum load for the barge is 6 tons.

Table 11. Material and component inventory table for the cultivation step including the yearly consumption for 20 tonnes and kg per one tonne of harvested fresh weight (fw) biomass (functional unit).

Component	Material	YC 20 ton	kg/F.U
Ropes/Lines		**kg**	**kg**
Longlines	PP (50%), PES (polyester silk, 50%)	33.2	1.661
Anchoring lines	PP, (polypropylene)	15.3	0.7668
Anchoring lines	PP, (polypropylene)	7.5	0.37275
Holding rope (sinking rope)	PES (polyester silk)	12.7	0.6355
Carrying line	PP (50%), PES (polyester silk, 50%)	148	7.4
A2 buoys rope	PP, polypropylene	0.2	0.00992
A0 buoys rope	PP, polypropylene	0.9	0.0434
Buoys			
Anchor buoys (large)	PU Foam, marker process	35	1.75
Small buoys A2	PVC	6.72	0.336
Small buoys A0	PVC	18.6	0.93
Markers	PE blow	16	0.8
Anchoring			
Screw anchor	galvanised steel	18	0.9
Shackles	galvanised steel	4.68	0.234
Thimble	Stainless 304	1.08	0.054
Longline clip	Stainless 304	0.31	0.0155

Table 12. Energy inventory table for the cultivation step, installation of infrastructure and harvesting including the yearly consumption of fuel in L for 20 ton and kg per one ton of harvested fresh weight (fw) biomass (functional unit).

Energy Cultivation		YC 20 ton (L)	L/F.U	kg/F.U
Diesel		0	0	0
Gasoline		141.5	7.075	5.30625
Energy Installation				
Diesel		88.2	4.41	3.59415
Gasoline		12.2	0.61	0.4575
Energy Harvesting				
Diesel		292.6	14.63	11.92345
Gasoline		39.8	1.99	1.4925
Total				
Diesel		380.8	19.04	15.5176
Gasoline		193.5	9.675	7.25625

5

Result and interpretation

In this chapter, the result and interpretation of the result is presented. First, the dominance analysis result of the base scenario is introduced with the performed sensitivity analysis, followed by a dominance analysis of the result for the future upscaled scenario. Lastly, the result of the exploratory literature search regarding local environmental impacts is presented.

5.1 Dominance analysis of the base scenario

In the following section, the LCIA result for the base scenario is presented followed by a sensitivity analysis. The result for the base scenario is divided into three main parts: (1) Impact result of the four different processes (spore preparation, seeding, cultivation and harvest), (2) impact result of the different components (non-electricity driven and electricity driven) and (3) impact result of the different raw materials.

5.1.1 Dominant processes

In this study, the production system of *Ulva fenestrata* was divided into four different main processes; spore preparation, seeding, cultivation and harvest. These four processes had different contributions depending on which impact category that was addressed.

The cultivation and spore preparation were the main drivers behind Global Warming Potential, with cultivation representing the largest share *(see Figure 5: B1)*. One reason is due to a higher use of materials, especially plastics which are a large contributor to greenhouse gas emissions (Center for International Environmental law, n.d). In the cultivation process, plastic is used for the different lines and buoys and in the spore preparation, plastics can be found in all components used except in the nutrient mix. In addition, the spore preparation process is energy intensive, and the cultivation process uses fuels for the boats which release much greenhouse gases during combustion. The harvest process had the third highest contribution, with an approximation of two-thirds of the spore preparations contribution. The seeding process is negligible compared to the larger impact of other processes.

The spore preparation and cultivation process had the highest impact on abiotic depletion and marine ecotoxicity (*figures 5: A1 and C1*): the spore preparation process represented the largest share and cultivation the second largest share. The seeding had a low contribution compared to the other two whereas the impact for the harvest process was negligible.

Viewing the result for eutrophication *(figure 5: E1)*, all processes except seeding had a high eutrophication impact, and where cultivation was shown to be the highest. The seeding contributed only about one sixth of the harvests process which had the third largest share of the impact.

In terms of the acidification *(see Figure 5: D1)*, the harvest process resulted in the highest impact, followed by the cultivation and spore preparation. Diesel is the fuel that is primarily used in the harvesting and is the most probable reason for harvesting being the highest impact process.

For the two merged energy impact categories, total non-renewable and total renewable, from the CED impact assessment method, spore preparation was the process which had the highest impact *(see Figure 5: F1 and G1)*. The second largest in the total non-renewable category was the cultivation process. However, the impact from the cultivation was only approximately one-fourth of the impact from spore preparation. Compared to the spore preparation's contribution, the other processes had almost no impact in either category. In terms of CED, spore preparation is the process that uses the most electricity and, according to this result, from the non-renewable category. Looking closer at the result distribution of the non-renewables, nuclear power is the largest contributor followed by fossils and lastly, a very small part form non-renewable biomass.

Spore preparation was one of the processes with the highest impact in most of the impact categories. Reasons for this could be that the spore preparation process has many electricity-intensive components and several components consisting of different types of plastics. Furthermore, spore preparation includes the step of maintenance of motherplant which is a continuous process all year round and requires both electricity and materials all year round. For example, filters which are exchanged once a month. Moreover, the process consists of single-use plastic components which requires more material. As the processes includes several of components with plastic and components which require electricity, it could explain the high impact in several of the impact categories. Furthermore, seeding is one of the processes with least impact which could depend on a relative low usage of both material and energy. Moreover, several of the material components used in seeding have a long lifetime and the impact is spread over several years. The cultivation process also often entails a higher impact, likely a driver from that the infrastructure installation is included in the cultivation process.

5.1.2 Dominant components

In this section the results for the different components' contribution to each impact category are presented. The section is divided into two parts: Contributions from non-electricity driven components and contributions from electricity driven components. Within each impact category, the largest 4-5 contributors are further described in text.

Contribution from non-electricity driven components

Appendix II shows the contribution from different components to the different impact categories. The carrying lines, longlines, anchor buoys and small buoys (A0) are the four most important components contributing to GWP; all mainly consisting of plastic.
The carrying line is also the largest contributor to marine ecotoxicity, followed by the screw anchor, anchor buoys (large) and longlines. The shackles and the seeding line also contributed to this impact, but at lower levels.

For acidification, the carrying lines were again among the top contributing components followed by the anchor buoys, longlines, small buoys and screw anchors. The largest contributors to eutrophication follow almost the same pattern as the rest of the categories; carrying lines as the main component followed by the anchor buoys, longlines, and screw anchors. For abiotic depletion, the screw anchors represent the largest contribution, followed by the carrying line, anchor buoys and shackles. Cumulative energy demand (CED) was dominated by the carrying lines, whereas the longlines, anchor buoys and polypropylene tanks followed. Regarding the division of renewable and non-renewable energy sources, the non-renewable category dominates significantly in regard to all the components.

Some components are associated with the highest impacts in several impact categories. These components are the carrying line, the screw anchors, the anchor buoys (large), and the longlines. The reasons behind this can be many: e.g., lifetime, volume, and the material it includes. Regarding the carrying lines, the amount of material used contributes with high impact per FU, more than double the material used for all other ropes and lines together. This is in part due to the short lifetime (estimated at five years), which is less than many of the other ropes and components. The anchor buoys have a high volume and use approximately half of the materials used for all buoys together. The importance of screw anchors will be assessed further in the sensitivity analysis, including an analysis of possible reasons for their high impact.

Contribution from electricity driven components

When it comes to the electricity use, the pattern is similar for each impact category. The seawater pump is the by far dominating contributor in each impact category (81% contribution). The air pump (8.1%) and lamps (8%) in spore preparation are two other categories that show to have smaller contributions. Other components (cooler, autoclave, fridge, LED stripes and lamps in the seeding) are not contributing significantly at all (less than 2.9% together).

Regarding CED, the seawater pump is also the largest contributor (81%), followed by the lamps (8%) and air pump (8.1%), where the non-renewable energy demand stands for the largest share of all the categories (around 71%).

The seawater pump is one of the components which belongs to the step maintenance of motherplants which uses its energy all year round. This could then be the primary reason for why the seawater pump has such a high impact compared to the other components.

Furthermore, the seawater pump is used around the clock. Meanwhile, other components, such as the lamps, are used only for some hours per day.

5.1.3 Dominant raw materials

Diesel is the material with the highest impact in all impact categories except in marine ecotoxicity and abiotic depletion *(Appendix III)*. Regarding acidification, diesel has such a high impact that the other materials can be neglected when standing in relation to diesel. This could also be applied to eutrophication, where diesel has a high impact in relation to the other materials. GWP100 and total non-renewable impact categories have a high impact from diesel; however, they are not as outstanding as in the formerly mentioned categories. Marine aquatic ecotoxicity and abiotic depletion are the categories where diesel is not one of the materials with the highest impact. The reason for why diesel is not one of the materials with highest impact in abiotic depletion is because our choice was to exclude the impact category of abiotic depletion (fossil fuels).

The result for the impact category GWP100 displays that several of the materials have an impact on GWP. Some materials have a higher impact in comparison to others. Looking at the *figure in Appendix III,* one can see that the materials gasoline, polyester (PES), and polypropylene (PP) have the highest impact. Other materials which have an effect on GWP are PVC and plastic foam meanwhile, ammonium nitrate, phosphate fertiliser, polystyrene (PS), and stainless steel have almost no effect.

The result for acidification displays that gasoline, polyester (PES), and polypropylene (PP) are the materials with the highest impact. Other materials of importance are PVC and plastic foam which have an impact just beneath the impact of PP. Materials with a minor influence or no effect are polyethylene (PE), galvanised steel, stainless steel, nylon, polystyrene (PS), and the two fertilisers, ammonium nitrate and phosphate. Acidification is caused by acid gases that are released into the atmosphere where one of the main reasons is due to fuel combustion. This could then explain why gasoline and several of the plastic types have the largest impact on acidification (Dincer et al., 2020).

Regarding eutrophication, the result is similar to earlier mentioned categories, with PES and gasoline at the top, followed by plastic foam and PP. Other materials have almost none or no impact compared to the materials with the highest impact. Eutrophication is caused by nutrients, often phosphorus and nitrogen (Water Resources, 2019). These are the two fertilisers that were studied in the LCA, however, the amount used was small which results in a very small impact in comparison to other components. Instead, plastics and gasoline had a higher impact which could depend on the large amount used in comparison to the fertilisers.
Materials with a high impact on abiotic depletion are PES, PP and plastic foam. All other materials can be seen as having a low impact compared to the materials with the highest influence.

The results for marine aquatic ecotoxicity are the category that differs the most compared to the other categories. PES, plastic foam, and PP are still the materials with the highest impact; however, gasoline has almost no impact compared to the other materials. Moreover, galvanised steel has a higher impact than in earlier categories. Ammonium nitrate and phosphate fertiliser are still the materials with the lowest impact, together with nylon, PE, and PS.

PP is the material with the highest impact on the category total non-renewable, followed by polyester and plastic foam which are the two materials with the highest impact on the total renewable impact category. PP is the material with the third-largest influence on the total renewable category. Other materials in this impact category have a lower impact than those mentioned above. For the total non-renewable category, PVC and plastic foam have an essential effect; meanwhile, other materials have a low or no impact in comparison.

Based on the figures in *Appendix III*, one can see that the raw materials with the highest impact are PES, gasoline, PP and plastic foam. Another material with high impact in at least two categories is PVC. Materials with almost none or a low impact compared to other materials for all impact categories are ammonium nitrate, phosphate fertiliser, stainless steel, nylon, PS and PE. Galvanised steel had a varying contribution to the impact depending on impact category. The reasons for why these materials had the largest impacts are manifolded. The primary reasons are due to the type of material and the amount of material used. For example, one can see that PES and PP are the two most used plastics in the production system.

5.2 Sensitivity Analysis

This chapter presents the result from the sensitivity analysis where six different inputs were changed and tested to see how it affected the result of the base scenario.

5.2.1 Components of infrastructure

The different alternatives of using the 1.2 mm seeding line or the 4 mm seeding line, affect the amount of PP and PES used. The result based on calculations displays that the base scenario will have a higher usage of both PP and PES compared to the alternative scenario. What differs is in which process that the material is used. As the 4 mm seeding line is thicker, more PES is used in spore preparation, meanwhile less PP and PES are used in the cultivation process as there is no carrying line.

5.2.2 Duration of electricity-intensive components

Using the components only half of the time will result in less energy used and lower the spore preparations impact. However, the changes will not affect the spore preparations position in relation to the other processes. This could depend on whether the components with lowest energy consumption were changed and not the components with continuous processes for the whole year.

5.2.3 Tanks in polypropylene or fibreglass

Based on data and assumptions, one can see that the tanks made of fibreglass have a higher impact in all impact categories except in abiotic depletion. Regarding abiotic depletion, tanks in fibreglass have almost half of the impact compared to tanks in polypropylene. Fibreglass is made from sand which is a non-depleting resource and could therefore be one reason for why it has a low impact in abiotic depletion (Fenestration & Glazing Industry Alliance, n.d.). However, the fibreglass tanks have at least double or more impact compared to polypropylene tanks in eutrophication, acidification, and global warming. Meanwhile, the result is more equal between the tanks in the impact categories marine aquatic ecotoxicity, total renewable and total non-renewable. One thing that could have affected the overall result is the choice of lifetime of both the fibreglass tanks and the polypropylene tanks.

5.2.4 Yield: one or two harvests

When testing the different options of one or two yields per year, the result showed that in most of the cases in all processes and for all impact categories, the alternative scenario of two harvests of a total of 30 tons results in lower impacts than one harvest of 20 ton. In some cases, there is almost no difference between the two alternatives; however, no result displays that one harvest is better than two harvests. This indicates then that it is beneficial from an environmental perspective to increase the use of some components to increase the yield by 50 percent.

5.2.5 Monitoring trips

Changing the monitoring data from one trip a month to adding eight more trips due to four storm events, did not change the results substantially. The global warming potential and acidification were the categories most affected with an increase of approximately 20-30 %. The increase in fuels are most likely also the largest drivers of these categories since combustion and production of fuels emits greenhouse gases and other chemical compounds that contribute to global warming and acidification.

Not included here is however, the possibility that hard storms could potentially risk damaging of materials and components and thus, entail the need for adding new materials and components and require re-installation.

5.2.6 Weight of screw anchors

Varying the weight of the screw anchors showed some changes in results of the different impact categories. Almost in every impact category, the highest weight of 50 kg makes the cultivation phase the most contributing of all the four processes, exchanging the previous leading process.

The most significant changes can be seen in the abiotic depletion, marine aquatic ecotoxicity and eutrophication category. The abiotic depletion factor increased significantly when increasing the weight of the screw anchor. Abiotic depletion is driven partly by raw material extraction, such as minerals and metals (Burchart-Korol & Kruczek, 2016). Iron and chromium are two materials to a high extent included in steel (Burchart-Korol & Kruczek, 2016), which is the material the screw anchors are made of. Possible contents in steel such as Selenium, Nickel, Copper, and Zinc, are all metals that also influence the marine aquatic environment (de Koning & Korenromp, 2004; Sternbeck, 1998) and therefore, also can be a reason for affecting the marine aquatic ecotoxicity category.

5.3 Dominance analysis of the future upscaled scenario

In this chapter, the impact results for the future upscaled scenario will be presented in comparison to the base scenario. The chapter will follow the same structure as the base scenario chapter with a presentation of impact results of the different processes followed by impact results of components, both driven and not driven by electricity, and lastly, impact results of the raw materials. The upscaled items can be found in *table 3* in *chapter 3.6.*

5.3.1 Comparison between dominant processes in the base scenario and the future upscaled scenario

The result for the future upscaled scenario in 2040 compared to the base scenario in 2022 shows both increases and decreases in impacts for the different processes and in the different impact categories.

The spore preparation process decreased in impact in all impact categories in the upscaled scenario in 2040. In all categories except in the impact category total renewable there was a significant change while there was almost no change in result for total renewable. The decreased impact for the future upscaled scenario for abiotic depletion could for example be due to the change of electricity mix where 100 percent renewable energy is used in 2040. In addition, less energy is used both due to more mature technology and a shorter duration time of electricity-intensive components. When comparing the impacts for the seeding process the result showed that there was an increased impact in all impact categories.

There was also a remarkable result for the cultivation process where all impact categories had less impact in the upscaled scenario compared to the base scenario. There was also a significant decrease except in the total renewable category where there was just a small decrease. One reason for this change could be that the infrastructure without a carrying line is used as the carrying line did have a large impact in the base scenario.

The result for harvest was also mixed. There was less impact in the upscaled scenario in the impact categories global warming, acidification, and eutrophication. Meanwhile, it was a higher impact in the upscaled scenario in the impact categories marine aquatic ecotoxicity and total renewable, abiotic depletion and total non-renewable. The change from diesel and natural gas are the change which affects the harvest the most and are one of the reasons for the change in the result.

There were some changes in impact categories regarding the process with the most impact. There was a change in the acidification category where cultivation had the highest impact which was a change from the base scenario where harvest had the highest impact. For eutrophication the change was that harvest was the process with least impact in the future upscaled scenario instead of the seeding which had the lowest impact in the base scenario.

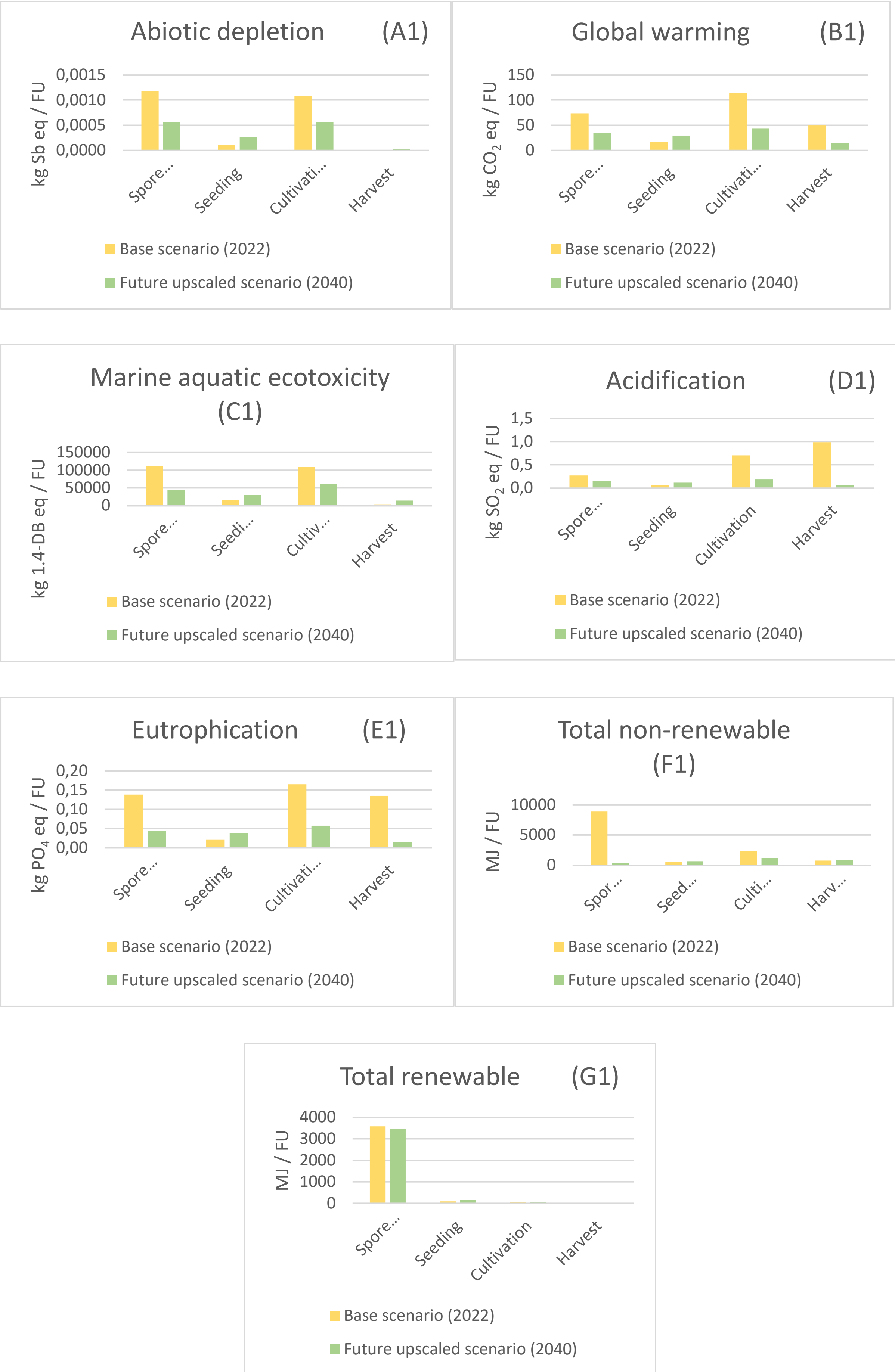

Figure 5 (A1-G1). Comparison of impact of each process between base scenario and future upscaled for the production system for the chosen impact categories.

5.3.2 Comparison between dominant components in the base scenario and the future upscaled scenario

Below the differences between the base scenario and future upscaled scenario is presented regarding non-electricity driven components and electricity driven components.

Contribution from non-electricity driven components

The contribution of the different components in the upscaled scenario compared to the base scenario resulted in a change of the most contributing components in several of the impact categories.

The carrying line was one of the components with the highest impact in all impact categories. An impact which disappeared in the upscaled scenario as it was not used. Instead, the impact from the use of a 4mm seeding line in the upscaled scenario did increase as it is a thicker line than the 1.2mm used in the base scenario. However, there was still a decreased impact when comparing the future upscaled scenario with the use of a 4mm seeding line to the base scenario with both a 1.2mm seeding line and a carrying line.

In regard to abiotic depletion, the 4 mm seeding line is the major contributor in the upscaled scenario compared to the base scenario where it did not have a high impact. Furthermore, the screw anchors still have a high impact and are the most contributing component in 2040 in the impact category abiotic depletion.

Viewing the result for global warming, the 4mm seeding line and the spools increased and had a higher impact in the future upscaled scenario. All other materials did decrease in the future upscaled scenario compared to the base scenario.

In the impact category marine aquatic ecotoxicity, almost all components decreased in impact in the upscaled scenario compared to the base scenario. Meanwhile, the 4mm seeding line and the single-use cups did have a higher impact in the scenario in 2040 compared to the base scenario. Additionally, the high impact from the carrying line did disappear.

In the impact categories acidification, eutrophication and total non-renewable, the result displayed similar changes. The single-use cups and the seeding line had a higher impact in the upscaled scenario. Meanwhile, several of the components in cultivation and harvest such as the anchor buoys (large), longlines and small anchor buoys A0 did have less impact in the upscaled scenario. This could be due to the efficiency of two harvests instead of one in the upscaled scenario, where several of the components could be used several times without any larger impact on the materials life length or function.

For the impact category total renewable, the biggest change was the single-use cups and the seeding line which had much higher impacts in the upscaled scenario. The reason could simply be that PLA is a renewable material meanwhile PS is not and the amount of seeding line increased as it was thicker in the future upscaled scenario.

Something that should be noted is that the reason for why several of the components had a higher impact in the upscaled scenario compared to the base scenario is because the upscaled scenario has two harvests instead of one as the base scenario has. Therefore, one reasonable cause of the higher impact is the increase of used material. Therefore, in some cases, it could be useful to compare the scenario in the sensitivity analysis with a base of two harvests.
Something of interest is that the single-use cups have a higher contributor in the upscaled scenario compared to the base scenario in all impact categories except in global warming and total non-renewable. Which could indicate that PLA is worse than PS in this case. However, the upscaled scenario uses double of the amount compared to the base scenario as it has two harvests which could have a large effect.

Contribution from electricity driven components

Regarding the electrically driven components, the distribution between the different components did not change in any impact category between the upscaled scenario and the base scenario. However, there was a significant decrease in impacts for most components in all impact categories. For example, the impact of the seawater pump in the impact category of global warming halved. The most significant change was in the impact category total non-renewable where, for example, the seawater pump decreased by approximately 97 percent. The main reason for this change is the change of electricity mix where the upscaled scenario only uses renewable energy. Other reasons for the total decrease could be the efficiency due to more mature technology and the shorter duration time for some components. This could also be why spore preparation had mainly decreased impacts in most of the impact categories, as this process is energy intensive. This resulted in a large decrease of impact in all impact categories of the total electricity use for the future upscaled scenario. Additionally, there was a change where the non-renewable energy demand stood for the largest share of all the categories (around 71%) in the base scenario while the renewable energy demand stood for the largest share in the future upscaled scenario (around 93%).

5.3.3 Comparison between dominant raw materials in the base scenario and the future upscaled scenario

The result for the upscaled scenario shows some changes in impacts from different materials compared to the base scenario. The major change was that the impact from almost all materials decreased in the future upscaled scenario compared to the base scenario.

In regard to abiotic depletion, marine aquatic ecotoxicity, and total renewable energy the largest change was that several of the materials, for example, PP, plastic foam and PES decreased in the upscaled scenario compared to the base scenario. Additionally, natural gas had a higher impact compared to gasoline and diesel together.

Viewing the results for global warming, acidification, and eutrophication the major changes was that most of the impacts from the material decreased. However, in these impact categories, there was a lower impact from natural gas than from the total impact of gasoline and diesel. Natural gas had approximately 71 percent lower impact than gasoline and diesel.

In the impact category total non-renewable there was a similar result as for the other categories where the impact for most of the categories decreased. Examples are for example, PP, PES, PVC and plastic foam where the largest changes were. However, for this impact category, there was almost no difference between a use of natural gas instead of gasoline and diesel.

5.3.4 Summarised total impact

Below in *table 13,* a compilation of the total result of the impacts from the different impact categories is presented, both for the base scenario and the future upscaled scenario. The results show that there is a significant decrease in all the impact categories from the base scenario to the future upscaled scenario.

Table 13. Compilation of the total impacts from the different impact categories for both the base scenario and the future upscaled scenario. Note that the numbers have been rounded.

IMPACT CATEGORY	CF UNIT	BASE SCENARIO	FUTURE UPSCALED SCENARIO
Abiotic depletion	kg Sb eq / FU	0.0024	0.0014
Global warming	**kg CO_2 eq / FU**	**271**	**122**
Marine aquatic ecotoxicity	kg 1.4-DB eq / FU	248 549	150 299
Acidification	kg SO_2 eq / FU	2.09	0.51
Eutrophication	kg PO_4 eq / FU	0.474	0.154
Total non-renewable	MJ / FU	12 990	3029
Total renewable	MJ / FU	3771	3684

5.4 Local marine environmental impacts

In this chapter, the result of the exploratory literature search is presented. It starts with local environmental impacts on marine ecosystems, followed by assessment of local effects from marine aquaculture systems in LCA and lastly, other environmental assessments to evaluate local environmental impacts of aquaculture.

5.4.1 Local environmental impacts on marine ecosystems

This section presents collected literature on potential positive and negative impacts on the local marine environment. As mentioned before, macroalgae cultivation has several potential positive effects compared to other production systems. However, seaweed cultivation is not only connected to environmental benefits and positive impacts on the local ecosystems. As the discussion on upscaling seaweed production increases, possible risks and outcomes regarding local environmental impacts are investigated.

According to Hasselström et al. (2019), who assessed a 2-ha seaweed cultivation on the Swedish west coast, the risk of seaweed farming negatively affecting the local marine environment in Sweden is low. They rather stress that seaweed farming will probably have mainly positive effects on the environmentally connected local ecosystem services on the west coast of Sweden. Compared to other forms of aquaculture, the environmental impacts of seaweed cultivation are rather favorable (Kim et al., 2017). The assessment on ecosystem services by Hasselström et al. (2019) was however made for a rather small-scale. According to, for instance, Campbell et al. (2019) and Tonk et al. (2021), the scale of the cultivation could potentially have a significant impact and is very important to consider. There are potential ecosystem changes that can be affected by the development of seaweed cultivation, and the scale of the development of macroalgal aquaculture systems could have important implications for the dimensions of the local environmental changes and is thus essential to take into consideration (Campbell, 2019).

Spatial implications

According to the Swedish Board of Agriculture (2012) Sweden has plans to increase the national aquaculture and the board expresses that aquaculture should be prioritized in terms of marine coastal space. To spatially prioritize up-scaling of aquaculture is a prerequisite for an economically feasible sector, however, coastal areas are also zones where risk of conflicting interest are large (Stévant et al., 2017; Haller et al., 2011, Voss et al., 2017). According to Hasselström et al. (2018), seaweed cultivation could potentially have negative impacts on cultural ecosystems services such as aesthetic values and cultural heritage. In addition, conflicting interests with maritime tourism (EC, 2018; Mardika et al., 2021) and wind power (Buck et al., 2008; Michler-Cieluch & Kodeih, 2008) are also a spatial conflict implication.

Habitat modifications and effects on benthos: Addition of infrastructure and cultivated biomass

The addition of biomass material and infrastructure to the marine environment could both entail positive and negative consequences for the marine ecosystems (Campbell et al., 2019; Langlois et al., 2014; Corrigan et al., 2022). Aquaculture infrastructure occupies underwater, surface space, and seafloor space in different ways (Campbell et al., 2019). This man-made occupied space can thus decrease the availability of virgin marine habitats. Seafloor activities and occupation such as anchoring could also potentially cause damage to the sea bottom floor (Langlois et al., 2014). Seabed damage is considered one of the essentials drivers of biodiversity loss (Woods et al., 2016). However, studies in, for instance, Chile made on a 21-ha large kelp farm over three years have shown no significant effects on seafloor damages (Buschmann et al., 2014).

Cultivation of macroalgae could increase the populations of certain fish since it can provide habitat, food and shelter. However, there is also a potential risk of the cultivation replacing original habitat and thus negatively affecting the natural initial ecosystems (Corrigan et al., 2022).

Seaweed cultivation could potentially also attract larger animals and mammals, attracted to the provision of fish. This aspect could however disturb the animal’s normal behavior and displace them from their normal habitats. Some animals might also be causing damage to the cultivations by eating the seaweed, however, this depends on geographical location and has been more documented in warmer tropical warmers than colder temperate waters (Corrigan et al., 2022). Damage can also happen due to entanglement which could hurt both the infrastructure and the animals (Campbell et al., 2019; Woods et al., 2016)

Growth of cultivated seaweed, anchoring infrastructure and buoys could also potentially create new additional habitats in the local marine environment through providing shelter, living spaces and feed for marine species and thus, potentially increase biodiversity (Inger et al. 2009; EC, 2019). Several studies of systems of Integrated Multi-Trophic Aquaculture (IMTA), e.g., when seaweed farms have been integrated with salmon farms, have shown that seaweed cultivations have increased the number of lump fishes, an essential species for salmon farms since they eat lice that can cause diseases among salmon (Hughes et al., 2016; Stévant et al., 2017; Hasselström et al., 2017). However, this aspect could also go the other way if seaweed farms instead become a place that attracts species and pathogens that could cause diseases (Stévant et al., 2017).

Additionally, the addition of seaweed cultivation and infrastructure could also entail growth of biofouling species that consumes biomass and thus can harm crop quality and affect the yield. Biofouling species can also inhibit photosynthesis and algal growth, encourage grazers, increase disease susceptibility, contaminate commercial products by introducing allergen or toxin risks and damage farm infrastructure. Issues on biofouling are especially important if the intended product of the macroalga are to be consumed by human (Corrigan et al., 2022).

Release of organic matter

Furthermore, seaweed cultivations naturally loose organic material and release of organic matter which eventually sink its way to the bottom and decompose. Decomposition requires oxygen. Large losses of organic material could cause potential oxygen depletion due to decomposition processes which could have effects on the seafloor environment (EC, 2019) (Viaroli et al. 2008). When looking at larger scale kelp cultivations in China, studies have shown a reduction in bottom biodiversity (Zhou, 2012).

Shading and uptake of nutrients and carbon

Shading is a local impact that floating seaweed cultivation infrastructures can have which can affect the local ecosystems. By decreasing or preventing parts of sunlight from reaching shallower zones beneath the cultivation system, photosynthesis can decrease and in turn, even decrease primary production (Stévant et al., 2017; Campbell et al., 2019; Langlois et al., 2015). Choosing a proper location for cultivation of seaweed is thus important for the impacts of shading.

Seaweed cultivations are close to the surface and absorb light. In a large-scale production scenario, this could potentially increase the competition of light thus, affecting the growth of phytoplankton (Campbell et al., 2019; Litchman & Klausmeier, 2001) Phytoplankton are essential in marine food webs as a food source for several marine species and a decrease in plankton communities could thus disturb the trophic flows. In addition to competition of light, when scaling up an extractive plant cultivation like seaweed, there is also a risk of large-scale seaweed cultivation becoming a competitor for nutrients which also is important for the growth of phytoplankton (Campbell et al., 2019; Hasselström et al., 2017).

The extractive property of seaweed can however also have a positive impact on marine ecosystems since it can decrease the effects of eutrophication and acidification by uptake of nutrients (such as nitrogen and phosphorus) and carbon (Campbell et al., 2019; Kim et al., 2019). Just like terrestrial plants, macroalgae takes up carbon dioxide (CO_2) through photosynthesis. Although the total climate change mitigation effect that seaweed cultivation might have through carbon sequestration is yet uncertain and assumed to be reasonably low, it is still shown to be a mitigating factor. Through photosynthesis, seaweeds also create oxygen and could locally, potentially increase the pH value through carbon uptake, which can mitigate local acidification problems (Campbell et al., 2019; EC, 2019).

Macroalgae cultivation can provide shelter and food for zooplankton and thus, have the potential of increasing the number of zooplankton. An increase in zooplankton can be beneficial for marine ecosystems in several ways. For instance, plankton is an important source of food for various marine organisms and animals. In addition, plankton helps the oceans' regulation of carbon, oxygen and nutrient cycles. However, an abundance of plankton could also affect macroalgae cultivations negatively by i.e., sedimenting diatoms forming felts on the seaweed which can cause algal bleaching (Corrigan et al., 2022).

Invasive species and diseases

There are European legislations supporting restrictions on marine farming management to minimize risk of negative effects on surrounding ecosystems. These legislations include restriction on choice of location that minimizes risk of damage to delicate environments, genetic diversity being maintained in the wild, spread of non-native species, fertilization and managing of infrastructure (Campbell et al., 2019).

Even though there is legislation, the large spread and increase in aquaculture activity may induce a risk of spreading non-native marine species (Naylor et al., 2001; Stévant et al., 2017; Langlois et al., 2014; Campbell et al., 2019) which is a large driver of biodiversity loss (Woods et al., 2016). Caution can be taken by only cultivating natively occurring seaweeds which may reduce the risk. Although precautions are often taken to avoid non-native species from spreading, the spreading can occur accidentally and water currents could potentially cause gene flows reaching different ecosystems and affect populations (Johnson et al., 2008). At large scale, crop selection and selective breeding could potentially lead to different genetic material spreading to wild populations (Stévant et al., 2017). Attached foreign non-native species can potentially cause disturbances in ecosystems and loss in biodiversity (Langlois et al., 2014; Ju et al., 2020). Mono-cultivation of seaweeds may also make the system more vulnerable and increase the risk of diseases and pests spreading (EC, 2019).

Scaling up and densifying seaweed farming could potentially increase the risk of infectious agents and bacterias that can cause biomass damage and diseases among the seaweed (Campbell et al., 2019). This risk is especially high during the summer months when the sea temperature is higher which entails a hindrance for cultivation all year round (Stévant et al., 2017).

The future global sea temperature rise could entail consequences for future macroalgae cultivations, varying depending on farmed species and geographical locations. According to Norwegian and Swedish governments (Swedish Commission on Climate and Vulnerability, 2007; Flæte et al., 2010), sea temperature rise due to climate change could entail problems for future aquaculture in the national areas, for instance, in terms of cultivated species adapted for colder waters and production disruptions.

Macroalgae also hosts a lot of microorganisms essential for healthy ecosystems. However, added cultivations and thus, also microorganisms, could also entail bacterial infections and induce changes in the microbiome structure in the cultivation ecosystem. This could spread diseases that in turn, potentially could spread to other wild ecosystems and macroalgal communities, with the potential to cause ecosystem damages (Corrigan et al., 2022).

Material entanglement

Another significant driver of biodiversity loss is marine plastic debris (Woods et al., 2016). Additionally, if infrastructure is not maintained and planned properly, detachment and loss of material could potentially cause harm to marine ecosystems and marine species (Campbell et al., 2019). Loss and drifting of material from the infrastructure such as ropes and nets, could induce a risk of creating entanglement and harm to larger marine species. Even though the risk is uncertain and lowered with well managed infrastructure, the risk cannot be precluded. With larger scale farming systems, the amount of infrastructure materials increases thus, the risk as well (Campbell et al., 2019).

Noise

Anthropogenic activities can sometimes create disturbing noises underwater, disrupting marine life. Such activities can be long-distance sonars, boats, and underwater construction (Langlois et al., 2014). In regard to off-shore seaweed farming, activities such as increased boat traffic, installation of infrastructure, cultivation and harvesting all pose a risk of increased noise underwater (Campbell et al., 2019). How big of a risk this kind of noise will pose is currently hard to estimate. However, there is reason to believe that significant up-scaling of aquaculture activity could increase the risk (Campbell et al., 2019).

Effects on the water movements and water column

Studies have shown that seaweed cultivations can affect the local hydrology by suppressing water currents and changing water flows and tidal currents, causing microclimates in the close surrounding environment. Changes in water flows and current patterns could lead to changes in levels of nutrients and thus affect the carrying capacity of surrounding water bodies, local ecosystems, and marine food webs (Campbell et al., 2019). Changed and suppressed water flows and currents could also decrease the exchange of fresh water and nutrients in the local cultivation area (EC, 2019).

5.4.2 Assessment of local effects from marine aquaculture systems in LCA

This section of the study presents literature and studies on methods and approaches that were found in the exploratory literature search, on how to include more local marine environmental aspects in LCA to reach a broader, more holistic environmental assessment of the aquaculture, especially for seaweed cultivation systems.

General recommendations for including local marine impacts in LCA

LCA is a method originally developed for evaluation of land-based industries and their environmental impacts, thus more adapted for the assessment of terrestrial ecosystems. The assessment of marine ecological impacts has not been developed and integrated in LCA as much and methodology is lacking (Woods et al., 2015). Aquaculture has been assessed with LCA methodology for over a decade, however, there are still limited approaches for including marine environmental impacts (Bohnes & Laurent, 2019). Local impacts on the surrounding environment such as biodiversity loss and effects on habitats is, in general, one of LCAs weaknesses (Winter et al., 2017). Not the least when it comes to the marine environment and knowledge in general about marine biodiversity (Ford et al., 2012; Costello et al., 2010). In addition, an essential challenge of LCA in terms of including local environmental impacts is that the impacts on the local ecosystems tend to depend on largely varying local conditions and not always so much on the area of production (Ford et al., 2012).

Based on over 60 LCA studies, Bohnes and Laurent (2019) have highlighted several issues with LCA and environmental analysis of marine aquaculture systems and recommendations on how to perform the LCA to better account for marine aquaculture environmental impacts. Main issues and respective recommendations to LCA practitioners were to choose a functional unit based on nutritional qualities, include as broad a set of environmental impacts as possible and focus especially on consistency and completeness check and the sensitivity and uncertainty analysis during the interpretation of the results.

Winter et al. (2017) investigated the inclusion of biodiversity within and outside of LCA and proposes ways of integrating biodiversity within the four main steps of LCA. For instance, a clear specification and definition in the goal and scope phase regarding biodiversity is needed to avoid misinterpretations and more relevantly focus on biodiversity. In terms of the inventory analysis the author stresses that all inputs and outputs that have an impact on biodiversity must be accounted for and that it is essential to gather data from a common spatial dimension, since most impact categories are region-specific. When it comes to the impact assessment, existing impact categories on all levels and associated impact pathways should be adapted to consider effects on genetic and ecosystem diversity and not only on species diversity which is mostly the case now. Regarding the last phase, Winter et al. (2017) mentions that even though LCA is supposed to give a global and general result, some regionalization of LCA is essential to obtain robust and meaningful results.

Moreover, regarding impact assessment, Bohnes and Laurent. (2019) highlights that over half of the studied aquaculture LCAs included and focused on the same impact categories (climate change, aquatic eutrophication, acidification, and cumulative energy demand). According to Woods et al. (2016), climate change, acidification and eutrophication are three of the most major drivers of marine biodiversity loss and therefore, important to include in LCAs. However, Bohnes and Laurent (2019) state that by focusing on the same, and only a share of the impact categories, excludes other important insights and perspectives on impacts from aquaculture and thus stress the need for a broad spectra of impact categories.

As Woods et al. (2016), Winter et al. (2017) highlights e.g., climate change, acidification, and eutrophication as large contributors to biodiversity loss. These three also do exist as impact categories within LCA software and is thus, easily accessible which also goes for eco-toxicity, that runs by pollution, another category important for including biodiversity within LCA (Winter et al., 2017). However, many of the relevant pressures on ecosystems that can increase biodiversity loss are not yet addressed within LCA. This calls for impacts such as noise, artificial light pollution, monoculture, overfishing and invasive species (Winter et al., 2017).

Just like Winter et al. (2017), Ford et al. (2012**)** addresses impact categories and indicators to incorporate local ecological impacts into LCA. However, Ford et al. (2012) focuses especially on marine systems and aquaculture. Ford et al. (2012) focus on the two impact categories: impacts of nutrient release and impacts on biodiversity. Even though they focus on the production of salmon farming, most indicators presented in the article are suitable to use for any aquaculture system. One indicator within the impacts of nutrient release, is the area altered by farm waste which could be possible to use based on site-specific data for that specific aquaculture system. Other indicators discussed in the article, such as change in nutrient concentration in the water column, percent of carrying capacity reached, percent of total anthropogenic nutrient release, and release of wastes into freshwater, could also be possible to integrate, however, more dependent on system and availability of data. In addition, the biodiversity indicator on the number of reported disease outbreaks could also be used for any aquaculture system.

Furthermore, knowledge of marine ecosystems and biodiversity loss is generally lower than terrestrial (Costello et al., 2010). For instance, loss of habitat is mentioned as another major driver for biodiversity loss generally and can be evaluated as an indicator with LCA (to some extent) with impact categories such as land use and water use (Winter et al., 2017). Land use and water use mainly concern terrestrial ecosystems; however, there are several methodological developments within LCA more specifically designed for local marine ecosystems. One development especially occurred in the development of impact assessment models and new characterization factors (CF) for marine ecosystems.

Development of new characterization factors (CF)

Taelman et al. (2014) developed a new LCIA method for quantifying sea surface occupation. The method is called CEENE 2014 and is based on the framework for land resources elaborated by Alvarenga et al. (2012). The framework for land resources presents a way to calculate exergy-based spatially specific CFs for land use including both used biomass and occupied area. Exergy is a thermodynamic unit, well suited for addressing and quantifying energy and natural resources (Taelman et al., 2015). More specifically, exergy can be explained as the following: *"Exergy is a thermodynamic unit which refers to the maximum amount of useful work obtainable from a system or resource, as it is brought to equilibrium with a reference environment through reversible processes."* (Quotation by Taelman et al. (2015), p. 178) With the CEENE 2014, Taelman et al., 2012, turned the land-based methodology into a method suited for evaluation of marine systems. By calculating a spatially specific marine surface occupation factor, the method showed to be useful for evaluating and quantifying shading as a local impact due to seaweed cultivation blocking sunlight (Taelman et al., 2015). The specific spatial factor was developed based on the potential net primary production (NPP) in photic zones of different geographical spaces (Taelman et al., 2015). The photic zone, also called the sunlight layer, is the zone closest to the surface of the ocean where there is enough sunlight for photosynthesis to happen (NOAA Office for Coastal Management, n.d.).

Langlois et al. (2015) has also developed CFs to assess sea use impacts by human interventions regarding activities such as fishing, seafloor destruction and seafloor transformation. Different from Taelman et al. (2015), this approach aims to assess how these aspects affect the life support function of marine ecosystems. Additionally, there is a broader scope of impacts included in this development. Apart from impacts of shading, impacts such as biomass removal, benthic destruction, and artificial habitat creation are also things that can affect the life support functions and are included in the evaluation method and developed CFs (Langlois et al., 2014; Langlois et al., 2015). Just like the Taelman et al. (2014; 2015) method, this framework is also built on a methodology originally developed for land use impacts, here by Mila i Canals et al. (2007), and then turned into a framework including evaluation of marine systems. Both these LCIA frameworks can be used for a variety of marine systems, including aquaculture, and can be used to assess both occupational activities and biomass and resource removal activities. Instead of using the exergy content (given in MJex) of NPP, Langlois et al. (2015) free net primary production in primary carbon equivalent (fNPPeq) and uses the CFs given in kgCeq kg−1.

Like the previously mentioned methods, by developing spatially differentiated CFs through parametrization of 17 European ecoregions, Woods and Verones (2019) also present an additional approach to LCIA. However, in this article, the authors specifically highlight the exposure and vulnerability of the benthic (sea bottom) zone and have focused their approach on the anthropogenically caused damages to the seabed and habitat destruction affecting the marine ecosystems. Evenly with other similar approaches, Woods and Verones (2019) quantify the CFs both for impacts of seabed transformation and occupation. This method, however, differentiates between two impact perspectives regarding ecosystems' recovery times: one single-impact perspective and another with a repeated-impact perspective. By including both these perspectives, the method can consider both recoverable and non-recoverable potential impacts anthropogenic activities can have on the marine benthic ecosystems for different ecoregions. This approach enables a more specified view on potential local damages that can cause damages to benthic ecosystems for instance, by species loss.

Preat et al. (2020) has followed up partly on the method by Woods and Verones (2019) but focused on development of an approach accounting for biodiversity in deep seafloor ecosystems. This approach contributes to a regional biodiversity assessment within LCA regarding deeper benthic zones of the oceans.

Another important driver of marine biodiversity loss is plastic debris. Woods et al. (2016) have worked for the inclusion of entanglement impacts on marine biodiversity due to plastic debris in LCA. By the development of an effect factor that connects the presence of marine plastic waste to the possibility of biodiversity loss due to entanglement. They do this by linking the density of current floating marine macro-plastic representing the pressure and the potentially affected share of species representing the effect which gives a quantifiable effect factor possible to include in LCIA steps of LCAs.

5.4.3 Other environmental assessments to evaluate local environmental impacts of aquaculture

In this section, other environmental assessment approaches found in the exploratory literature search, apart from LCA, to evaluate local environmental impacts of aquaculture are presented.

Ecosystem service approaches

Instead of using and developing species and spatially related indicators as mentioned in previous chapter, other indicators such as ecosystem services could be used to assess biodiversity (Winter et al., 2017). A globally adopted approach for evaluating aquaculture uses is the Ecosystem Approach to Aquaculture (EAA). The framework was elaborated by aquaculture specialists at the FAO by observations of well-established aquaculture industries and resulted in three strategic principles aiming to provide guidance for the sustainable development of aquaculture industries (FAO, 2010). The three principles are as follows: *1) "Aquaculture development and management should take account of the full range of ecosystem functions and services and should not threaten the sustained delivery of these to society." 2) "Aquaculture should improve human well-being and equity for all relevant stakeholders." 3) "Aquaculture should be developed in the context of other sectors, policies, and goals."* (FAO, 2010).

Regarding kelp farming, Grebe et al. (2019) used these principles to recommend sustainable practices for the kelp farming industry. The authors stressed the need for further quantification of ecosystem services and environmental carrying capacity connected to kelp farming to reach concrete guidelines and boundaries for unsustainable expansions of kelp aquaculture.

Corrigan et al. (2022) focus on macroalgae cultivation and habitat provisioning at a local scale and, just as Grebe et al. (2019), on Ecosystem Approaches to Aquaculture (EAA). Marine habitat provisioning is an ecosystem service that supports biodiversity and aquatic ecosystems as well as provides benefits for maritime industries. Corrigan et al. (2022) does not propose a specific method but instead highlights local impacts that macroalgae cultivation regarding habitat provisioning can cause and compiles, from literature, potential ways to quantify these respectively. In the article Corrigan et al. (2022) writes about local marine impacts concerning microorganisms, presence of plankton, biofouling organisms, effects on benthos and attraction of fish and other marine animals, all within potential habitat provisioning of seaweed cultivations. These impacts could be quantified by, for instance, samples from waters and sediments, diving inspections and other monitoring methods. In summary, the article stresses the need for improved monitoring approaches by engagement with local stakeholder and site-specific monitoring but with standardised methodologies where it is possible.

Another similar approach is environmental evaluation based on ecosystem services. Hasselström et al., (2019) has made an assessment on seaweed cultivation on the Swedish west coast based on an ecosystem service approach. The methodology of the assessment was based on a specific mapping of ecosystem services from Swedish oceans. The article presents a qualitative assessment of how seaweed cultivation positively or negatively affects different ecosystem services provided by the Swedish west coast and surrounding environment. The identification of ecosystem services was done with a basis in the Swedish Agency for Marine and Water Management status report by Bryhn et al. (2015), and by collecting site specific data.

Broad strategic frameworks

Strategic Environmental Assessment (SEA) and the Environmental Impact Assessment (EIA) are two methodologies and procedural directives, used to assure that environmental implications are appropriately considered in decision-making and policies internationally (Hooper et al., 2014). EIA is a globally used approach of evaluating anthropocentric impacts including regarding coastal and marine environment and has for a long time been one of the foremost methods for environmental management and evaluating policies (Gibbs & Browman, 2015). SEA are more suitable for public programmes whilst EIA are more suitable for individual projects (Hooper et al., 2014).

As well as the ecosystem service approach, the SEA and EIA both consider more than the ecological perspectives for sustainable evaluation (Hooper et al., 2014). However, with a criticality for SEA and EIA, Hooper et al. (2014) has developed a methodology for implementation of Environmental Benefits Assessment (EBA) aiming to simplify local ecosystem service evaluation. The EBA approach aims to be more systematic and comprehensive in the practicality of the methodology of assessing local ecosystems. In addition, it seeks to simplify the valuation part of the environmental assessment and decrease the risk of duplication and overlaps when using both SEA and EIA. Furthermore, it aims to support the identification and quantification of local scale ecosystem benefits. In this way, the approach engenders a systematic, practical approach to evaluating local scale environmental benefits. The procedure of an EBA, according to Hooper et al. (2014) starts with characterisation of local sites and identification of stakeholders which is done to obtain information and an understanding of the system and potential benefits that the development can provide. The development is then described by compiling an environmental benefits inventory to frame the scope followed by quantification of the current level of delivery of each found benefit, determining their relative importance and lastly, examining the change in the level of delivery of the environmental benefits. Due to the locality focus, the procedure can enable an assessment of local environmental impacts on ecosystems, including marine ecosystems.

Ecological Risk assessment

Ecological Risk Assessment (ERA) is a method that is becoming more common within aquaculture (Gibbs & Browman, 2015). The World Health Organisation (WHO) even has developed a framework with Guidelines for Ecological Risk Assessment of Marine Fish Aquaculture (Fairgrieve & Nash, 2005; Nash & Volkman, 2008). ERA in general can be defined as *"... the process for evaluating how likely it is that the environment might be impacted as a result of exposure to one or more environmental stressors, such as chemicals, land-use change, disease, and invasive species."* (EPA, 2021).

As mentioned earlier, invasive species is seen as a large driver for marine biodiversity loss (Winter et al., 2017). Leung and Dudgeon (2008) have investigated the ERA of invasive species and exotic organisms associated with aquaculture activities which can be done both qualitatively and quantitatively. According to the authors, the quantitative approach is more refined and subtle and can entail rather accurate predictions on the studied matter, e.g., invasive species. However, quantitative approaches are also complex and need highly qualified people for execution. In contrast, qualitative methods are rather simple, flexible, and user-friendly and more likely to be adopted by regulatory authorities.

Based on another method called DPSIR (driver, pressure, state, impact, response), Tonk et al. (2021) have developed an ERA framework adapted to seaweed aquaculture and have compiled various methods and techniques to quantify pressures and ecosystem impacts related to seaweed farming. The framework was developed based on three tasks: (1) *How to monitor farming activities (intensity, spatial/temporal distribution); (2) How to measure pressures (and link to intensity of activity); and (3) How to measure ecosystem response (and link to pressure/activity, dose-response).* The approach that was developed was a prioritization approach of the main pressures and impact risks adapted for the specific seaweed farm in question where size, the local ecosystem and temporal and spatial distributions are essential to move forward with the suggested monitoring tools. With the help of experts within marine ecology, aquaculture, blue growth, and risk assessments, they showed practice of a semi-quantitative assessment to prioritize impact risks for a seaweed cultivation. The monitoring tools presented where physical and technical measuring tools to evaluate a specific ecosystem. Pressures that could be monitored were, for instance, accumulation of organic matter in the sediment by using sediment traps or shading caused by the cultivated seaweed measured by quantum sensors.

6

Further discussion and recommendations

This chapter is divided into different parts where discussions and recommendations are given. The first part consists of discussions of the result and main findings regarding both hotspots and improvement potentials based on the base scenario and the future upscaled scenario. In addition, a discussion regarding local impacts and a future outlook for including local impact assessment is given. Secondly, a discussion about the uncertainties and limitations of this study is done, followed by a discussion of the method used. Lastly, recommendations for further research are given.

6.1 Result and main findings

The thesis aimed to identify both the environmental impacts of an initiated implementation of a Swedish *Ulva fenestrata* cultivation and to point out future environmental impacts that an upscaling of the studied system could entail. The thesis was divided into different parts, one assessing the environmental impacts of the initiated implementation, which were referred to as the base scenario, and one which evaluated the potential environmental effects of a future upscaled system referred to as the future upscaled scenario. In addition, the assessment was divided into different parts where an evaluation of the processes, components and materials was done. Lastly, the thesis also aimed to find approaches on how to assess impacts on local marine ecosystems, both within and outside of the LCA methodology.

6.1.1 Hotspots and improvement potential for the future production of *Ulva fenestrata*

What could be seen in the base scenario was that the most dominant processes were spore preparation and cultivation. The harvest process did also have an impact in some of the impact categories; for example, it was highest in acidification. Reasons that can explain this result are, for example, the high use of both material and energy in relation to other processes. In addition, maintenance of mother plants which was a continuous process all year round could affect the high contribution of spore preparation. For example, the seawater pump accounted for 81 percent of the total electricity use. Looking at the result from the article by Thomas et al. (2021), where continuous processes in the spore preparation were excluded, this resulted in a low impact of the spore preparation compared to other processes. Other reasons which could explain the high impacts are that several components used in the processes had a short lifetime or, even worse, were single-use components. Lastly, both spore preparation and cultivation had several components that included plastics. Looking at the result for the components, one can see that the most dominant components were those which included plastics, had a short lifetime and where a high volume was used. The most dominant components in the base scenario were the carrying line, the screw anchors, the anchor buoys (large), and the longlines. Additionally, the seeding line had a high contribution in the future upscaled scenario. This is, to some extent, consistent with Thomas et al. (2021), where the longline ropes (referred to as carrying lines in our thesis) consisting of PES and the seeding lines had an overall high contribution. It is also consistent with van Oirschot et al. (2017) where one of the most important material components were PP ropes. Furthermore, Thomas et al., (2021) had a high contribution from galvanised steel chains. These were not used in our infrastructure, however, the screw anchors consisting of galvanised steel in our study had a high contribution. Therefore, the use of galvanised steel and potential substitutes to, in our case, other types of anchors should be further assessed. The impact hotspots of the components can be further assessed by looking at the most dominant raw materials: diesel, PES, gasoline, PP, and plastic foam, which all are included in most of the prevalent components. PVC did also have a higher impact in some impact categories.

The harvesting process showed minimal environmental impact in terms of abiotic depletion even if the fossil fuels in terms of diesel (majority) and gasoline are the only included components in the harvest. The environmental impact was however high for the harvesting process in terms of acidification. Since fossil fuels are large drivers for both acidification and abiotic depletion, this result might be found strange. Worth noting is that this is since the abiotic depletion potential of fossil fuels components is excluded and only the abiotic depletion potential for the material component. Therefore, fossil fuels and transportation does not play a large part in the ADP for material components but still in acidification.

To summarise, one could then say that the reason behind many of the most dominant parts is the use of plastics and fossil fuels, lifetime, volume, and duration. Therefore, recommendations for future production would firstly be to minimise the use of plastics and fossil fuels. The result for the future upscaled scenario displayed a decreased impact in some of the impact categories when diesel and gasoline were changed to natural gas. This could then be an alternative to further investigate for future production of *Ulva fenestrata.* Furthermore, PLA was used as an alternative to PS in the future upscaled scenario. The result displayed a varied change in impact depending on impact categories. The recommendations will be to investigate further into substitutes for plastics as these had high impacts. This could also be supported by the result from Ahlgren (2021), which stated that the type of plastics used in the system could have a significant effect on the environmental impacts, where the result was based on a comparison of five different LCAs done on algae. Additionally, the advice is to prolong the lifetime of components and decrease the total amount of components used. For example, by using components several times or changing materials. Lastly, a proposal will be to minimise electricity use by shortening the duration or using more efficient technology. This could be strengthened by the result of the future upscaled scenario as the result showed that it was preferable to have two weeks instead of four weeks of the duration of electricity-intensive components. According to the result of the future upscaled scenario, having more efficient technology requiring 15 percent less energy would also decrease the impact of electricity use. Additionally, if there were an electricity mix in Sweden only consisting of renewable energy, this would reduce the impact.

As there was some uncertain data, a sensitivity analysis was conducted. The sensitivity analysis result can give some recommendations regarding improvement potentials for future production of *Ulva fenestrata*. For example, the result showed that using a 4mm seeding line and no carrying line will be better as less PES and PP are used. This is accordant with Thomas et al. (2021) where he discusses the choice to find substitutes to the carrying lines (referred to as longlines in Thomas et al. (2021)) as these have a relatively high contributor due to the use of crude oil in the production. It is also better to use electricity-intensive components for two weeks instead of four weeks if possible. Furthermore, it is advantageous to focus on developing methods that could enable two harvests instead of one per year as the results show a decrease in total impacts. This is consistent with Seghetta et al. (2017), Van Oirschot et al., (2017) and Thomas et al., (2021) where all of the articles discuss the output as one of the most influential parameters to reduce the relative impact of the system. Additionally, tanks in fibreglass are less preferred as these have a higher impact in almost all impact categories. However, the lifetime was set to 20 years for fibreglass tanks and ten years for PP tanks. The lifetime affected the result and if the tanks in fibreglass could be used longer than 20 years, they may still be an alternative. The increased monitoring trips did not have a highly increased impact. It could still be discussed that it is better to have as few trips as possible. However, hard storms could potentially risk damaging of materials and components and thus, entail the need for adding new materials and components and require re-installation which potentially could have increased the impact. More monitoring trips could then prevent eventual breakage of the infrastructure, which could extend the lifetime of the infrastructure in the long run. Lastly, the weight of the screw anchors could have a significant effect and is therefore an important factor to take into account.

However, one aspect not included in the sensitivity analysis nor the future upscaled scenario quantitatively is the potential future alternative of anchoring solutions. Currently used in the evaluation of the production system are the screw anchors, however, in a future upscaled scenario, one could assume that there potentially could be a switch to concrete blocks, as for instance, as the LCA study on kelp by Thomas et al. (2021) had, as anchoring solution due to the upscaled size of the cultivation and concrete blocks are more robust. There were a lot of uncertainties regarding the anchoring aspects and therefore, it has not quantitatively been included in the future scenario.

Even though it can be hard to compare LCA study results due to, e.g., different system boundaries and FUs, it can be interesting to compare to get a perspective on the result. According to a compilation of six LCA studies on brown macroalgae made by Ellen Ahlgren (2021), the carbon emissions for the six studies stretched between 21.54 - 84.32 kg CO_2 per FU which is less than our result. Our result showed that for the entire studied system, the total carbon emission per FU was 271 kg CO_2 eq. for the base scenario and 123 kg CO_2 eq. for the future scenario. Looking closer at Thomas et al. (2021), one of the LCA studies in the compilation, with several similarities to the studied system in this thesis, they reached a result of 45.85 kg CO_2. The lower number compared to our study could be due to several things but e.g., the amount of yield produced. The studied system by Thomas et al. (2021) had a significantly higher yield than the one in this study.

Another factor that is different in our studies is that we included the step of maintenance of the mother plants which is a continuous step that is ongoing all the time. This step of the spore preparation process stands for 91 % (base scenario) respectively 95 % (future upscaled scenario) of the total spore preparation process. Most LCAs on macroalgae found have not included this part. If we were to exclude this part, it would reduce the carbon footprint to 203.7 kg CO_2 (base scenario) respectively 89.9 kg CO_2 (future upscaled scenario). This would mean quite a significant difference in terms of the results and more in line with other LCA studies. In addition, a reduction of the spore preparation would entail the cultivation being the largest process which is also a more common result in the other studied macroalgae LCAs. Additionally, we included this step based on the current situation. In the future when the production perhaps is more industrialised, having a continuous large process like this might not be as feasible due to unprofitability.

6.1.2 Local impacts on the surrounding marine ecosystems

In a future upscaled scenario, producing 100 tons, this LCA study indicates a reduction in most of the impacts. If only looking at that result, one could argue that an upscaling is not an environmental issue, rather the opposite. Compared to land-based agriculture and other aquaculture such as fish farms, seaweed aquaculture is a more environmentally beneficial production. However, there can be risks when it comes to local marine impacts. There is still a lot of uncertainty regarding local marine impacts due to cultivation of seaweed and it is hard to state how a future upscaling of seaweed farming will impact the local marine ecosystems in Sweden. Therefore, we cannot say for certain how an upscaled seaweed cultivation will impact the local marine environment on the Swedish west coast since the potential impacts on the local marine environment have not been explicitly assessed in this study. However, they have been addressed and discussed.

Some literature is stressing that seaweed cultivation probably will not have a large impact on the local marine ecosystems (Hasselström et al., 2019; Visch et al., 2020; Campbell et al., 2019), however, others say that scale is an essential factor that will be important (Campbell et al., 2019; Tonk et al., 2017). By increasing the production to 100 tons, the occupied surface area will be 10 hectares which is the same size as approximately 18 common football courts. According to the definition on scale presented by Campbell et al. (2019), a 10-hectare aquaculture infrastructure is still regarded as a small-medium scale cultivation. Thus, a 10 hectare rig most likely will not induce significant risk of local impacts. However, if there are many future initiatives of seaweed cultivation, the effects could be of essence. From this study, the risk of significant local impacts on marine ecosystems of seaweed farming in the future is low. It is, however, important to find ways to assess it. Even though the seaweed cultivation is a good alternative compared to other aquaculture, it is still going to be important to learn to holistically assess the potential impacts and consequences of an increase in seaweed farming.

As mentioned earlier in the discussion, an alternative not included in the future scenario in this study could be to use concrete blocks instead of screw anchors in future scaling of seaweed farming. Concrete blocks are both larger and heavier than screw anchors which could be an important factor to consider in terms of seabed damage. This could also be the case for screw anchors even though they are not occupying as much seabed per unit as the concrete block would possibly do. To put alternatives on anchors in perspective, parallels can be drawn from other seaweed cultivations and sea-based production systems. For instance, if a future 10-hectare kelp cultivation producing 10 kg of kelp per metre of the carrying line would include concrete blocks as anchors, an assumption made based on Thomas et al. (2021) LCA study on kelp cultivation, the amount of bottom area that approximately could be occupied by the concrete anchors would be around 46 m^2. Since *Ulva fenestrata* is a much lighter and smaller macroalgae, approximately would require barely half of the number of concrete anchors. The amount of occupied bottom area would thus be around 20 m^2. Compared to wind turbines built offshore whose concrete foundations can be about 15 m in diameter, which takes up an area of about 177 m^2, for a single wind turbine (Hammar et al., 2010), an entire seaweed cultivation occupying 20 m^2 is a fraction. The local marine impact of noise and vibrations can also be significant from wind turbines and disturb the local marine environment, fish and organisms living in the surroundings (Boverket, 2021; Andersson, 2011), and can be assumed to be a larger issue than a seaweed cultivation.

Moreover, there are other marine productions inducing a larger risk of severe damage than seaweed cultivation. Fishing and harvesting for seaweeds and shellfish with bottom trawling is an example of an often destructive fishing method that can destroy and even out the seabed, making it incapable of remaining as marine habitat (Naturskyddsföreningen, 2021; Woods et al., 2016). For instance, are the waters around the Baltic Sea, Skagerrak and Kattegat intensively trawled areas in Europe and the negative local environmental effects on seabeds and their surroundings is tremendous (Naturskyddsföreningen, 2021). There are a lot of known impacts and proof of environmental effects due to trawling such as seabed destruction, biodiversity loss, high levels of lethal bycatch and habitat removal (Woods et al., 2016 ; Sköld et al., 2018). Compared to bottom trawling and the likeliness of severe risk of environmental local impacts with seabed damage, seaweed cultivation seems rather harmless. In addition, as mentioned earlier in the report, seaweed cultivation is a fairly new development in Europe and awareness is coming along. There is also control and regulations such as The Ecosystem Approach to Aquaculture (EAA), a widely adopted framework for evaluating aquaculture practices developed by FAO (FAO, 2010), helping to minimize impacts due to aquaculture. In addition, it is important to note that seaweed cultivation can bring a lot of beneficial environmental value such as carbon and nutrition uptake. Compared to fish cultivation which in reverse, is a more emitting production rather than extractive. Important to note is however, that the impacts of seaweed farming on the marine ecosystem are largely unknown (Tonk et al., 2021) the local impacts identified in this study are not all. This topic is something that needs to be further studied and explored.

6.1.3 Local assessment and LCA: Future outlook

It is still generally hard to include local impacts in LCA and denoted is that many types of local ecological impacts are still poorly studied and understood, which complicates the inclusion of biodiversity indicators in LCA (Winter et al., 2017; Ford et al., 2012). but even harder for marine environments since there is a clear research gap in this area. In this study, an LCA has been performed alongside an exploratory literature search related to local marine impacts and aquaculture. Even though the amount of literature on explicitly how to include evaluation is limited, the amount of literature that is used here is only a start of such an evaluation. As mentioned, we have not explicitly assessed the potential local impacts on the marine ecosystems in Sweden, but rather compiled information on approaches and aspects that could be used and integrated to make an environmental assessment of seaweed aquaculture fully holistically.

The existing ”add-ons” to LCA, such as specifically formed CFs, is focused solely on one or few local ecological impacts. To assess all possible local impacts on marine ecosystems, one would need many different approaches to fulfil the quantitative possibility. Including all potential local impacts in an LCA, would require many different sources and data on different CFs, EFs or indicators.

Impact category methods and respective CFs are often used and obtained through LCA softwares such as SimaPro. Newly developed, specific CFs such as the above mentioned for marine environments, are not yet to be found in softwares and thus, requires more work to access. This is a factor that could complicate LCA studies and make it harder to reach a more holistic assessment of aquaculture systems, since the data collection and time consumption for the study would increase. The CEENE 2014 impact category method adapted for marine environments developed by Taelman et al. (2014) is usable but, however, neither available in all softwares. The CEENE 2014 impact assessment method was, however, not to be found in the SimaPro software used for this study.

However, as literature also highlights, there are accessible CFs that can be integrating into LCA, such as climate change, ocean acidification, eutrophication, all important drivers of marine biodiversity loss (Winter et al., 2017; Woods et al., 2016). Other CFs important for marine ecosystems are available such as seabed damage (Woods et al., 2016; Woods & Verones, 2019), seafloor destruction and seafloor transformation (Langlois et al., 2015) and marine plastic debris entanglements (Woods et al., 2016). However, even though they are available and some also available in LCA software, most of them are seldom used in common LCA practice (Winter et al., 2017) which should be changed to improve the environmental assessments on marine local ecosystems. There are also still various impacts that has still not been addressed methodologically such as noise and artificial lights (Winter et al., 2017). These aspects not yet, however, seem as significant for current seaweed farming as e.g., seabed damage or invasive species, but is still important to acknowledge in the future development to reach holistic results.

The occupation of seafloor and surface area might be especially important in relation to the discussion on scale of cultivation and its potential importance for the local impacts. Since the industry of aquaculture, including seaweed farming, is rapidly growing, a more complete understanding of the scale dependent changes is important to assess the environmental impacts and consequences holistically.

Adding an external method or approach such as ecological risk assessment or evaluation of ecosystem services to an LCA study could be a good compliment in terms of including local marine impacts. However, this entails lots of data and resources.

What could be beneficial is including more local experts of different fields, in combination when examining an LCA to include local impacts on marine environments during an execution of the LCA study. This could thus extend an LCA study with more qualitative site-specific information. The data collected from experts, the production manager and researcher at Tjärnö, and local knowledge in this study have mainly been focused on inventory data for the LCA.

There are still few large-scale macro algae production systems in Europe and therefore, little data and practical examples is yet to found regarding the effects on local marine ecosystems. The systems that have been evaluated are often of a smaller scale and the conclusion are often that there are potential impacts but not of major significance. It is still hard to evaluate and predict what the local marine impacts of future upscale of seaweed farming could be and yet, there is no method that can generalize and include all local impacts.

There is a clear need for more knowledge and more research on assessments in terms of local marine ecosystems. A challenge for the future methodological issues regarding environmental assessment of aquaculture and seaweed farming is that there is a need for both more simple and standardized methods as well as the need for site-specific data and approaches. For the future, simplified, standardized and more collected methodologies of qualitative and quantitative combined solutions specified for different regions and local ecosystems is needed.

As seaweed farming might get more common in Sweden, a suggestion for future studies would also be to develop a specific approach specified for Sweden's west coast for a specific infrastructure and type of aquaculture.

LCA is a beneficial tool for evaluating environmental impacts and an interesting and promising tool to combine with others. Currently, the data necessary to assess marine local impacts holistically environmentally on ecosystems within LCA is not yet fully accomplished. Foreground and background data are not often available for the same spatial dimensions (Winter et al., 2017). LCA is generally a method for general and global results however, in relation to local marine impacts, it might need to be somewhat regionalized. The combination potential of LCA and other methods would have to be studied further and tested for aquaculture and more data related to seaweed production is needed.

6.2 Uncertainties and limitations of this study

There are several factors which could have influenced the result. Examples of factors that could have affected the outcome are limitations, assumptions, and choices.

Firstly, regarding the base scenario, there was much reliance on the experts, both the production manager and the researcher at Tjärnö, and their assumptions when collecting data for the LCI. During the study visit, there was much verbal data collection directly from the production manager which made approximations. For components and processes with a high impact, this could have had a crucial effect as a small change could affect the result much. Parts that we think would significantly affect the result have been considered in the sensitivity analysis. However, there may be parts that have not been included in the sensitivity as we rely on that experts have given the right information. However, human factors are a part of this, and there may be wrong information or approximations. One solution could have been to involve more experts in the data collection to increase the robustness and reliability of the result. An example of an aspect not included in the sensitivity analysis was the installation of infrastructure. In the study for the base scenario, we included solely one installation for the entire year in terms of materials and components. Realistically, one could assume that some of the infrastructure might have to be maintained, changed, and reinstalled during time of use. Including additional parameters regarding the infrastructure and maintenance could have increased the robustness of the study even more.

Another uncertainty of this study is the modelling in Excel. As the result has been calculated and modelled in Excel, mistakes such as miscalculations or forgotten adjustments can occur. Regarding the modelling, choices of processes in SimaPro and EcoInvent could also influence the result. There have been several assumptions and adaptations regarding processes in the software. Sometimes, exact processes could not be found, and choices needed to be made on the most suitable process. For instance, in regard to the processes of diesel and gasoline, the difference between those two processes and CFs used in this study differed quite a bit. Using other processes for diesel and gasoline could have changed the results. Furthermore, some materials, such as the fertilisers, were created by the research and development engineer at RISE who based the calculations on a cultivation in the USA. In addition, the fertilisers were not exactly calculated based on the solution used on the production site on the Swedish west coast. It is also difficult to affect the processes and know where, for example, the production is made and which countries' electricity mix that is accounted for.

An aspect to consider is that the data was mainly site-specific which could affect the result positively and negatively. The positive with site-specific data is that the data are more exact and correct as it has been collected directly from the production system. However, as the data is site-specific it makes it more difficult to compare with other studies and gives a more average result on the impacts of a production system of *Ulva fenestrata*.

Other factors that could have influenced the result are the choices made in the goal and scope definition, as these have formed the execution of the LCA. For example, the choice of FU for this study was based on the limitations of a cradle-to-farmgate perspective where the preservation was excluded. This option was mainly based on the fact that this has not been realised for Ulva fenestrata and therefore it is difficult to know which preservation processes to prefer. The choice to have one tonne of fresh weight biomass did work well for our study. However, there are also other similar studies which use other types of FU, for instance, one tonne of protein where they include preservation processes. Additionally, the data on nutritional content of the *Ulva fenestrata* algae is not abundant and can vary depending on different factors such as whether it is dry weight, fresh weight, where and how it is cultivated (Steinhagen et al., 2022). In our case, the uncertainty regarding nutritional content and after harvesting management was the main reason for not choosing a functional unit based on nutritional value. Therefore, the choice of FU affected the comparability of our study with other studies, which could affect the relevance and validity of the study (Baumann & Tillman, 2004).

Another factor that could affect the result is the choices of impact categories. We limited our study to some of the impact categories in the CML-IA baseline method, however, to get a broader assessment of the impact, it could have been reasonable to include all impact categories. Moreover, the choices of which impact categories to include were mainly based on other literature and most used impact categories. However, there were very different results for different studies, therefore, it may have been relevant to include all in our case as there is a knowledge gap for us regarding the most suitable impact categories. According to Bohnes and Laurent (2019) it is important to include a broad scope of impact categories for LCAs on aquaculture. Important to note is however, although LCA gives a result on environmental impacts, the result does not necessarily mean impacts in the region but could be impacts from the production related to the system from around the world. Therefore, the choice of impact categories that have been done, might not reflect the total picture and would probably not even if the scope was broader. For example, the fuel consumption for the boats was included in this study, however, the production of the boats was not included. Furthermore, factors related to the maintenance of boats, such as coatings, have not either been included in the inventory analysis due to the complexity and in relation to difficulties with LCA. If coatings and other substances and components related to boats were included, the LCA would nevertheless not show the local emissions and effects.

One thing that can be further discussed is assumptions and choices regarding the boats and their capacity and duration. The production manager made many assumptions which could have affected the result as diesel and gasoline were two materials with a high impact in several impact categories. Small changes in duration and fuel consumption could have significantly affected the total result. Furthermore, for a future upscaled scenario, calculations on fuel consumption were still based on the boats for the base scenario. It may have been reasonable to calculate fuel consumption for boats with other motors used for a more extensive operation. In addition, combustion processes were not included in the calculations, which could have affected the result. Moreover, changes in distances due to, for example, longer distances between cultivations have not been included which could have affected the result as well. Another aspect related to vehicles is not including cars and their fuel consumption. This would have affected both the base scenario and the future upscaled scenario as changes in distance may have been relevant to consider for the upscaled scenario. It could also affect the total result as diesel and gasoline have large impacts.

As a predictive scenario was created for 2040, assumptions regarding data and alternatives could have affected the result for the comparison between the upscaled scenario and the base scenario. Several of the choices made were based on literature, however, it does not ensure that the alternatives will be used in a future production system. Moreover, as the result was predictive, it can have affected the availability of suitable processes in EcoInvent. For example, based on literature, PLA was chosen as a more sustainable alternative to PS. However, the result displayed that PLA had a higher impact than PS in most impact categories. One reason could be the choice of processes in EcoInvent. Furthermore, the data was mainly site-specific which could affect the result for the upscaled scenario as it may be more outspread on the Swedish west coast. For example, differences in salinity, temperature, and the total number of days with sun per year could affect the growth rate, the spread of diseases and possible material substitutes.

As mentioned, the seaweed industry is fairly new in Europe, not the least in Sweden, and the development and thus data is constantly changing. This also includes processes, data and other factors that we might not have taken into account. Things that were uncertain or unknown during this study, might be established processes in a current point of time.

6.3 Method discussion

The use of LCA as a method to fulfil the purpose of this thesis has both advantages and disadvantages. LCA as a method is clear, systematic, and good for giving a general and global picture of environmental impacts. Additionally, it gives an assessment of environmental impacts of the specific production system. However, when it comes to the possibilities to compare the result with other studies, several limitations occur. For example, the same FU and version of databases and software must be used to be able to compare the result between different studies. As the versions of databases and softwares updates over the years, it can be difficult to find studies with both the same FU and versions. Therefore, a discussion regarding whether the whole system is more or less environmentally beneficial compared to other systems has not been done. However, conducting a pLCA allows a comparison between a base scenario and a future upscaled scenario. Conducting a sensitivity analysis as an addition to the LCA will also strengthen the robustness and increase the reliability of the LCA and the study.

In regards to the literature search on marine local impacts and how to assess these, the review could benefit from being more comprehensive with a larger amount of literature and more concrete selection criteria in order for the result to be more robust. This is something that we would encourage for future studies since we however acknowledge an important field regarding how to assess local marine impacts both outside and within LCA and aquaculture, not the least of which is seaweed cultivation.

6.4 Further research and recommendations

This thesis was limited to a cradle-to-farmgate perspective. Therefore, the processes after the harvesting were not included as the production system was still in an early implementation phase when the thesis was conducted. Assumptions could have been made; however, they would not have given a trustworthy result due to uncertainties. The recommendation for further studies on more developed processes will be to include a more extensive system boundary, including all processes in the production system. By including the more processes in the production system, the comparability with other algae studies would be easier and would, in that way, strengthen the reliability and the relevance of the LCA.

Another recommendation for further studies is the inclusion of distances with cars. It was excluded in this study as processes that included transports in the foreground system have not been realised yet. This could also be seen as important for a larger scale as it may include more transport. Fuels were seen as a material with a large impact in several impact categories. Including all types of transport will thus, affect the total impact of the system.

Further recommendations can also be given regarding the inclusion of all material. This study was limited to include mostly consumables and components including only a few materials as maximum. Therefore, materials including several different materials such as the boats and the electricity-intense parts were excluded. This was mainly due to the time limit and access to databases and Software. Including these materials could then give a more comprehensive assessment of the system. For example, by including the material for the boats and consumables related to maintenance of the boats, for example, coating, a more accurate result could have been given.

Other interesting aspects for further studies to include are different types of alternatives for a future upscaled production system. This thesis was limited to only one option per upscaled item. However, it could be interesting to see other options as well. For example, PLA was chosen as an alternative to PS, however, when searching in literature, there are several different substitutes which potentially could have been used. A more comprehensive assessment of choices could then have been interesting to include to find the most suitable alternative for a future upscaled production system.

In regards to the question on how to evaluate local impacts both within and outside the scope of LCA, further recommendation will be to try to conduct the different methods found in this thesis. The purpose for this study was to find relevant methods to evaluate local impact, the next step will then be to integrate these in a furthermore developed study.

7

Conclusion

This thesis aimed to identify the environmental impacts of an initiated implementation of a Swedish *Ulva fenestrata* cultivation and to point out future environmental impacts that an upscaling of the studied system could entail. In addition, the purpose was to find improvement potentials based on the results. Through the pLCA, dominant factors contributing to environmental impacts proved to be mainly the processes of spore preparation and cultivation. The most dominant components were the carrying line, the screw anchors, the anchor buoys (large), the longlines, and the seeding lines (4mm). Additionally, diesel and gasoline had high impacts in most impact categories. Major factors that contributed to a higher impact were the use of plastics and fossil fuels and the lifetime, volume and duration of the components used in the system. The future upscaled scenario proved to generate decreases in environmental impacts compared to the base scenario regarding pLCA results hence to two harvests, two weeks on some electricity requiring steps and a 4 mm seeding line without any carrying line. Other areas of interest that should be further assessed for future production are the type of plastic used for the components, number of monitoring trips, anchoring solutions, type of material for the tanks, and type of fuels for the boats.

From the exploratory literature search, several local impacts of upscaled aquaculture and seaweed farming, both positive and negative, that could affect local marine ecosystems were identified. For instance, carbon and nutrient uptake, shading, animal entanglement and seabed damage.

The purpose of the thesis was also to find approaches on how to assess impacts on local marine ecosystems, both within and outside of LCA methodology. It is still generally hard to include local impacts in LCA, and even harder for marine environments since there is a clear research gap in this area. LCA is a suitable method for evaluating environmental impacts but needs compliments, preferably both qualitative and quantitative, to reach a holistic environmental assessment of both general and local impacts on marine ecosystems. This study suggests that seaweed farming can be an environmentally welcoming production for the future Swedish west coast. With proper holistic approaches to locally assess marine impacts of aquaculture activity we can make sure to mitigate environmental impacts of future upscaled seaweed farming.

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Appendix I – Component data and sources

Table 14. Compilation of component data of the processes and data sources

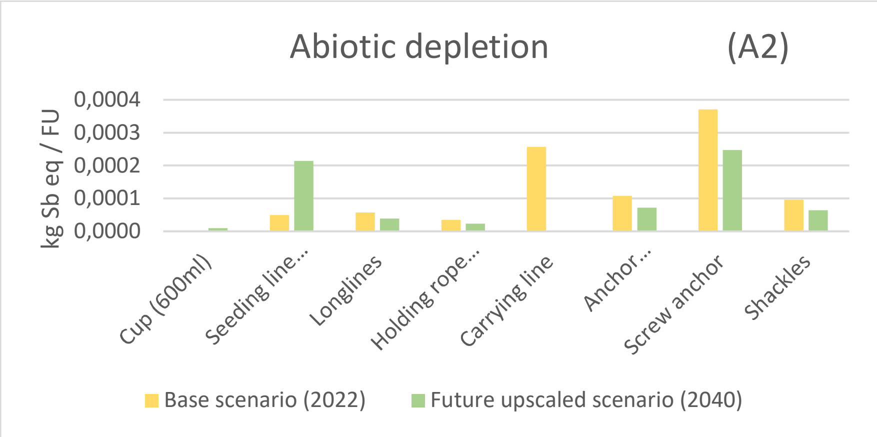
Components					
Spore preparation	**Specification**	**Unit**	**Lifetime**	**Unit**	**Source**
Tank	150	L	10	years	Göran Nylund, Nordic Seafarm
Filter (10µm)	00.27	kg/unit	1	month	J-B.E. Thomas, personal communication, february-may 2022
Filter (5µm)	00.37	kg/unit	1	month	J-B.E. Thomas, personal communication, february-may 2022
Filter (1µm)	00.19	kg/unit	1	month	J-B.E. Thomas, personal communication, february-may 2022
Nutrient mix (Phosphate)	01.34	kg/FU	-	-	Personal communication with research and development engineer at RISE
Nutrient mix (ammonium nitrate)	00.28	kg/FU	-	-	Personal communication with research and development engineer at RISE
Single-use cups	01.28	kg	1	use	(Big Buy, n.d.) https://www.bigbuy.eu/en/polystyrene-container-143982-600-ml_104462.html
Lamps	34	W	-	-	Göran Nylund, Nordic Seafarm
Air pump	275	W	-	-	Göran Nylund, Nordic Seafarm
Seawater pump	3000	W	-	-	(Alibaba, n.d.) https://www.alibaba.com/product-detail/Heavy-Duty-16-L-min-High_60316820694.html
Cooler	165	W	-	-	Göran Nylund, Nordic Seafarm
Autoclave	2000	W	-	-	Göran Nylund, Nordic Seafarm
Fridge	190	W	-	-	Göran Nylund, Nordic Seafarm
LED stripes	24	W/m	-	-	Göran Nylund, Nordic Seafarm
Seeding	**Specification**	**Unit**	**Lifetime**	**Unit**	**Source**
Seeding line (1.2mm)	00.09	kg/m	1	use	https://www.swedishrope.se/?s=polyestersilke
Seeding line (4mm)	01.28	kg/m	3	years	https://www.swedishrope.se/?s=polyestersilke
Spool	03.01	kg/m	20	years	J-B.E. Thomas, personal communication, february-may 2022
Filter (0.2µm)	0.2	kg/unit	1	use	J-B.E. Thomas, personal communication, february-may 2022
Filter (0.5µm)	0.2	kg/unit	1	use	(Assumption based on 0.2µm from JB) - J.B. Thomas, personal communication, february-may 2022
Filter (5µm)	0.2	kg/unit	1	use	J-B.E. Thomas, personal communication, february-may 2022
Tanks	150	L	10	years	Göran Nylund, Nordic Seafarm
Nutrient mix (Phosphate)	01.34	kg/FU	-	-	Personal communication with research and development engineer at RISE
Nutrient mix (ammonium nitrate)	00.28	kg/FU	-	-	Personal communication with research and development engineer at RISE
Air pump	90	W	-	-	Göran Nylund, Nordic Seafarm
Lamps	42	W	-	-	Göran Nylund, Nordic Seafarm
Cultivation	**Specification**	**Unit**	**Lifetime**	**Unit**	**Source**
Longlines	0,151	kg/m	10	years	Göran Nylund, Nordic Seafarm and https://www.swedishrope.se/?s=scanlin
Anchoring lines	0,355	kg/m	10	years	Göran Nylund, Nordic Seafarm and https://www.swedishrope.se/?s=danline
Anchoring lines	0,355	kg/m	10	years	Göran Nylund, Nordic Seafarm and https://www.swedishrope.se/?s=danline
Holding rope (sinking rope)	0,41	kg/m	10	years	Göran Nylund, Nordic Seafarm and https://www.swedishrope.se/?s=danline
Carrying line	0,037	kg/m	5	years	Göran Nylund, Nordic Seafarm and https://www.swedishrope.se/?s=scanline
A2 buoys rope	0,062	kg/m	5	years	Göran Nylund, Nordic Seafarm
A0 buoys rope	0,028	kg/m	5	years	Göran Nylund, Nordic Seafarm

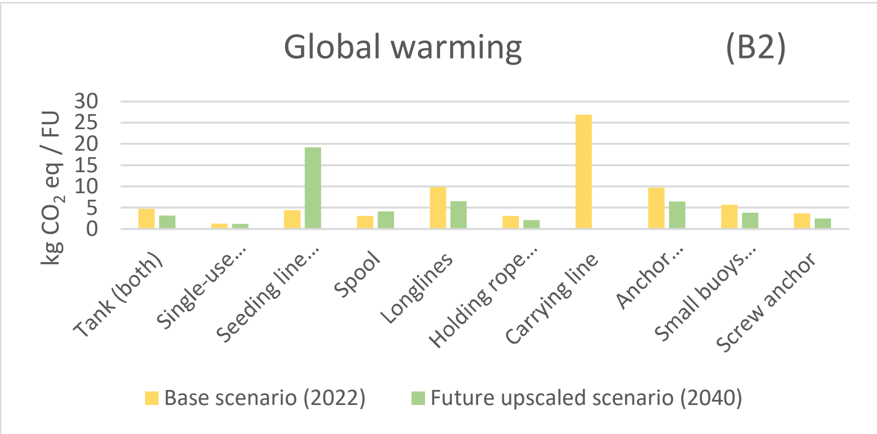
Anchor buoys (large)	25	kg/unit	10	years	Göran Nylund, Nordic Seafarm; https://www.nauticexpo.com/prod/doowin-underwater-lift-bags-water-weight-bags/product-196283-571970.html
Small buoys A2	2,1	kg/unit	5	years	Göran Nylund, Nordic Seafarm; https://polyform.no/inflatable-buoys-and-fenders/a-series/
Small buoys A0	0,6	kg/unit	5	years	Göran Nylund, Nordic Seafarm; https://polyform.no/inflatable-buoys-and-fenders/a-series/
Markers	20	kg/unit	5	years	Göran Nylund, Nordic Seafarm; https://www.rotationsplast.se/produkt/farledsprick-160-4-mumrik/

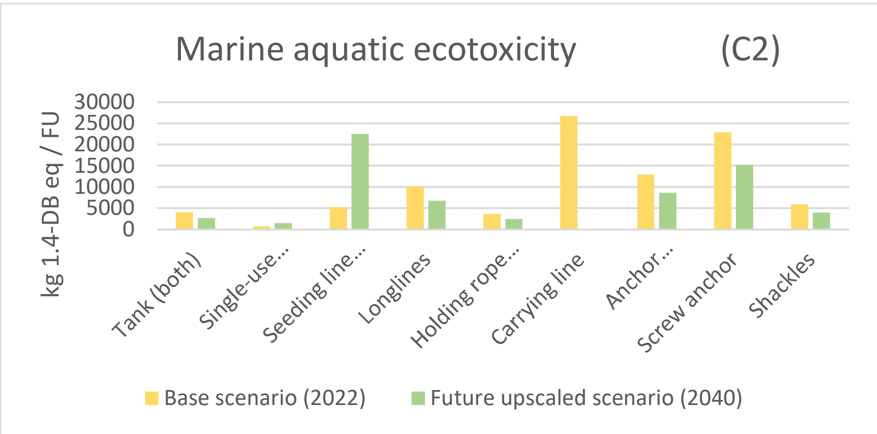
Screw anchors	10	kg/unit	10	years	Göran Nylund, Nordic Seafarm; https://www.carapax.se/marine-mooring; https://helixmooring.com/round-shaft-anchors/; https://ecputility.com/hta1-34square/
Shackles	1,3	kg/unit	5	years	Göran Nylund, Nordic Seafarm; https://www.ikh.se/sv/schackel-12-0t-sak120p?gclid=Cj0KCQiAmeKQBhDvARIsAHJ7mF7a4WT7mbKi2XaINNwbdfXsbQran84AzuBmnUMNRsnKtyekZmgNzo8aApJoEALw_wcB
Thimble	0,3	kg/unit	5	years	Göran Nylund, Nordic Seafarm; https://www.repbutiken.se/marina-tillbehor/kaus-tagvirkesbeslag/kaus-rostfritt-stal; https://www.skruvat.se/batdelar/Kaus-Galvaniserad-P231141.aspx; https://www.boatlab.se/om-boatlab/
Longline clip	0,01	kg/unit	5	years	Göran Nylund, Nordic Seafarrm; https://www.fehr.com/16mm-type-304-stainless-steel-wire-rope-clip-swrc625; https://www.repbutiken.se/marina-tillbehor/bygellas

Boat transportation	**Fuelt ype**	**Specification**	**Unit**	**Source**
Aluminium boat (outboard motor 150 hp) Regular speed	Gasoline	22,63	l/h	Göran Nylund, Nordic Seafarm; https://www.boat-fuel-economy.com/forbrukning-utombordare-mercury; https://www.mercurymarine.com/sv/se/engines/outboard/fourstroke/80-150-hp/
Harvesting boat (Nereus) Regular speed	Diesel	50	l/h	Göran Nylund, Nordic Seafarm; https://www.gu.se/tjarno/studera-och-arbeta/fartyg
Aluminium boat (outboard motor 150 hp) TOMGÅNG	Gasoline	1,33	l/h	Göran Nylund, Nordic Seafarm; https://www.boat-fuel-economy.com/forbrukning-utombordare-mercury; https://www.mercurymarine.com/sv/se/engines/outboard/fourstroke/80-150-hp/
Harvesting boat (Nereus) TOMGÅNG	Diesel	2	l/h	Göran Nylund, Nordic Seafarm; https://www.gu.se/tjarno/studera-och-arbeta/fartyg
Harvesting boat (Nereus) Unloaded Barge 150%	Diesel	74,97	l/h	Göran Nylund, Nordic Seafarm; https://www.gu.se/tjarno/studera-och-arbeta/fartyg
Harvesting boat (Nereus) Loaded Barge 200%	Diesel	99,96	l/h	Göran Nylund, Nordic Seafarm; https://www.gu.se/tjarno/studera-och-arbeta/fartyg
Harvesting boat (Nereus) Unloaded Barge 150% TOMGÅNG	Diesel	3	l/h	Göran Nylund, Nordic Seafarm; https://www.gu.se/tjarno/studera-och-arbeta/fartyg

Appendix II – Comparison between dominant components in the base scenario and the future upscaled scenario







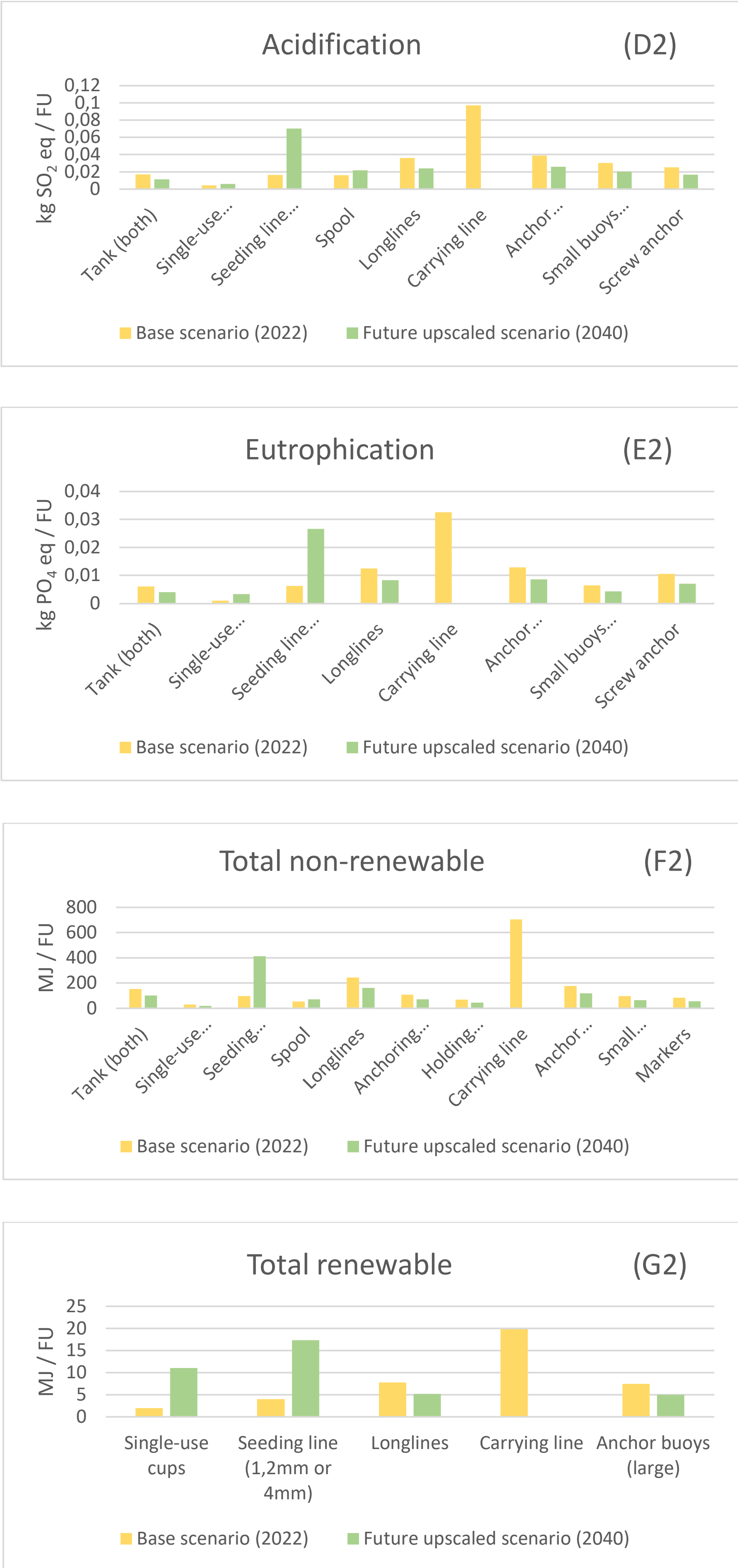
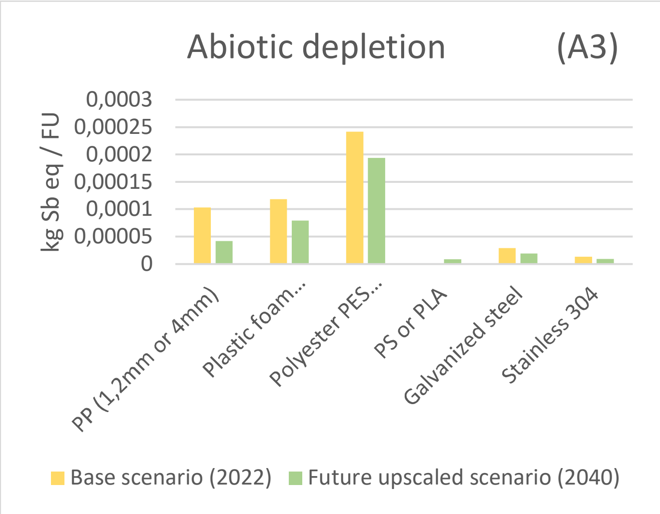
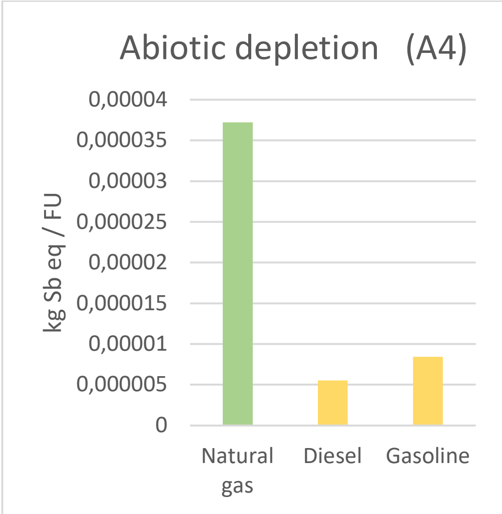
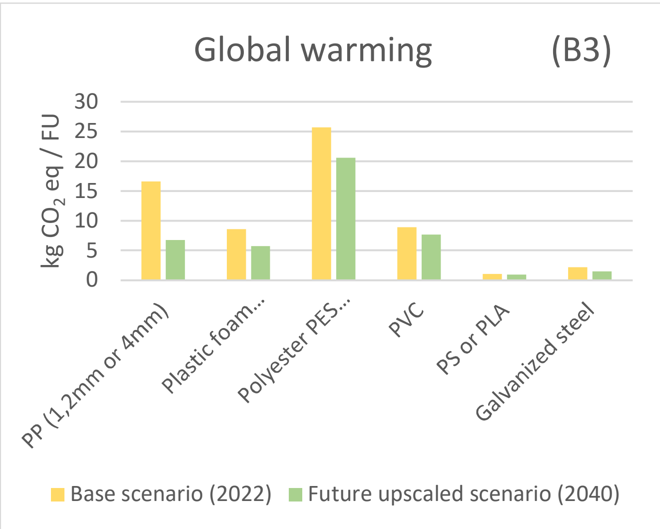


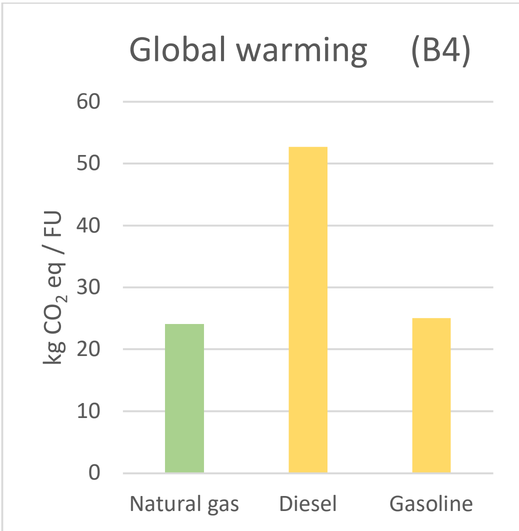
Figure 6 (A2-G2). Comparison between base scenario and future upscaled scenario of most dominant components in the production system for each chosen impact category.

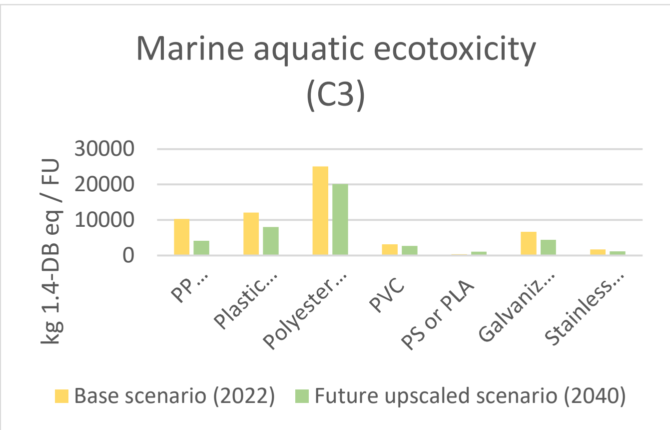
Appendix III - Comparison between dominant raw materials in the base scenario and the future upscaled scenario

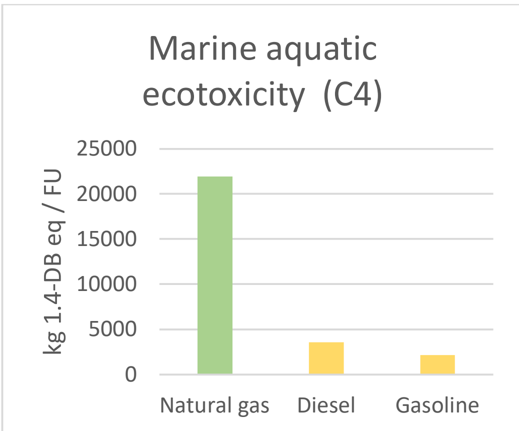












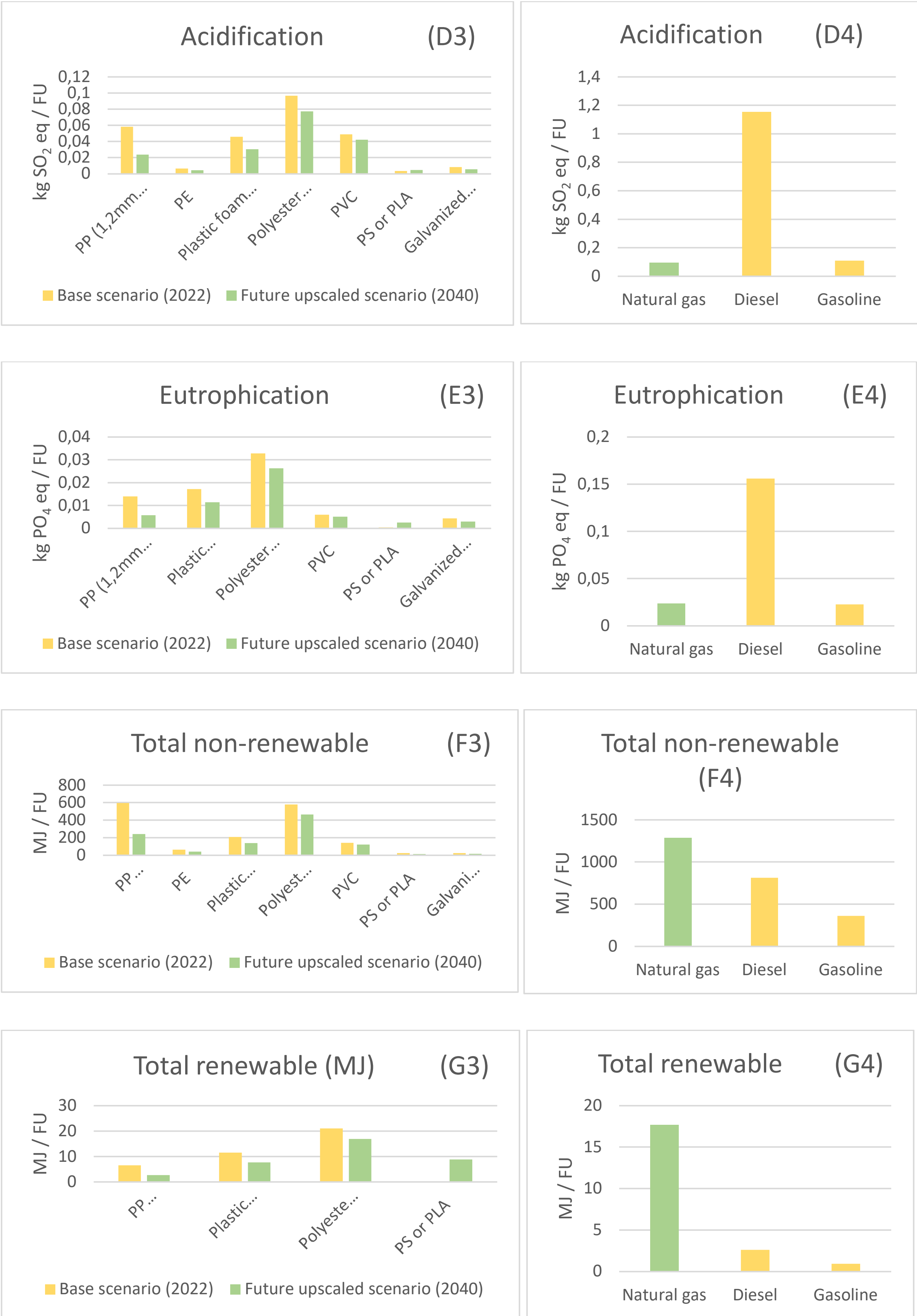


Figure 7 (A3-G3;A4-G4). Comparison of base scenario and future upscaled scenario regarding most dominant impacts of raw materials in each chosen impact category.

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