Agroecological Mariculture

A case study of seaweed farming in Denmark

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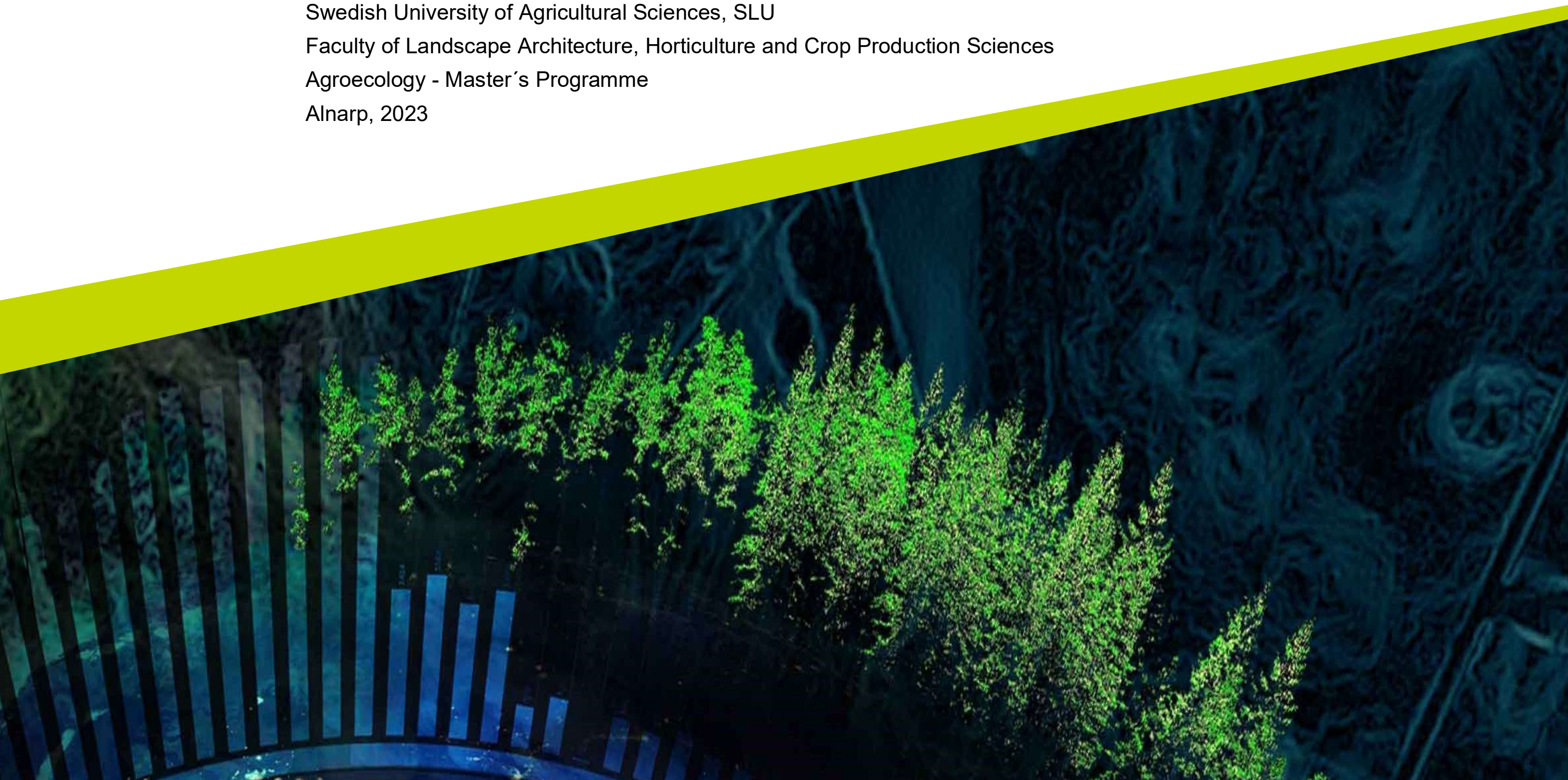

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Abstract

This thesis will seek to analyze the current state of seaweed farming in Denmark through an agroecological perspective. The focus is on the production systems and their challenges. Additionally, the future scenario for seaweed cultivation in Denmark and to what extent an increase is possible without compromising environment are discussed. To conduct this research, a farmer interview coupled with an overview of the history of seaweed production in Denmark have been performed. It was evident that seaweed agroecosystems are a new addition to the food system in Denmark. It occupies a very low market share, but with increased interest from consumers due to its environmentally friendliness and the health properties of the seaweed. The main challenges faced by the seaweed farmers are political and economic in nature. This new farming system, as well as the new food source, are not widely known amongst regulators and consumers, thus, infrastructure to support its development is lacking. It was also observed that while both the society and the farmers were in learning phase, the farmers still were confident in their ability and the future of seaweed in Denmark. The thesis found that it is most likely that seaweed cultivation will increase in both production and interest. The main reasons for this are the environmentally friendly production, the health properties of seaweed and increased interest in their bioactive compounds. Thus, the future of seaweed farming will ultimately be determined by the priorities of consumers, producers and politicians.

Keywords: Seaweed, Macroalgae, Seaweed farming, Agroecology, Aquaculture, Mariculture

Foreword

Agroecology is a very broad subject. It seeks to synthesize natural science, social science economy etc. It does not attempt this in the way that, say, the field of economy does, in which it tries to emulate the rules of natural science in a social scientific setting. Rather it attempts to create a scientific field that is open to a broad range of perspectives, ontologies and epistemologies. This is quite a big endeavour, and it has been something that has scared many of my fellow students away; the feeling of aimlessness of that often comes with open structures. But it has been a field in which I have felt right at home.

Coming from a political science background, studying agroecology has been an uneven experience. I spent the first semester and a half unsure what tilling meant and there were a lot of times I had to play catch up to understand what was being talked about. However, it has been rewarding to stick with it and to learn many things I would have missed if I had stuck to political science. It has also been a joy to work with other students from a broad range of cultural and educational backgrounds.

It feels natural that I should end up writing about aquaculture. Its an often-forgot aspect of the food system, and one that has the ability to do a ton of good or significant damage. When studying and gathering information for a project the size of a thesis, you need to triage your energy and information gathering. You often find avenues and issues that you have to put on the backburner to focus on your work. I hope now that when I finish my thesis that I can work in seaweed farming and aquaculture and build knowledge. And that it can help me in working in developing and steering aquaculture in Europe to be a force for the preservation of biodiversity and to fight global warming.

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Abbreviations

°C	Degrees Celsius
AI	Artificial Intelligence
CO_2	Carbon dioxide
Dkr	Danish Kroner
EU	European Union
Eq.	Equivalent/equivalence
FAO	United Nations Food and Agricultural Organization
g	Gram
HVBC	High-Value Bioactive Compounds
ha	Hectare
kg	Kilogram
L2L	Laboratory to line
LCA	Life cycle analysis
m	Meter
N	Nitrogen
P	Phosphorus
ppt	Parts per thousand
t	Ton
V2L	Vegetation to line

1. Introduction

By 2050, food production needs to increase to accommodate the growing global population with an estimated 35-58% (van Dijk et al., 2021). Simultaneously, the environmental impact from food production needs to be reduced significantly (Sala et al., 2017). This is going to require a restructuring of the whole food system including techniques, technology and distribution. One aspect that has met increased interest is the opportunities afforded by the ocean, and in particular: seaweed (Fleurence. 2016). Seaweed is an umbrella term for photosynthetic aquatic organisms. It has received significant interest lately due to its nutritional content, high-value bioactive compounds (HVBC) and its environmentally friendly production. Seaweed is seen by scientists as a great opportunity for dealing with the many crises of the current food system. However, in Europe, harvesting seaweed has been a miniscule industry and seaweed cultivation is a recent arrival in the European context. Both direct harvesting and cultivation of seaweed are currently rising, and significant research and analysis are therefore required (Campbell et al., 2019).

This thesis will analyze a seaweed agroecosystem in Denmark. This will be conducted through an analysis of the ecological and historical factors that has underpinned seaweed cultivation in Denmark. The thesis will also provide an analysis of the only major seaweed agroecosystem in Denmark.

1.1 Agroecology

The common approach to agroecology is that it is a science, a movement and practice. From the scientific side, the ontological approach is the analysis of the agroecosystem. An agroecosystem differs from naturally occurring ecosystems in that it is a system that directly requires human intervention for its survival (Gliessman, 2015). Naturally occurring ecosystems are a result of complex biotic and abiotic interactions stimulated by competition, symbiosis and evolution. Agroecosystems on the other hand are in many ways more complex as the people cultivating the systems are not just affected by these biotic and abiotic factors, but also human made systems such as culture, politics and economics.

1.1.1 Theoretical framework of agroecology

Gliessman defines agroecology as:

> Agroecology is the integration of research, education, action and change that brings sustainability to all parts of the food system: ecological, economic, and social... The approach is grounded in ecological thinking where a holistic, systems-level understanding of food system sustainability is required. (Gliessman, 2018: 599)

One of the central epistemologies of agroecology is systems-thinking, i.e., the focus is on the constituent parts of the systems and understanding how these parts interact to make up a system is the main focus. This is encapsulated with the agroecosystem as the unit of analysis. It is inclusive of different approaches and perspectives and in practice seeks to analyze food systems through a synthesis of the natural and the economic, political and social sciences (Gliessman, 2018).

Another aspect that makes agroecology unique is its ontological criticism of the industrial food system. Much research on agroecology has focused on the idea that agroecological methods are based on hundreds or even thousands of years of trial and error and information passed down between generations. As industrial methods of agriculture have depleted soil and currently are the source of much environmental destruction, revitalizing techniques that are built on the ecology and climate of the agroecosystem can reduce agriculture's role in the climate crisis. Thus, tackling the current climate crisis and global hunger requires reengaging with and reexamining these 'old' approaches to agriculture (Gliessman, 2015).

An aspect emphasized by Gliessman (2015: 27) is the border of what is external and internal to the agroecosystem. All human inputs are, by definition, external since they occur from outside of the system. This is both an important aspect to developing the boundary to the systems analysis and becomes more complex when analyzing a maricultural system.

Gliessman (2015) envisions a five levels-approach of transition from the current, industrial and corporate, food system to an agroecological one. This begins with improving efficiency and mitigating the damage from industrial food production. The second level involves substituting industrial practices with alternative agroecological ones. The third level involves redesigning the agroecosystem to be in line with its local ecology. The fourth is a stronger social link between the producers and consumers of food. The fifth and final level is a global food system based on the third and fourth level, i.e., a global food system of agroecologically and both socially and environmentally sustainably produced food.

Mariculture as agroecosystems

What makes the approach of agroecology to agroecosystems different from more literal views (i.e., with an emphasis on the *agro-* part of agroecosystems) is its emphasis on the agroecosystem being centered around food systems. This means that agroecology must include aquatic food systems and production as these forms an integral part of the current global food system as a whole and many local food systems as well.

1.2 Seaweed

Researching seaweed and its cultivation provides a unique challenge. Compared to agricultural research, seaweed cultivation is in a relative infancy, particularly in the west, with research having picked up steam in recent decades (van den burg et al., 2016; Seghetta et al., 2017; Nilsson et al., 2022; Yong et al., 2022). Many concepts within phycology, the study of algae, of which seaweed is a part of, are not agreed upon (Morais et al., 2020). The classification of the species of seaweed is therefore weaker than would be expected in agricultural research. Seaweed is an umbrella term encompassing thousands of different species with different taxonomies and even from different kingdoms. Much research uses the concept of seaweed, or macroalgae, as a generic term.

As will become clear below, the question of taxonomy is beyond the scope of this thesis. This section will, however, provide a brief overview of the biology and systematics of seaweed as a broad category. Seaweed, as well as the term macroalgae, is generally an informal term for several autotrophic organisms spanning two kingdoms. For pedagogical reasons, the term seaweed will be used as the generic term throughout this thesis.

1.2.1 Seaweed taxonomy

Seaweed is also known as macroalgae. Algae is broadly divided into two categories, macro- and micro algae. This distinction is based on the size, microalgae are single cellular and macroalgae are multicellular algae. Macroalgae subsequently have a large range of size that ranges up to over 50m (Biris-Dohoi et al., 2020). They constitute a vital part of coastal aquatic ecosystems (García-Posa et al., 2020).

Seaweed is divided up into three different taxonomic groups based on color: brown (*Phaeophyceae*), red (*Rhodophyceae*) and green (*Chlorophyceae*) (Biris-Dohoi et al., 2020). The category of seaweed spans two different kingdoms. Red and green seaweeds are part of the Plantae kingdom and brown seaweeds are part of the Chromista kingdom (Dawes, 2016). This taxonomy is not strict and there may be some deviation in color (Baweja et al., 2016, see also appendix 1). The taxonomy of seaweed is underdeveloped, some scholars claim that there is little taxonomic basis for this categorizing (Morais et al., 2020), however much research explicitly divides the attributes and bioactive compounds based on color (ibid).

Green seaweeds (Chlorophyceae)

Green seaweeds are the least common type of seaweed, but the most common type of microalgae. They get their color from having chlorophyll type ‘a’ and ‘b’, which is similar to plants found on land. There are about 6000 known species of green algae, both macro- and micro-, and only about 10% of these live in marine habitats, others live in terrestrial and freshwater habitats (Dawes, 2016). Green seaweed tends to dominate during high levels of eutrophication due to their high nutrient level tolerance (Baweja et al., 2016). An example of green seaweed which is popular in cuisine is *Ulva lactuca* (For examples, see Appendix 1).

Brown Seaweeds (Phaeophyceae)

Brown seaweeds are a more common seaweed than green seaweeds. There are fewer known species of brown seaweed, just over 3000. Unlike red and green seaweeds, brown seaweeds are not considered a part of the plantae kingdom, instead part of the chromista kingdom. Unlike green seaweeds, all known brown algae are seaweeds (i.e., macroalgae). Their brown color comes from the chlorophylls ‘a’, ‘c_1’ and ‘c_2’ with additional pigments that color its cells brown (Dawes, 2016).

Approximately 95% of brown seaweeds are found in marine environments. Most brown seaweeds are found in temperate to arctic or boreal waters, the larger species are more prevalent in tropic to subtropic regions (Dawes, 2016). Brown seaweeds are the largest group of seaweeds growing up to over 50m (Baweja et al., 2016). Examples of popular brown seaweeds eaten are *Fucus vesiculosus*. *Ectoparus siliculosus* is also interesting example as it is green in many cases and also a major biofouling species (For examples, see appendix 1).

Red Seaweeds (Rhodophyceae)

Red seaweeds are the oldest group with some fossil records suggesting that they may be up to 1.2 billion years old. Red seaweeds are also the most common type of seaweed. There are approximately 7000 different species of red seaweed and 97% live in marine ecosystems. The only chlorophyll found in red seaweeds are ‘a’ with other pigments creating the red color (Dawes, 2016). One of the pigments, phycobiliproteins, allow red seaweeds to grow in deep waters (Baweja et al., 2016). An example of red seaweeds is *Gracilaria vermiculophylla*, both as a popular edible seaweed and also a major invasive species (For examples, see appendix 1).

1.2.2 Seaweed biology

Marine flora is generally considered more primitive than land flora (Baweja et al., 2016). Algae lacks organs found in flowering plants such as true roots, stems, leaves and vascular tissue. Their cells are similar to plants with plastids, cell walls and vacuoles (Dawes, 2016). The lack of roots means that seaweed is reliant on continuous water motion for nutrient uptakes. This also means that seaweed faces a large degree of mechanical stress from the motion of the ocean. In order to cope with this, the stipes and blades of seaweed are strong and flexible (Baweja et al., 2016). Most seaweed reproduce sexually, although some, mostly red, reproduce asexually (Dawes, 2016). Seaweed can also be subjected to vegetative propagation (Baweja et al., 2016).

1.2.3 Seaweed ecology

Seaweed serves an important role for the ecology and biodiversity in marine ecosystems, in part. Seaweed generally serves as one of the most important biotic factors for other species (including other species of seaweed). They provide a source of food and hiding spots for many species and regulate nutrients and kinetic energy in their ecosystems. Seaweed has been described as the 'trees of the ocean' due to them serving the same functions as trees do on land (areas heavily populated by seaweed are often referred to as seaweed forests) (Baweja et al., 2016).

Seaweed grows in a variety of ways, most are lithophytic, i.e., attached to hard surfaces. Other forms of growth involve growing on other seaweeds or seagrass in a symbiotic relationship, other seaweeds grow in a parasitic relationship with other autotrophic aquatic species. Some seaweeds are able to attach themselves to softer surfaces such as mud and other grow free-floating in the ocean (Dawes, 2016).

Global warming has a significant effect on the ecology of seaweed. As the temperature of oceans increases, the ability for seaweed to thrive in certain areas changes. Similarly, increased CO_2 gets absorbed by the water, leading to acidification. This alters the ability for seaweed to survive in these areas (Baweja et al., 2016). Seaweed also has an increased ability to serve as invasive species. Invasive species are able to use pathways created by international trade amongst other ways that allow them to establish themselves in new areas. An example of this is *Gracilaria vermiculophylla* in Danish waters (Thompsen et al., 2007).

1.2.4 Seaweed and seagrass

A common misconception is that seaweed and seagrass are the same. An example for this can be seen with the fact that the Danish name for the seagrass genus *Zostera* was for many years call Bændeltang (tang being the Danish word for seaweed). This is also compounded by the fact that both seaweed and seagrass will emerge on beaches together in piles. Seagrass is, however, its own taxonomic group of flowering plants that grow on the seabed. Thus, in the absence of prior taxonomic knowledge, the difference between seaweed and seagrass is that seagrass has roots and thus grows rooted to the sea floor. This distinction is important when analyzing seaweed agroecosystems as seagrass has completely different uses and regulation and are in most cases a protected species (Orth et al., 2006)

1.3 Seaweed cultivation

Since the 20th century, seaweed has been cultivated. Seaweed has still primarily been cultivated in East and Southeast Asia and most of the world's seaweed supply still comes from this region. The largest producers in the world are China and Indonesia with Indonesia increasing its production more than five-fold between 2006 and 2015 (García-Posa et al., 2020). Like most other forms of cultivation for biomass, there is a wide variety of cultivation systems for seaweed. The type of system depends on climate, resource and capital availability, region and species amongst other things. Seaweed can both be grown off-shore and on-shore and these techniques differ in both inputs and outputs (Garcia-Posa et al., 2020).

1.3.1 On-shore cultivation

On-shore techniques can both be done in tanks or inland bodies of water such as ponds and lagoons. On-shore techniques have the benefit that the seaweed is grown in a controlled environment and therefore nutrients, temperature and sunlight can be controlled to give the crop the optimal environment. Similarly, inputs can be added to the seaweed without (or with less) disturbance of the biological balance, particularly in tanks where the producer has control over where the wastewater and its nutrients end up (Garcia-Posa et al., 2020).

This, however, requires the producer to manually add the needed inputs making this technique significantly more resource intensive. One possible solution to the input issue has been proposed by Stedt et al. (2022), they found in small-scale experiments that seaweeds of the varieties *Ulva fenestrate, Ulva intestinalis* and *Chaetomorpha linum* could be effectively grown in food processing waters. The experiment found that the seaweed grown in food processing waters had 5 times the protein content as the control grown in sea water. This opens up an avenue for a circular economy and even aids in dealing with food processing waters, an issue that has been a source of pollution from food processing.

Another potential issue with on-shore techniques is that it fails to live up to one of the advantages of off-shore techniques, namely land use. On-shore production of seaweed requires an inland body of water or a tank. It thus rarely competes directly with agriculture and some research have even shown that it can be intercropped with agricultural production (Aubin and Jerome, 2018). However, as will be discussed below, on-shore cultivation still fails to provide the significant benefit of increasing the area and therefore the production of biomass that off-shore seaweed methods provides.

1.3.2 Off-shore cultivation

Off-shore techniques refer to cultivating seaweed in the crop's natural habitat, or a habitat that the crop can naturally grow in. Like on-shore techniques, it has its own advantages and disadvantages when it comes to cultivating. The main disadvantage is that the producer has much less control of inputs, and which crops to produce (Phillips, 2009). This can also be considered an advantage through bioremediation as will be discussed below. Adding nutrients to offshore seaweed farming is a rare occurrence and in most cases the seaweed is grown using the nutrients naturally (or from eutrophication) occurring by the coast (Charrier et al., 2017). In Asian countries, such as Japan, seaweed farming is often handled by fishermen organizations. Due to its recent development, seaweed farming in Europe is usually handled by new aquaculture-centric companies and organizations (Delaney et al., 2016).

Pollution serves as an important factor and has an impact on where seaweed can be grown and for what purpose it is grown. Depending on the area cultivated, the water can be too polluted to make edible crops, though still eaten if the regulatory framework is too weak. This is a particular issue when it comes to heavy metals (Phillips, 1990).

Other issues with offshore production are the labor requirements needed to produce seaweed. Dependent on the distance from the coast, the depth and the climate, boats are increasingly needed and getting around the area of cultivation takes more time and effort than in agricultural production (Marín et al., 2019). Biofouling is also an issue which requires treatment and therefore labor and/or inputs. Two treatment options for fouling today are either exposing the seaweed to air, killing the fouling organisms or using organic acids while the crop is still growing on the lines (García-Posa et al., 2020). Similar issues are found in other forms of aquaculture such as shellfish production with similar treatment options (Sievers et al., 2019)

Many issues of seaweed production also pose an opportunity. As will be discussed in more detail below, seaweed can be used to mitigate climate and environmental issues posed by agriculture. One of the opportunities often posed by off-shore seaweed production is carbon sequestration. Seaweed cultivation can be produced with no inputs. It thus has the ability to take up carbon from the atmosphere and is a useful source of carbon sequestration (Seghetta et al., 2017).

Seaweed can also be used in bioremediation for eutrophication. Seaweed grown near areas with intensive agriculture can use the nutrients that leak from it. This both provides a use for seaweed as a source for biosorption, but also allow seaweed farmers to grow their crops without the need for any nutritional inputs. Some research suggests that nutritional run-off from other aquaculture activities such as salmon farming can be used as fertilizer in seaweed cultivation if a seaweed farm is placed in its proximity (Xinxin et al., 2014). In a life cycle analysis of various scenarios focusing on production of seaweed for the use as biofuel feedstock or fish feed, Seghetta et al. (2017) estimated a decrease of 13.6-43.4 of Kilogram (kg) nitrogen (N) equivalence (eq). and a decrease of 1.5-6.7 kg phosphorous (P) eq per hectare (ha) on a 208km^2 seaweed farm.

In addition, off-shore seaweed production can be used as a bioremediation of heavy metals in the ocean. Some seaweed species such as *Ulva* sp. are able to accumulate heavy metals, removing them from the ocean (García-Posa et al., 2020). This comes with trade-offs as seaweed used to accumulate heavy metals and other toxic compounds cannot be used for human consumption.

Offshore seaweed also has the advantage of not competing with agriculture for land. Since seaweed is grown in the ocean it provides an opportunity to significantly increase the area of land available for the production of biomass, for use of food and otherwise (Charrier et al., 2017).

Although many scholars have lauded the environmental advantages of offshore seaweed cultivation, it is not completely free of negative environmental impact. Campbell et al. (2019), focusing on production in Scotland, identified several possible environmental impacts from seaweed, mainly impacting marine biodiversity. These impacts involve attracting invasive species and taking up light from plants below the surface. However, due to the small-scale seaweed cultivated in Europe, many of these concerns are theoretical. Their biggest finding was the knowledge gap of the environmental risk from large seaweed farms. Research in China, with a much larger seaweed farming industry, has found that the biggest environmental impact from seaweed is the use of fossil fuels primarily used in boats required in the cultivation (Marín et al., 2019).

1.4 Wild harvesting of seaweed

While seaweed cultivation systems are increasing their presence in Europe, the majority of seaweed is still harvested from wild stocks, as much as 95% in 2016. Harvesting of wild seaweed has the advantage over cultivation that species considered invasive can be harvested, which are banned for cultivation. This might even be encouraged to reduce stocks (Fleurence, 2016).

The harvesting of wild seaweed has two general techniques, manual or mechanical (Delaney et al., 2016). Mechanical seaweed harvest began in Europe in the 1970's to meet the demands of seaweed for alginate production. These harvesting techniques are primarily done in Norway and France. This technique is done with special equipment from a boat and the largest seaweed harvesting boats can harvest up to 70 t daily (ibid). Mechanical seaweed harvesting is done with specialized equipment which dredge the ocean floor, this has the potential to destroy the local ecologies through overharvesting (Mac Monagail et al., 2017).

Manual harvesting is also still an important source of seaweed in many European countries. Seaweed can manually be harvested as beached seaweed, or in the water.

In some countries, seaweed is being manually harvested by divers. This is a popular mode of harvesting in South Korea and South Korean divers sometimes work as foreign laborers in countries such as Japan and Russia. These divers are usually women. The manual harvesting of seaweed is often timed alongside the tides, with low tides being optimal for gathering seaweed. Several tools are used when harvesting such as knives, pitchforks and nets (Delaney, et al., 2016).

1.5 Uses of seaweed

Seaweed has historically been used for food and feed, being easily available near coastal areas (Morais et al., 2020). As time has progressed, scholars and industries have looked at the myriad of possibilities in seaweed from the vast amount of nutrients and bioactive compounds. Today there are many uses for seaweed. This ranges from the production of biofuel, biomaterial, feed, food (both used in food processing and eaten directly), cosmetics, pharmaceuticals, treatment of water and carbon sequestration amongst other uses (Biris-Dohoi et al., 2020).

1.5.1 Food

Seaweed has been part of human diets for all of recorded history in coastal regions. It is a foodstuff with a broad nutritional profile. In Asia, seaweed has been eaten quite regularly, this has been partly popularized in the Global North through seaweed used in sushi, particularly the kelp *Undaria pinnatifida* (wakame). The most common types of seaweed eaten are brown, often kelp, and red types, although green seaweeds are also eaten (Fleurence, 2016).

In Asia seaweed is eaten much more regularly, the average daily intake of seaweed in Japan, for example, is estimated to be between 4-8g (dry weight). When eaten directly, seaweed is a popular ingredient in salads and soups or eaten as a nutritional supplement (Fleurence, 2016). In Europe, seaweed is not considered a traditional food even though some traditional foods contain seaweed, such as in Ireland (ibid). Seaweed is either eaten directly or its compounds are used as additives in food processing. The most common use has been its use in food processing, as additives to give the food texture (Biris-Dorhoi et al., 2020) and serving as food dyes (Pereira et al., 2014). Seaweed as a source of proteins have garnered research as a source of vegetarian proteins (Stedt et al., 2022).

The most common derived substance from seaweed used in the food industry is alginate. Alginate is used as thickening and gelling agents in different foods, for example desserts and ice cream (Delaney et al., 2016). Alginates are classified in the European Union (EU) as E401 and E405. Other food processing ingredients derived from seaweed are carrageenans and agar. Carrageenans are used as a thickening substance in different sauces and gels amongst other foods and its EU additive nomenclature is E407. Agar has the properties of being insoluble in cold water and soluble in hot water and is used in food products such as canned meats and pie fillings. Its EU additive nomenclature is E406 (Fleurence, 2016).

Nutritional profile of seaweed

The nutritional profile of seaweed differs between the different species. The biggest variation seems to be its protein content with brown seaweeds having the lowest content and red seaweeds having the highest content. However, a high level of several nutrients, including vitamins, minerals such as calcium and magnesium and fiber, are seen in many types of seaweed. Lipid contents are also very low for most types of seaweed and seaweeds are generally considered a low-calorie food (Fleurence, 2016).

The largest component of the biomass of seaweed is fibers, and it therefore serves as a healthy source of dietary fibers. Other nutrients beneficial for human health include ions and antioxidants. A seaweed rich diet has been linked to increasing cardiovascular and gastrointestinal health and reducing many chronic illnesses such as obesity. Other research has suggested that seaweed also has a positive effect on the gut flora. Certain bioactive compounds present in seaweed are being investigated for their potential in slowing the development in neurological conditions such as Alzheimer's and anxiety amongst others (Déléris et al., 2016).

The country currently eating the most seaweed in the world is Japan. The primary species eaten in Japan is *Laminaria japonica*, *Undaria pinnatifida*, *Hizikia fusiforme*, *Porphyra tenera* and *Nemacystus decipiens*. This diet is believed by some researchers to have reduced several chronic diseases such as cancers. This has been supported by incidences such as an increase in certain cancers for Japanese emigrants to the United States as well as an increase following the westernization of Japanese diets. This has led to research looking to identify the anti-cancer bioactive compounds in seaweed. Some of the suggested compounds are carrageenans, laminarin and alginate amongst other (Déléris, et al., 2016).

According to the United Nations Food and Agriculture Organization (FAO), one of the most nutritional seaweeds is *Porphyra* spp., eg, *Porphyra tenera*, *Porphyra pseudolinearis* and *Porphyra yezoensis*, all colloquially known as nori. These seaweed species have a large amount of protein content, 30-50% with 75% of this content being digestible, low sugar content and a high content of various vitamins including A, B_1, B_2, B_6, B_{12}, C, niacin and folic acid. Accordingly, these seaweed species also compose a large amount of the diet in Japan (Delaney et al, 2016).

Toxic and harmful substances in seaweed

The ability of seaweed to absorb various harmful substances has created some concern of the possible negative health effects of seaweed. Heavy metals such as cadmium, lead, mercury, copper, zinc and arsenic are known to be absorbed by several seaweeds in high concentrations. Other health concerns are the high amount of iodine present in seaweeds such as kelp, this can help people with an iodine deficiency, but for other people this can create an iodine overdose. Due to the difference in the biology of different seaweed species and even the same species grown in different areas, it is not possible to give an exact number of how much seaweed has to be consumed before it becomes dangerous (Cheney, 2016).

Carrageenan, the extract used in food products for its gelling properties have also been the subject of controversy. Some studies in the early 1960's pointed to carrageenan as being related to several gastrointestinal illnesses such as ulcerations and cancer. Newer studies have pointed to this being caused by degraded carrageenan as opposed to undegraded carrageenan. While undegraded carrageenan is generally considered safe under EU and the United States, degraded carrageenan is banned by both organizations. Undegraded carrageenan is also banned for the use in baby formulas by the EU (Cheney, 2016).

Feed

Much research has gone into the use of seaweed as feed for animals. Particularly the protein content of seaweed has been met with interest as much of the protein in feed is coming from soy and maize, which has to be imported from the American continents in the EU. The opportunity of replacing soy-proteins with seaweed-proteins has the potential to significantly reduce as the climate impact of animal production, the sector of the food industry which is the most polluting (Morais et al., 2020).

Not all animals are created equal when it comes to seaweed. For ruminants, seaweed is seen as a very opportune source of feed. Some research has shown that feeding cows with the red seaweed *Asparagopsis armata* reduces the methane production in their stomach. Seaweed has also been researched as a replacement for fish meal in fish aquaculture. However, for swine, the high mineral content in seaweed does not allow for it to be a significant part of the diet. It is recommended that feed contain a maximum of 10% seaweed without seeing adverse effects from it, although it depends on the species used in the feed (Morais et al., 2020). Some research is looking at the refining of seaweed, extracting its proteins from its mineral content which has the opportunity to increase the use of seaweed proteins in animal feed. This, however, is still at the theoretical stage (Nilsson et al., 2022).

1.5.2 Other, future and industrial uses for seaweed

The myriad of bioactive compounds has made seaweed an attractive prospect for several industries. Currently seaweed is used in a large number of different industries including pharmaceutical, cosmological, and industrial, with researchers looking with increased interest into the possibilities of seaweed afforded by the high amount of HVBCs.

Biofuels is a topic that has picked up steam in the last couple of decades. Spurred by the need for green and renewable energy, using crops to produce ethanol, biogas and biodiesel has been met with significant interest (Fernand et al., 2017). Ethanol and biogas are relatively simple to produce and can be produced on a farm for its own consumption through anaerobic digestion and fermentation. Biodiesel requires more processing and requires a dedicated processing facility (ibid). Seaweed contains a relatively low amount of lipids and has therefore not garnered considerable attention as a source of biodiesel compared to more lipid-rich microalgae. However, much attention is paid to seaweed for biogas and ethanol due to its low impact on the environment (Nagula, et al., 2022). Some seaweed species such as *Enteromorpha compressa* have found a relative success as a source of biodiesel (Suganya et al., 2013).

Similar to the food industry, alginate derived from kelp are used in several pharmaceutical applications, including wound dressing and binding agents for tablets (Delnaey et al., 2016). Alginate has also been used as an active ingredient to as an appetite suppressor and laxative (Vonthron-Sénécheau, 2016). One of the primary issues of seaweed in pharmacology is the fact that most bioactive compounds used have been primary metabolites. Researchers believe that there is potential also in secondary metabolites. Possible uses of seaweed secondary metabolites could be as antimicrobial and antiparasitic compounds (Vonthron-Sénécheau, 2016). Similar bioactive compounds also provide an opportunity for their use in cosmetics and extracts of *Laminaria* are popular to use in moisturizers (Couteau and Coiffard, 2016). In addition, many kelp species are also used in slimming products due to their high iodine content (ibid).

Seaweed has historically been used for fertilizer near coastal regions before the onset of industrial fertilizer (Delaney et al, 2016). In addition, much recent research has been done on seaweed as a biostimulant. Several compounds from seaweed extracts have been found to aid in the taking up nutrients among other factors, this is particularly useful under abiotic stress where nutrients or water are scarce (El Boukhari et al., 2020).

The fact that offshore seaweed cultivation can be performed with no inputs in terms of fertilizer and biocides means that it usually provides a net decrease of atmospheric CO_2 (Zheng et al., 2019). Similarly, due to the lack of fertilizer used in seaweed cultivation, it is able to accumulate nutrients leaking from agriculture, leading to a reduction of eutrophication (ibid). This also gives seaweed a further secondary economic function as it serves as ecosystem services for many fishing, aquatic harvesting and maricultural industries (Sunny, 2017).

Currently several issues are faced by the seaweed industry in Europe. One is the price of transport since the wet material of seaweed provides extra weight and subsequently extra costs. A second is a lack of raw materials that are able to be produced and/or harvested in Europe. Thus, a large amount of seaweed is currently being imported from outside of Europe (Delaney et al., 2016).

Hafting et al., (2015) argues that current cultivation techniques may not be suitable for the more high-value aspects of seaweed. They suggest that genetic engineering is an opportunity for the future of seaweed cultivation to increase the extraction of HVBC's. Hafting et al. (ibid) argue that much of the current research on the extraction of various bioactive compounds in seaweed is driven more by research than consumer-demand.

2. Objectives

The objective of this thesis is to analyze in detail a seaweed agroecosystem in Denmark. Most research in seaweed mariculture, the cultivation of marine organisms, has focused on the effectivizing the cultivation system (Boderskov et al., 2023; Stedt et al., 2022; Boderskov et al., 2021), its potential as a source of nutrients, feed etc. (Xueqian et al., 2022; Biris-Dohoi et al., 2020; El Boukhari et al., 2020; Morais et al., 2020), and its potential harms and benefits for the environment (Forbes et al, 2022; Yong et al., 2022; Garcia-Poza et al., 2020; Campbell et al., 2019; Bruhn et al., 2016; Hafting et al., 2015; Marinho et al., 2015).

These are all valuable research goals for understanding and improving seaweed mariculture, however, in order to improve and make seaweed farming sustainable, both environmentally and economically, seaweed farming need to be approached with a systems theory lens. Agroecology and its methodology allow for such an approach. In that frame, the study of the mariculture of seaweed in Denmark provides a useful approach in understanding how agroecosystems form and how they can be developed sustainably. As seaweed farming in Denmark is a relatively new type of farming in Denmark, we get to see the trials and errors in action.

This is paired with the fact that our understanding of biology and phycology is much more sophisticated than our predecessors and can therefore direct our trials. In a trial-and-error development, enhanced communication between farmers, scientists and industries can make the sustainable development of seaweed farming more rapid as both successes and errors are shared. Understanding seaweed farming in Denmark does not only provide an insight into an avenue of increasing our food production, but also how agroecosystems develop.

Based on the objectives outlined this thesis will work with these research questions:

- What are the current seaweed agroecosystems in Denmark?
- What challenges are faced by seaweed farmers and what techniques are used to meet these challenges?
- What is future scenario for seaweed cultivation in Denmark and which increase is possible without compromising environment?

3. Methods

3.1 Agroecological methodology

The interdisciplinary systems approach to analyzing the agroecosystem developed for the field of agroecology requires a method that can facilitate it. The primary method in this thesis will be a farmer interview adapted to the unique challenges that arise in mariculture. In this case, seaweed is able to provide a unique insight into the development of an agroecosystem, however the nature of seaweed does provide some specific methodological issues discussed below. this thesis will approach the farmer's operation as an agroecosystem to represent its part in food systems and thus agroecosystems, unless the fact that it is a maritime agroecosystem need to be emphasized in which it will be referred to as an mari-agroecosystem.

3.2 Overview of the seaweed harvesting in Denmark

The first part of the research will focus on providing an overview of seaweed in Denmark. This section will provide an overview of the environment, species, and history of seaweed farming that make up the current Danish situation for seaweed. The data for this section will primarily be based on reports and scientific literature. Denmark has fairly advanced ocean monitoring systems and several research programs as well as an increased interest in seaweed cultivation. The overview will be supplemented with data from the interviews. Data from the interview will mostly be focused on the social, historical and economic aspects of the overview. Incongruities found between the interviews and scientific literature and reports will be discussed in the discussion.

3.3 Interviews

The primary method of this thesis will be based on semi-structured interviews of seaweed farmers in northern Sjælland, Denmark. Gliessman (2000: 267) argues that interviews are a central aspect of understanding an agroecosystem. Farmers have the most complete knowledge of the agroecosystem in question, and they are therefore an invaluable source of information. Since agroecology focuses on the agroecosystem as its primary unit of analysis, the people who work with the agroecosystem have invaluable knowledge about it.

It is important to remember that farming is an economic activity, while many farmers are engaged in farming for reasons that go beyond profit, they must still earn their keep and the farm must therefore be economically viable. That is a second reason for why farmer interviews provide valuable insight into the methods of cultivation and techniques that affect the agroecosystem. This also provides a useful avenue of analysis into the agroecosystem as what the farmer may want and what they need to do to stay afloat may contradict.

Semi-structured interviews are the most useful style of interview when conducting a small-n analysis. The loose structure has the advantage over structured interview by allowing the researcher to focus on topics of interest, while being able to delve deeper into issues that might occur during the interview. It also provides a more natural environment for the interviewee, allowing them to speak more freely and feel less interrogated.

One important question of interviews is the question of bias. The researcher inevitably carries with them a set of values which they must set aside when conducting the interview. This is more an issue in the question of political science in which the question of values is in the center (Halperin and Heath, 2017). However, agroecology's interdisciplinary and particularly normative ontology and epistemology can create pitfalls when interviewing.

Interviewing a farmer with a different world view can create an antagonistic relationship as the interviewer's questions, facial expression or body language can betray their opposite views. Similarly, being too sympathetic can also reduce the quality of the interview, due to a failure in asking probing or critical questions. While there is no panacea in tackling these issues, it must be kept in mind when doing interviews so that the interview can provide the highest quality data.

3.4 Farmer interview

The farmers were first met in February of 2023 for an informal meeting tour of their seeding and drying facility. Based on this meeting and on previous literature a set of semi-structured interviews were prepared that focused on the views of the farmers in terms of plans, aspirations and economics and another set based on the biological factors and technical developments. The first interview was conducted on the 09/03/2023 based on the availability of the farmer. A tour of their planting process and harvesting process was also made for pictures and for a direct experience of the process. The second interview was conducted the 18/04/2023. Additional correspondence was conducted through email and phone for details and clarifications.

Gliessman (2000) provides some key areas that must be investigated in order to get an understanding of the agroecosystem and the effects both to and from the farmer:

- Pest management; Maintenance of soil health; organic matter management
- Cultivation; Weed management; use of "good weeds"
- Cover cropping; use of fallow cycle
- Crop combining; polyculture
- Farm diversity; integration with natural vegetation
- Use of animals
- Erosion control
- Use of energy
- Soil moisture management and irrigation
- Use of trees and other perennials
- Connection with the local community
- Marketing; economics of the farming enterprise (ibid: 270)

This has served as the primary foundation for the interview questions with some modifications since mariculture is a different system than agricultural systems.

Questions such as soil health, while paramount in agricultural systems, are not important in mariculture, particularly seaweed which gains its nutrients from the ocean's body of water. However, it does become valuable to research the health of the ocean's body of water which can be considered the 'soil' of the seaweed. Cover cropping and fallow cycle are also not important aspects of mariculture due to the way that mariculture is conducted, similarly is the question of erosion control. Soil moisture and irrigation are not particularly interesting topics to cover in the cultivation of aquatic plants, since it safe to assume that they got enough moisture.

The scarcity of seaweed cultivation in Denmark can be seen by the fact that the interviewers chosen are the only major farmers of seaweed in Denmark. While there are other companies in Denmark that harvests wild seaweed and many clubs and counties grow seaweed for carbon sequestration, eutrophication control or for sea gardens, the researched company are the only in Denmark that cultivates seaweed as a significant economic activity (Information based on interviews).

The interview document is available in appendix 2 and appendix 3 respectively for the first interview and the second one. These are both presented in both English and Danish. The transcribed interview is not added to the document due to the protection of the farmer's privacy. The interviews were all conducted in the farmers' and interviewer's native language of Danish. The interview was translated in situations where translation was appropriate such as direct quotes from farmer, the quote in their original language can likewise be found in their respective appendixes.

Description of the 'farmers'

Throughout this thesis the producers of seaweed and the interviewees will be referred to as the farmer or farmers for pedagogical purposes and for clarity. During the interviews the farmers had an ambivalent feeling about their relationship to agriculture in Denmark (this will be discussed in the next chapter in detail), and what they should call themselves was not entirely clear, but they did call themselves that in the absence of a better word, i.e., the Danish word for seaweed farmer (*tangbonde*). This will be discussed in greater detail in the discussion.

4. Results

This chapter will focus on the results of the investigation. It will begin with presenting the current climate for seaweed in Denmark, both economically, socially and environmentally. This will be followed by a presentation and analysis of the farmers and their agroecosystem.

4.1 Marine ecosystems and seaweed in Denmark

This section will discuss the state of seaweed in Denmark and the environmental and biological factors that has affected its populations. Denmark is an archipelago in which approximately 71% of the country is ocean. The ocean area of Denmark covers 10,500 ha (Kystdirektoratet, 2015). Marine activities have subsequently been an important aspect of the Danish economy and life since humans first settled on the archipelago. While seaweed has not been a significant source of economic activity in the country, many activities has affected seaweed and its ecosystems near the Danish coast: Some major effects on seaweed has been eutrophication, fishing, stone fishing and global warming.

Denmark's geographical location means that it has a large variety in its marine environment. This is due to Denmark being the transition zone of the Baltic Sea and North Sea. There are subsequently a large variety of differences in the factors that make up the biome such as salinity, clearness of the water and nutrients in Danish waters despite the modest size of its area (Boderskov et al., 2023).

Seaweed is an important component in the ecosystems and biodiversity in the ocean. The plants provide both food and cover for a large variety of fish, benthal and mammal species in the ocean. Seaweed is a photosynthetic organism and therefore requires enough light to survive. In the less clear waters of Denmark, seaweed is most comfortable at less than 10m depth (Helmig et al., 2020).

4.1.1 Eutrophication and seaweed in Denmark.

One of the major consequences of Danish agriculture has been a high degree of eutrophication in the Danish marine environment which has led to a fraught environment for naturally growing seaweed as much of the nutrients leaked from agriculture is taken up by microalgae, creating a layer that blocks out the light for seaweed. The Danish landmass is also developed from soil moved during the moraine ice age. This means that the flat, wet and mountain free Danish landscape has been conducive to agriculture. Throughout the history of Denmark, the country has had a strong agricultural output. This has become part of the county’s identity and has become a politically fraught subject, particularly in recent years (Landbrugsavisen, 2022).

As can be seen in figure 1, most of Denmark’s coasts have a ecological rating that ranges from poor to moderate with only small parts of the southern islands being considered good and no excellent ecological conditions are present throughout the country.

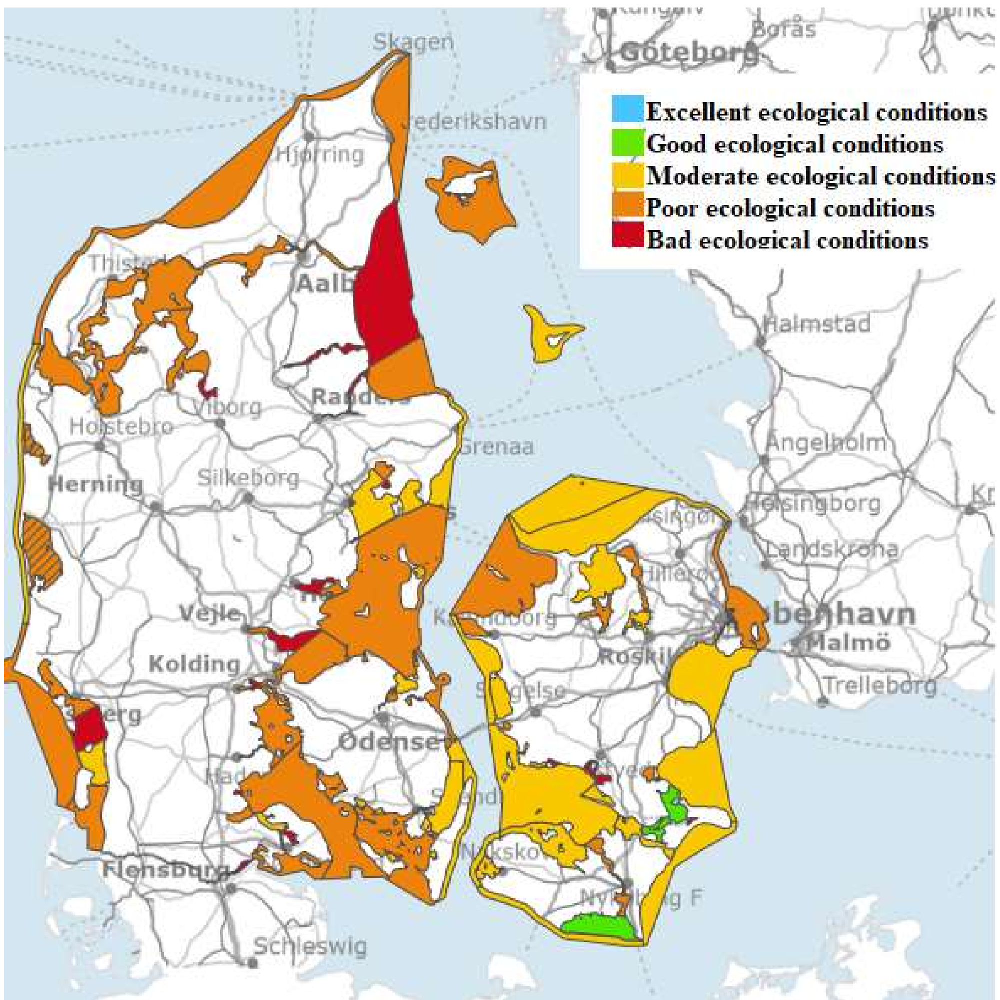

Figure 1: Map of Denmark, excluding Bornholm and its autonomous areas, showing the overall color graded ecological conditions of coastal regions in 2016. Note: The exact parameters are not available for this map, but it entails parameters such as eelgrass, chlorophyl and ocean floor fauna. The ecological conditions are thus not purely from eutrophication, but it has played a significant part in it. Developed from Miljøministeriet (2016).

This has however also produced a conducive environment for cultivated seaweed as they can be produced near the surface of the water and therefore have a better chance at competing with microalgae. Between the 1990 and 2010 there was a decrease in the leakage of nutrients in the Danish oceans. This development unfortunately reversed in the 2010's and there has since been an increase of eutrophication since (Bendtsen et al., 2020).

The most exposed areas to eutrophication are the many fjords of Denmark. The fjords of Denmark are often surrounded by agriculture and due to its geography nutrients has little chance of escaping compared to more open bodies of water. The most exposed fjord for eutrophication is Limfjorden in the Jylland peninsula which receives approximately 8.2 t N and 0.3 t P per year (Bruhn et al., 2016). One limiting factor of growing seaweed in Danish eutrophicated water is that sewage treatment limits the leakage of P compared to N, reducing the growth of seaweed (ibid).

4.1.2 Stone reefs

Understanding the state of seaweed in Denmark is impossible without understanding the impact that stone fishing has had on the Danish marine ecology. Stone fishing is the activity of fishing stones from stone reefs on the ocean floor. Stones in ocean floor provide a necessary ecosystems service. Seaweed does not have roots, instead, many species attach themselves to surfaces that allow them to accumulate nutrients in the water. Seaweed cannot therefore grow directly on the sandy bottom of the sea as this would not allow the plant to stay sedentary. The most favorable environment for seaweed is therefore the stone reef. In Denmark, stone reefs are classified as reefs in which the ocean floor is covered by more than 10% by stones larger than 20mm (Helmig et al., 2020).

These reefs are a favorable environment for seaweed as the current in Denmark is no longer able to move the stones in significant ways, allowing the seaweed hard surfaces which are sedentary. There has been a lack of research on the effect of stone reefs and stone fishing in Denmark, but gross estimates put the loss in seaweed biomass to be 14.980-15.790 tons, this however is believed to be a conservative estimate (Helmig et al., 2020).

Danish waters have been a popular area for stone fishing, depleting a large part of the Danish stone reefs. The stone has been used for wave breakers and to make harbors. Stone fishing in Denmark was heavily regulated in 1998 and was outright forbidden in 2009. However stone fishing was active since the 19th century and large amounts of stone reefs have been depleted or thinned out. Stone reefs are considered a non-renewable recourse as these stones were moved in the Weichel ice-age and the current is no longer strong enough to produce stone reefs (Helmig et al., 2020).

The most common depth for stone fishing in Denmark was approximately 4-7m. This was done because of convenience to accommodate the heavy stones. This is problematic because this is also the depth that is most optimal for the growth of seaweed due to lighting. Stone fishing is approximated to have removed more than 8.2 million m^3 of stone in Denmark throughout the 20th century, which is approximated to be more 82 million stones. There have been projects to restore stone reefs by the Danish coast, but these have so far been relatively small scale compared to what has been removed and only around 1.4 % of the lost reefs has been restored (Helmig et al., 2020).

4.1.3 Global warming and invasive species

One of the significant impacts of global warming is the introduction of invasive species to the Danish marine ecology. Invasive species are introduced in to Danish, and European waters due to a variety of factors such as global warming and international trade. Invasive species can have a series of possible detrimental effects on the ecosystem it invades such as changes to habitats, this can even lead to the loss of species. As of 2014, 77 invasive species have been recorded in Danish waters. The dominant group observed was phytoplankton, followed by benthic species and then seaweed (Staehr et al., 2020).

Research have shown that several invasive species are well established in Denmark and may be the cause of up to 10% of annual changes in marine populations. Invasive species have not currently caused an overall shift in the ecological composition of Danish marine ecology; however, they do have the ability to change the composition in spatially and temporarily smaller areas (Staehr et al., 2020). The invasive seaweed *Sargassum muticum* have established itself to be the dominant species in some coastal areas of Denmark (ibid). Researchers have argued that the placement of Denmark also provides an access point for invasive species into the Baltic Sea (ibid).

The effect from phytoplankton and seaweed has serious possible consequences for the local flora of the Danish marine ecosystems: phytoplankton has been observed to produce adverse algal blooms and invasive seaweed has been found to outcompete native seaweed (Staehr et al., 2020). One of the threats posed by invasive species is that they might be more suited to the new environment created by global warming (Gustavson, 2001). One such issue was observed by the farmers as the hotter-than-usual water in the previous growing season had killed several of their cultivated *Saccharina latissima*, a native species to Denmark.

4.2 Seaweed harvesting in Denmark

Although seaweed harvesting is millennia old, seaweed cultivation is a fairly new endeavor world-wide starting in Asia in the early 20th century (García-Poza, 2020). There are approximately 400 species of seaweed growing in Danish waters (Bruhn and Mouritsen, 2020). This section will present a brief overview of the history and state of seaweed cultivation in Denmark.

In contemporary Denmark, the exploitation of seaweed is in a process of being rediscovered. However, much archeological research suggests that seaweed has been a staple food in the diets of cavemen and Vikings. Research suggests that following the end of the last glacial period settlers in what is now considered the Nordics had a staple diet of various marine animals including mussels, fish and marine mammals. While seaweed does not leave the same degree of remains as animals with bones or shells, it is not a stretch to believe that seaweed has a place in the settlers' diets (Mouritzen, 2015).

As agriculture changed diets for much of the population, seaweed still had a place in the diets of many. Seaweed is often mentioned in sagas and other histories, although these mostly took place in Iceland. It is believed that the Vikings would make use of dried seaweed as provision for their long journeys (Mouritzen, 2015). Seaweed would later become less of a source of food in the Nordics. As agriculture developed, seaweed became more of a food source for poor people or for use in times of poor harvest or famine. It still had an important role in societies in the Faroe Islands, Iceland and Greenland, but in the European Nordics it received less attention. It still received a degree of attention in various other needs, particularly as feed and insulation. Seaweed was also considered as a folk medicine for various ailments as mentioned in the introduction (ibid).

4.2.1 History of seaweed cultivation in Denmark

Despite having been present in most of Danish, and Nordic, history and the large amount of water that makes up the country of Denmark, modern forms of seaweed harvest and cultivation is a recent development in the country. In Denmark, seaweed cultivation is very young and has only been practiced in the 21st century (interview). The most common seaweed cultivated in Denmark is *Saccharina latissima* which is also reflected by the amount of research conducted on this species in the country (Boderskov et al., 2023; Bruhn et al., 2016), however other species of seaweed are both harvested and cultivated.

4.2.2 Environmental factors for seaweed cultivation in Denmark

Denmark generally has a lower harvest than most other European countries such as Scotland, Norway, Spain and the Faroe Islands. Harvest yields in biomass in Denmark are approximated to be 50-90% less than other European countries. The factors that contribute to these lower numbers are not widely understood, but it is believed that it is a mixture of environmental parameters, genetic differences in cultivars and less efficient design of the cultivation system (Boderskov et al., 2023).

Salinity and temperature have been theorized to have a significant impact of the yields. Salinity and temperature are highly variable in Denmark due to its geographical location and varies from >30 parts per thousand (ppt) in Skagerrak to <10 ppt in the Baltic Sea. *Saccharina latissima* generally prefer a salinity of <25 ppt and thus yields are going to vary based on location. While temperature does not vary as much geographically as salinity it does vary significantly based on the season (Boderskov et al., 2023).

4.2.3 Saccharina latissima

As will be discussed below, the farmers harvest and cultivate several different types of seaweed, however, their most harvested type is *Saccharina latissima*. Of the 400 species of seaweed growing in Danish waters, by far the specie that have received the most attention is *Saccharina latissima.* Known in layman's terms as sugar kelp (Danish: *sukkertang*) it is a brown algae and kelp (Boderskov et al., 2021). It therefore makes sense to provide a brief overview of this seaweed and why it has become the focus as the 'Danish seaweed'. The seaweed grows attached to a solid object, usually a stone or sometimes shells, that allows it to stay in place (Bruhn et al., 2016).

One beneficial aspect of *Saccharina latissima* is its content of proteins. *Saccharina latissima* can provide a useful source of amino acids which can both be used for food for people as well as animals. The pigment of seaweed also provides several bioactive properties which are beneficial. These contents, however, differ dependent on the cultivation or harvest site dependent on nutrients, salinity and light sources (Bruhn et al., 2016). The flavor profile of *Saccharina latissima* is described as a mix of shellfish, sea, cucumber and umami (Bruhn and Mouritsen, 2020).

4.3 The seaweed agroecosystem

This section will present the analysis of the seaweed agroecosystem. As stated in chapter 3, this section is primarily based on interviews with one of the farmers.

4.3.1 Overview of the farmers and history of the agroecosystem

The farmers run their operation through a company located in Northern Sjælland which is also their primary area for cultivation and harvest. The company was started by a father and a son. They currently have four full-time employees (including the father and son) and three part-times employees. There is currently no scheme for seasonal workers, but the part-time employees are more 'on-call' when they are needed.

The company began in 2016 as an attempt to increase the amount of local food available in Northern Sjælland, Denmark. Northern Sjælland is in large part agrarian, despite this, the farmers saw a lack of local food available in the area. The farmers looked to seaweed as an option due to its healthiness and availability of seaweed in the fjords. They had contacts in the local restaurant environment and asked a local chef about the viability of seaweed as food. The chef responded positively, and they saw an opportunity in selling seaweed. The founders of the company subsequently had no formal education in seaweed, aquaculture, biology or phycology and had to learn as they went with support from Danish universities.

For the first three years the company only harvested wild seaweed found in the fjords of Northern Sjælland. Demand increased rapidly with help from the New Nordic Movement, a movement that seeks to make food based upon Nordic ingredients that goes beyond the traditional ones[1], and they realized that they had to cultivate their own seaweed to meet demand. This has led them to grow their own seaweed since 2018 with varying success.

The farmers expressed a goal that went beyond profit. They do run a business and therefore need to turn a profit, however in the interview they stated quite explicit that their reason for the business was to provide a healthy and low-impact source of nutrients. As stated by the interviewee:

> "Yes and of course we want to make money on it and stuff like that, but as we always say: the CO_2 calculations are as important as the economical calculations, if one of them does not make sense then we do not do it. They have to follow hand in hand" (interview (appendix 4)).

This was reflected by the farmer as they made several comments on their frustration with the inaction of politicians, and the environmental damage caused by fishing and agriculture in Denmark.

4.4 Products of farmers

As pointed out by Gliessman (2000), the economic challenges of farming mean that farmers often engage in secondary economic activities. For the farmers, it is no different. As the farmers often stated in interviews one of their primary challenges

[1] Non-traditional ingredients mean ingredients that are not commonly found in supermarkets and in value chains. It could be argued that the movement is trying to rediscover traditional food since ingredients such as nettles and weeds have been eaten for thousands of years in Denmark (Nordisk Samarbejde, n.d.)

is to get costumers to eat seaweed as this is not a common ingredient in Danish diets. This this section will briefly outline the economic activities of the farmers.

4.4.1 Seaweed and seagrass

The primary products of the cultivators are seaweed and seagrass. Of seaweed they sell 20 different species, see table 1 for an overview. Seaweed is harvested both from wild and cultivated stocks. The one seaweed species and the two that they are currently seeking permits for cultivation (see section 4.6) are primarily due to the ability to be sold. The seaweed is sold either dried, mostly to health stores, or fresh, mostly to caterers and restaurants. The shelf life for fresh seaweed is 5-7 days, however this number can be increased if they are placed in a tub with salt water and a pump that can generate a current. Harvesting, both wild and cultivated, is done manually using floating tubs, boats and knives primarily.

Seagrass can only be harvested from what is beached and can therefore only be sold as packaging materials or as materials for insulation. While the farmers both harvest and cultivate seaweed, they are currently not able supply the entirety of their demand and are therefore buying some part of their seaweed which they sell to their customers.

The cultivators expressed that they prefer to sell seaweed for direct consumption rather than for seaweed to enter a food production chain. Recently, they have begun working with a manufacturing company to develop plastic out of seaweed. This is

Figure 2: Fucus vesiculosus from wild stocks being dried (Photo L.S. Klausen)

still in its developmental phase; however, the farmers believe that it has a future. While they prefer to sell to customers directly, the farmers sell seaweed for animal feed amongst other things. The farmers are also currently selling seaweed to universities and other research groups who research seaweed. Beers are also produced out of seaweed that they sell; however, this is not something that they make significant profit from and are considered more of a ‘gimmick’ product.

Currently the farmers are not able to cover their entire demand with their current harvest. They therefore need to make up the difference by importing seaweed from France, the Faroe Islands, Ireland, and Sweden. Although Norway is a major producer of seaweed, they do not import it from them due to the geography of the country. The farmer estimated that approximately 20% of their price is from transport due to Norway’s geography. Import of seaweed is an issue because most large-scale seaweed cultivation operations in Europe focus their production on the refining of bioactive compounds. The farmers therefore need to make special agreements with these maricultural operations for dried seaweed.

Price of seaweed

Approximately 90% of the seaweed is still harvested from wild stocks. The farmers still make most of their profit, relatively to labor, on fresh seaweed. The farmers sell fresh seaweed for about 250 Danish kroner (Dkr) per kg and dried seaweed goes for about 500-1000 Dkr per kg. However, water content amounts for about 90% of the weight of fresh seaweed so once the seaweed is dried the price per fresh weight goes down to 50-100 Dkr per kg.

Thus, dried seaweed reduces the fresh weight price by between 60-80% with addition to the extra labor and space requirements for drying. While dried seaweed has the advantage that it can be stored for much longer than fresh seaweed (fresh seaweed can be stored for about 5-7 days according to the farmers), the requirements of space and labor for drying and smaller price per kg makes it less economical than fresh seaweed.

4.4.2 Seaweed Safari

As one of the only major seaweed companies in Denmark, quite a large amount of their time and labor is spent on lectures and a tour of their cultivation site, what they call seaweed safaris (*tangsafari*). The farmers considered the seaweed safaris as an integral part of their business, they saw it as an opportunity to teach people about the health and environmental benefits of seaweed.

4.4.3 Work with researchers and governments

The farmers work with researchers, primarily from Danish universities, on various projects based on seaweed research. The farmers have cultivated relationships with several researchers and share knowledge with them often. They are also working with researchers on seagrass-based projects. The farmers distinguish between when they sell seaweed for research and when they are actively participating in research, when they are simply selling seaweed to researchers, they consider them customers. The research also helps the farmers financially as they receive grants from various funds. They also cooperate with other seaweed farmers in other countries, particularly in the Faroe Islands[2]

4.4.4 Aquafarms and permits

One of the differences between agriculture and mariculture is land-tenure. While land-tenure is not the same between every country, the question of tenure usually differs between land and the ocean in every country. In Denmark, it is not possible for a private person to own part of the ocean (DN, n.d.). This means that in order for someone to engage in mariculture, they need to get permits from the coastal authority (Danish: *kystdirektoratet*), a part of the ministry of environment (kystdirektorated, n.d.).

Permits for the cultivation of seaweed are based on the type of seaweed and the location of its cultivation. This means that in areas of cultivation or marine farms (Danish: *havbrug*), you are only permitted to cultivate a certain type of seaweed on a site in which you are permitted to grow on. The farmer currently has permits for one site of approximately 1ha in which they grow *Saccharina latissima*. At the time of writing, the farmers have one year left on the permit, but they hope that by next year they can renew the permit with a 10-year permit. They are also applying for permits on *Chondrus crispus* and *Laminaria digitata* which they have made successful tests.

Quite a lot of their energy is spent on acquiring these permits, although artificial intelligence (AI) programs have made the system easier. On a given year, the farmer approximates that a week's worth of work is used on acquiring permits. It is also beneficial that usually once a permit is acquired it is available for a long time. The farmer expressed sympathy towards the coastal authority in that they are underfunded, and that seaweed is a relatively new industry.

The question of permits becomes an issue when tests need to be made for new sites and new types of seaweed. According to the farmer, the most common practice is to take a small line on your desired site with the seaweed species you believe is able to grow on the site for testing. This is not strictly legal but operates in a grey

[2] The Faroese Islands are a member of the Kingdom of Denmark but are an autonomous region with its own economy and culture. It is therefore in many regards often considered an independent country and their cooperation could therefore be considered international.

area of the law that is required for finding new sites for seaweed cultivation. Wild-growing seaweed can often be used as a rule of thumb for what species of seaweed are able to be cultivated, however this is not a bullet-proof method, and the habitats of seaweed can change quite dramatically in a relatively short distance. Thus, testing is required.

4.4.5 Marketing

The primary marketing strategy for the farmers is focusing on the sustainable and health aspect of seaweed. While they sell primarily their fresh seaweed to restaurants and catering companies, they hope to make their product available to the general public. This requires an easier way of buying and a cheaper product. The price of the product right now is constrained by time and labor. The farmers hope that once the company expands, they can reduce the price of seaweed, making it more available to the public.

The farmer's aim is to make their product more available to the general public, both culturally, by spreading awareness of seaweed, and economically, by producing a cheaper product. Currently they do not have any issues with selling their seaweed and the farmer described that their crops "often sells themselves while they grow" (Interview (appendix 5)). They also have a good relationship to several restaurants and have become the go-to supplier for many restaurants based on their reputation.

The farmers made it clear that they see their primary goal as environmentalism. They aim to change Danish diets and believe that seaweed is a sustainable source of food that should be expanded. They therefore also see their seaweed safaris and their harvesting go hand in hand. One interesting aspect is that they expressed an interest in having more seaweed companies in Denmark. As expressed by the farmer:

> [We would] like there to be other companies around that start to cultivate [seaweed] so we are not alone in illuminating these issues, because it can get lonely... And that just means that it takes longer for to make people used to seaweed. (Interview (Appendix 6))

As the farmers are part of a new industry in Denmark, the law is not conducive to seaweed farming which puts a strain on the farmers.

Sustainability has also been leveraged by the farmers politically. The farmer estimated that have had visits from 8 members of Danish parliament in the last year, including the Danish minister of food, agriculture and fishing. They also work directly with several Danish universities which also serve as experts for politicians. However, despite the popularity of sustainability in Danish politics and much interest from politicians and public institutions, the road to changing laws are long and were still considered one of the biggest hurdles for the farmers.

4.5 Harvesting of wild seaweed

As outlined in table 1, the farmers harvest 20 different species of seaweed from wild stocks. This still amounts to about 90% of their total harvest. Wild harvest is done throughout the year as different species grow in different times. The seaweed safaris also involve the customers harvesting their own seaweed for self-consumption. A few steps are taken to ensure that the wild stocks are not depleted, this involves only cutting away the shoots or other edible parts, leaving the holdfasts (which anchor the seaweed). This means that the seaweed does not require to grow completely new, but simply needs to regenerate. They also rotate and spread out where they harvest to prevent depleting the wild stocks.

Table 1 : Overview of the seaweed species harvested from natural stock from the farmers and when they are harvested. The seaweed is harvested when the quality is highest and does therefore not reflect when these seaweeds are able to survive. This is an estimated harvest time as global warming make the times in which the seaweeds are harvested less reliable [a]Palmaria palmata is harvested in low quantities and is mostly bought from other companies. [b]Porphyra is a new addition the farmer estimated there might be available for longer (developed from interviews)

Species	Type of seaweed	Season harvested
Fucus evanescens	Brown seaweed	Winter to late spring
Fucus spiralis	Brown seaweed	Late spring to summer
Fucus vesiculosus	Brown seaweed	All year
Saccharina latissima	Brown seaweed	December to late spring
Laminaria digitata	Brown seaweed	December to late spring
Halidrys siliquosa	Brown seaweed	Spring
Fucus serratus	Brown seaweed	All year
Chorda filum	Brown seaweed	Late spring to early autumn
Laminaria	Brown seaweed	Winter
Ulva lactuca	Green seaweed	Late spring to October
Ulva Intestinalis	Green seaweed	Late Spring to October
Chaetomorpha linum	Green seaweed	Mid spring to October
Furcellaria lumbricalis	Red seaweed	All year
Delesseria Sanguinea	Red seaweed	Spring to early summer
Palmaria palmata[a]	Red seaweed	January to early summer
Chondrus crispus	Red seaweed	All year
Gracilaria vermiculophylla	Red seaweed	Mid spring to November
Dumontia Contorta	Red Seaweed	January to late spring
Porphyra	Red seaweed	Summer[b]
Callithamnion corymbosum	Red seaweed	Winter

Wild seaweed is harvested dependent on quality. The seaweed will often survive beyond the timeframe outlined table 1, however outside of their stated timeframe they are not of the quality that is required of them to be sold. This means that seaweed is highly seasonal. This method is also less reliable than cultivation since they are not always able to acquire the seaweed they need and sometimes need to import seaweed from other harvesters. Temperature changes from global warming have made the harvesting times swing more than outlined in table 1.

4.6 Cultivation of seaweed

The farmers are exclusively growing their seaweed in off-shore systems in the fjords of Northern Sjælland. While the farmers were aware of onshore cultivation of seaweed, they were unwilling to use that method for a number of reasons; Labor constraints, the environmental benefits of off-shore cultivation, the available nutrients in eutrophicated fjords and a preference for not using land for seaweed cultivation. This section will outline the cultivations methods used by the farmers for growing seaweed. The farmer pointed out that part of the reason they needed to cultivate seaweed was due to the high amount of stone fishing occurring in the area, removing natural habitats for seaweed.

While harvesting wild seaweed is still the primary part of the farmers' operation, the farmers are spending most recourses on developing and expanding seaweed cultivation. The cultivators are currently cultivating one type of seaweed: *Saccharina latissima* due to permits, although they are aiming to begin cultivating *Chondus crispus* soon in a vegetative-to-line (V2L) system (see below). The farmers are in the testing phase of cultivating *Laminaria digitata*, a brown kelp similar to *Saccharina latissima* and during the time of interviews, the farmers were developing the sporing process for the seaweed. Figure 3 provides an overview of the cultivation methods used for *Saccharina latissima* using laboratory-to-line (L2L) system see figure 3. Both of the impending seaweeds the farmers aim to cultivate is naturally occurring in Danish waters and they are waiting for permits.

The marine farm is located approximately a 15-minute drive from the site in which they spore the seaweed and process the harvest. They cultivate an approximately one-ha field with *Saccharina latissima*. *Chondrus crispus* is a perennial crop that they hope to cultivate soon. They have tested it for one growing season. The seaweed is harvested as mature from the ocean and placed in a net on a line, similar to their other seaweeds. The farmers can then harvest the edible parts of the seaweed once a year so it will grow out again without the need for intervention. This form of cultivation will be described as V2L in this thesis.

The farmers have ambitions to cultivating *Gracilaria*[3], a red seaweed, however this seaweed is classified as an invasive species and are therefore banned for cultivation in Danish waters. The farmers stated that if gaining permission for the cultivation of *Gracilaria* they may resort to on-shore cultivation methods due the seaweed's fast growth rates and demand. However, they prefer to grow seaweed with off-shore methods.

One issue that can sometimes arrive from mariculture, including seaweed, is the fact that seaweed is often grown on near beaches. Since beaches are used for recreation, some people may feel that marine farms are a disturbance to their enjoyment of the beach, either through a reduction aesthetic value, due to buoys polluting their view or the seaweed lines making them unable to swim in certain areas. In the farmer's view, the local reaction to their farm has been overwhelmingly positive with many locals favoring the environmental benefits and the novelty.

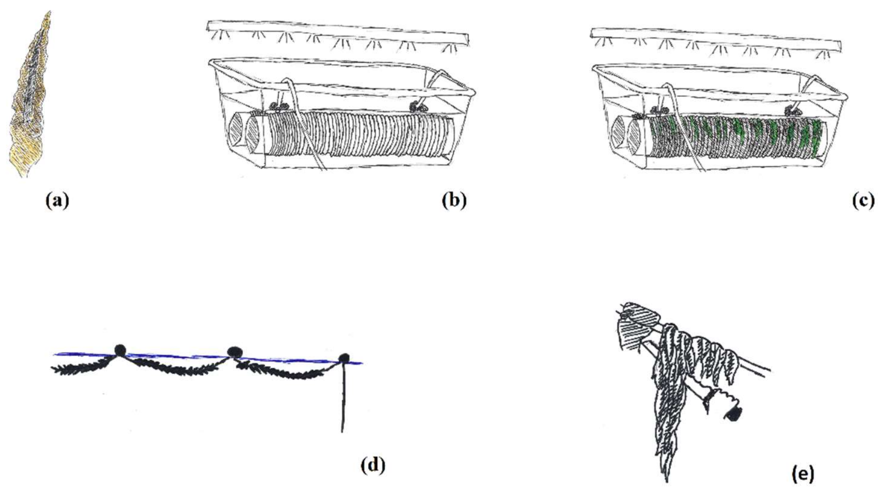

Figure 3: A model of a L2L seaweed cultivation system of Saccharina latissima. First fertile seaweeds are found from wild stocks, they are recognizable from the black streak running down their body (a). This is followed by the spores from the fertile seaweed being released into tubs containing rope where they will attach to the ropes. The ropes turn brown-green as they seaweed grows (b-c). Once the seaweed spores are ready, they are placed on ropes in the marifarm attached to buoys (d). When needed for harvest (seaweed has a short shelf life so they are often harvested based on orders), they are cut from the rope using a knife (e) Developed from interviews and inspection of the marifarm, (artist: L.S. Klausen).

[3] The exact species of *Gracilaria* was not stated by the farmers and the more generic term when referencing this particular seaweed will be *Gracilaria* throughout this thesis. However, based on academic literature it is assumed that the *Gracilaria* in question is *Gracilaria vermiculophylla* (Thompsen et al., 2007)

Figure 4: The seaweed farm taken from near the beach, the black dots are from the buoys with the yellow marking the edge of the farm. Without being near the lines, they are practically invisible (Photo L.S. Klausen)

4.6.1 Learning how to cultivate seaweed.

Seaweed cultivation is a new activity in Denmark and there is subsequently no traditional knowledge of it. The farmers subsequently needed to seek out the methods of seaweed cultivation in Danish waters. Throughout the 4 years of cultivation, the farmers have experienced varying amounts of success. Although they had more success in the beginning of the cultivation with a large harvest, the following growing seasons were patchier. This is due to what the farmers described as beginner mistakes and a process of trial and error as well as hot summers. They believe and hope that most of the mistakes are made at this point and that they can begin to see a large harvest again.

The farmers learned how to cultivate seaweed at first with help from local universities. The universities also provided materials for cultivating seaweed at first

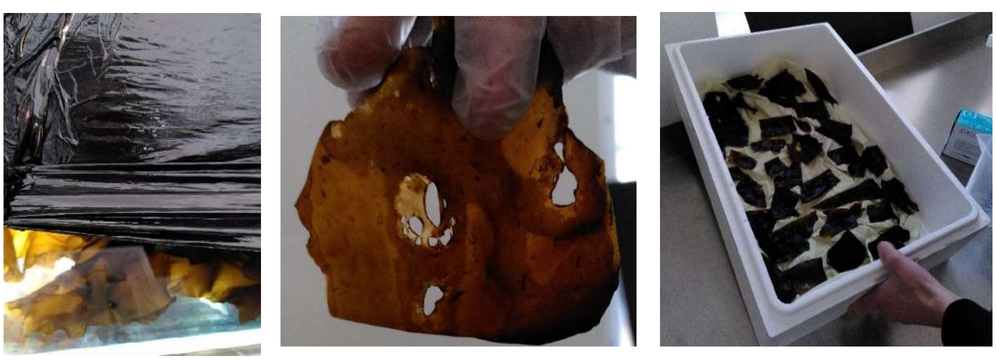

Figure 5: Left picture: Saccharina latissima placed in tub with a black plastic covering, the seaweed will experience that it is autumn, the season in which it becomes fertile. Middle picture: Fertile Saccharina latissima, the holes in the seaweed are from already released spores. Right picture: Saved fertile Saccharina latissima in preparation for releasing spores. (Photos: L.S. Klausen)

and as they began to learn the ropes, they had less need for the help of universities. They are currently working in a partnership with Danish universities and are cooperating in the development seaweed cultivation in Denmark. The farmers were also lucky in that the fjords of Northern Sjælland have a favorable environment, in terms of nutrients (through eutrophication) and currents, for the cultivation of seaweed. Early mistakes involved as simple mistakes as using the wrong knots which were unable to withstand the currents, leading to lost crops. Most other painful lessons are based on timing, i.e., when to put out the seeded lines as putting them out too early can make the seaweed uncompetitively relatively to wild species.

4.6.2 Seeding of seaweed

One of the primary attributes of algae is that they absorb nutrition from their body, rather than from a root system. This is a particularly useful feature in the cultivation of seaweed due to the farmers being able to produce seaweed on ropes, rather than needing to seed it in the ground. The major hurdle of seaweed cultivation for the producer was supply lines as seeds and spores were needed to be acquired from other countries such as Norwegian and Dutch producers. The farmer complained that they were frustrated with constant supply-line issues from any producer that they found and decided to produce their own seeds.

The seeds that they currently use is harvested from fertile seaweed bodies. On *Saccharina latissima*, the fertileness of the seaweed is recognized by a black streak running down the length of the body (figure 3: a, see also figure 5). This is done by manually diving and scouring for fertile seaweeds. The fertile kelp is cut up and the spores are released and counted using a microscope. If no or not enough fertile seaweed is available through natural stocks, fertile seaweeds can be generated from unfertile stock through manually replicating the conditions of autumn, i.e., low temperature and low light, see figure 5.

The spores are then moved to a tub with ropes inside where they attach to the ropes and begin to germinate (figure 3: b), as they grow, the line begins to take on a brown-green color (figure 3: c). This phase is called the laboratory phase. *Saccharina latissima* spores are capable of swimming and the ropes can therefore be freely placed in the tub. Seaweed spores can be stored for several years if they are kept cool.

The tubs are placed on shelves under strictly controlled lighting as the crops need different wavelengths of light dependent on the life stage and cultivar of the seaweed. Nutrition is added to the tub as well. The nutritional and light needs of the crops are still poorly understood and much of the early cultivation process is developed on a trial-and-error basis. An example of this was during the first visit to the farmers, they had found that adding an extra red light over the seeded ropes increased the growth during the laboratory face. Upon the second visit the farmers said that the red light had actually been a hindrance to the growth of the seeded ropes and were forced to tape over the red lights.

After one to one and a half months to two months of germination on the ropes for *Saccharina latissima*, the ropes are placed in the sea on about 25m lengths and kept just beneath the surface (figure 3: d). This is done in the fall and the seaweed overwinters and are ready to be harvested in late spring to early summer.

One of the major hurdles to the early stages of seaweed production is genetic material. Choosing the best genetic material is still beyond what the farmers are able to do, and they still rely on finding the best seaweed through wild stocks. They hope that they can selectively reproduce the best genetic material in the future. This also serves a benefit due to if the farmers become able to selectively breed and their stocks attract a disease or pest, they will always be able to harvest genetic material from wild stocks. Although the farmer said that there is an international debate on future diseases in seaweed, currently it is not an issue.

4.6.3 Maintenance of the crops

One of the benefits of seaweed cultivation is that there is minimal maintenance of the crop once it has been put in the water. The only point in which the farmers used any form of fertilizer was in the laboratory phase. The fertilizer used is developed specifically for seaweed and was originally developed for research purposes, the farmers stated that using normal fertilizer would create too much growth of microalgae. The farmer estimated that approximately 40Dkr worth of fertilizer was used for every 500m of line of seaweed. The farmers check on the farm about once a week.

When in water, there is almost no maintenance for the lines. Biofouling was not considered an issue by the farmers. When the lines have been out in the ocean for several years there is a need to weed out different seaweed. In tests of *Chondrus crispus* V2L systems, the farmers needed to weed the lines for unwanted species of seaweed. However, the farmer estimated that 500m of line takes approximately an hour. An interesting aspect of *Fucus vesiculosus* is that it is also an edible seaweed that the farmers harvest wild. Therefore, when *Fucus vesiculosus* is growing on L2L lines as a biofouling organism it makes sense to not weed it from the line. The farmers are able to harvest the seaweed from the line. It is therefore debatable how much *Fucus vesiculosus* is an actual weed. However, the farmer prefers to harvest the crop that they have seeded (an example of *Fucus vesiculosus* being dried can be seen in figure 2).

In the season the farm was analyzed, however, several crops were lost due to biofouling from the brown seaweed: *Ectocarpus siliculosus*. The seeded lines were put out in the farm too early and were outcompeted by the biofouling seaweed on several areas of the lines, see figure 6. As the biofouling had occurred in the early stages of growth, the farmers did not bother to weed the lines as the damage was already done. This was also the first season the farmers had any problem with *Ectocarpus siliculosus*. *Ectocarpus siliculosus* is a bigger issue than *Fucus vesiculosus* in that it does not have a known productive use.

For the farmers, L2L cultivation, such as *Saccharina latissima* requires almost no maintenance because unwanted organisms do not have time to settle on the lines before it is harvested. The farmers do regular checkups of the lines. They also stated that they wished to treat the ocean with as much respect as possible which is the reason, they would not use processes such as acid treatment to treat biofouling. The farmers are currently not aware of the nutrients present in the waters of the marine farm. Although they expressed that due to the high degree of eutrophication, it is not necessary to know the nutrient load around their farm as they can safely assume that there will be enough.

4.6.4 Harvesting

The harvesting of *Saccharina latissima* and the expected harvest time of *Laminaria digitata*, is between May and June. The process is fairly simple due to the seaweed growing on ropes, which can simply be removed from the water with the fully grown crop (figure 3: e and figure 6). The perennial crops are harvested by cutting off the edible parts, leaving the rest to grow new crops.

The farmer explained that *Chondrus crispus* had a slow growth, particularly in relation to *Gracilaria*, which would have a lot higher growth rate, both of which can be cultivated V2L. However, they are unable to grow it presently due to its status as an invasive species. *Chondrus crispus*, which they have done tests on cultivating, still has high value in the eyes of restaurants. The farmers argued that *Gracilaria* can be harvested approximately 3 times a year, increasing its potential for mitigating eutrophication.

Figure 6: Left picture: Mature Laminaria digitata from tests ready for harvest Right picture: Ectoparus siliculosus (visible in the red circle) is a biofouling seaweed species which have outcompeted the spores of Laminaria digitata (Photo: L.S. Klausen).

4.6.5 The perfect *Saccharina latissima* year

The interviewed farmer was asked about the perfect *Saccharina latissima* growing year, what parameters would make up a perfect growing season. The farmer explained that the perfect year would simply follow normal Danish seasons. This means not too hot summers and not too cold summers.

Saccharina latissima thrives in cold waters without ice. Thus, normal winter temperatures without ice would provide the perfect winter climate for the seaweed. Similarly, not too hot spring is also optimal. If the waters become too warm the crop will die. The timing of when they put out the spored ropes is paramount for how successful the harvest will be. This is one of the only parameters that the farmers can control because the nutrition in the water comes from eutrophication.

Of the year of writing, the farmers have experienced a fairly successful growing season despite mistakes being made. This includes using a red light in the seeding process, which at first seemed to yield positive results, but showed to be a detriment to the sporophytes, leading to lost lines. Other issues included putting out lines too early, leading to loss of yields due to the *Ectocarpus siliculosus* biofouling.

4.6.6 Processing

The seaweed is sold primarily as fresh to restaurants and as dried to health stores as health food. One of the biggest issues highlighted by the farmers was sand that needs to be washed off. The different types of seaweed harvested have different needs considering washing processes. While there is some fouling on the lines when harvested, the farmer explained that sand is the biggest issue and therefore takes precedent in the processing. The farmers did comment that they could harvest further out into the ocean to avoid sand sticking to the harvest, however this would be expensive due to needing more infrastructure for the deeper waters as well as the fjord in which they have such a large scale of eutrophication that it would be a waste to not to use the nutrients ravaging the fjords.

The seaweed is most often sold fresh to restaurants and dried directly to consumers through various health stores. The seaweed is packaged in Styrofoam containers on ice. The customers are asked to take the produce out from the containers when delivered and the Styrofoam containers are used again by the farmers.

When dried, the farmers do the drying themselves. They explained that they prefer to dry their seaweed during the summer where it can be done as energy efficient as possible. This is beneficial because cultivated *Saccharina latissima* is harvested in early summer and therefore the most optimal time for sun-drying their product, except for the fact that Denmark is a rainy country and sun-drying seaweed is not always the most reliable option. The farmers do have access to industrial dryers that are able to dehydrate the seaweed. This option is also the only one available for seaweed that are harvested during the winter.

Ropes are repurposed if they are not too frayed. The ropes go through a process of being boiled, frozen, then boiled again to ensure that they are sterile and able to be seeded once again. The ropes need a tensile strength of at least 250kg to be able to withstand the currents, thus if they become too frayed, they get replaced.

4.7 Future plans for the farmers

The agroecosystem is currently in its early stage of development and the farmers hope to expand their business in the coming years. The farmers did express a series of ambitions; however, they are currently not making concrete plans. This is due to the constant changing laws regarding mariculture in Denmark.

4.7.1 Expansion of the cultivation

The farmers are currently expanding their sporing lab. Currently the seeding is happening on a series of small tubs on a shelf. The farmers have found a space that has the capacity for large scale tubs, and they hope that they can begin to increase their sporing output.

The farmers are seeking to employ more seasonal workers. Currently they have four full-time employees and three 'flex-employees' or part-time or 'on-call' employees. However, their working needs are very seasonal with winters being less work heavy than summers. Thus, the farmers are looking to put together a scheme in which they can employ seasonal workers.

Currently the vast majority of seaweed is harvested from wild stocks, approximately 90%. The farmers hope that they can change that to about 50/50, meaning that they can increase their stocks from cultivated seaweed to half of their product coming from cultivated seaweed. The interviewed estimates that this can be done in two years. This also provides the farmers with additional security as algae blooms are detrimental to wild stocks in the waters with a high degree of eutrophication.

They also see an opportunity in increasing the cultivation of *Saccharina latissima* by growing it for two seasons before harvesting. This would increase its biomass and give it a head-start during its second season of growing, reducing biofouling of the line. This does provide some issues in that they would need to find a way to put the lines on land to protect the crops from the hot summers. This would add an increased labor requirement. Another issue is the fact that *Saccharina latissima* becomes thicker the second year, reducing its desirability when eaten fresh.

One important question is that of carrying capacity. If demand for seaweed increases, especially if the uses expand, such as for plastics and as a staple food in western diets, then there is a possibility for seaweed to have negative environmental consequences. Due to the large amount of coast in Denmark and due to the high levels of eutrophication, the farmer estimated, and that Denmark has the ability to provide all the needs for Danish demands as well as most of Europe's. as shown in figure 1, the nutrient availability in Danish coasts is high and should be able to provide a significant expansion of Danish seaweed production with a net positive environmental effect.

4.7.2 Marketing developments

The farmers saw a possible future in developing their company into a cooperative in similar fashion to the Coop chain of supermarkets located in Denmark, i.e., where the costumers own a piece of the company, when the company would grow larger. However, they are still facing many structural challenges such as gaining permission to cultivate seaweed. They are currently considering themselves as building the foundation for a broader food system in Denmark.

The farmers see themselves becoming industry leaders of seaweed in Denmark and hope to cultivate other seaweed agroecosystems throughout the country. They believe that seaweed has the capacity to become as popular as mushrooms in Denmark as well as having a future in in plastic production. One significant bet the farmers have made is to become the key seller of seeded lines, in this way they can become the harbinger of seaweed production in Denmark and hopefully spawn more production areas in the country.

5. Discussion

This thesis has sought to answer the following research questions:

- *What are the current seaweed agroecosystems in Denmark?*
- *What challenges are faced by seaweed farmers and what techniques are used to meet these challenges?*
- *What is future scenario for seaweed cultivation in Denmark and which increase is possible without compromising environment?*

The above chapter have sought to answer these research questions by analyzing the only major seaweed farm in Denmark. This chapter will discuss the findings in the context of the research questions and discuss the limitations and further possible research.

5.1 The purpose and development of the agroecosystem

Comparing the agroecosystem to Gliessman's (2015) stages of agroecology shows an interesting aspect of seaweed farming and mariculture: It is difficult to develop a mari-agroecosystem that is not based on Gliessman's third stage. The nature of mariculture makes it harder to control than agriculture. The farmers have taken this a step further by seeking to only cultivate seaweed within its natural habitat and using a minimal amount of external human inputs.

Of course, one could discuss the 'naturalness' of the highly eutrophicated coasts of Denmark and whether the nutrients are external human inputs since they are not actively put there by the farmers of the analyzed agroecosystem. They are outputs of other agroecosystems, but they are not actively put in by the farmers. They also make up the significant aspect of the current coastal ecosystems and could therefore still be considered as being used through the principles of ecological processes, though Anthropocene ecological processes. In this agroecosystem, it is thus unclear whether the nutrients constitute an external input. However, in practice, this does not constitute an input from the farmers.

One of the interesting aspects of the agroecosystem is that they are one of the few seaweed farms in Europe that sell seaweed primarily as produce. As mentioned above, the farmers were unable to fill their whole demand through harvesting. They thus had to import seaweed from other producers. These producers however were mainly selling seaweed for the production of food additives and the farmers needed to establish special agreements for raw seaweed.

The farmers, on the other hand, are selling their products directly to consumers (although most consumers are restaurants). They are similarly in an ongoing campaign to reach out to regular consumers and to teach them about seaweed and hope to make seaweed a staple part of the Danish diet. Their approach to food is thus in line with Gliessman's (2015) idea of the fourth level of agroecological conversion that focuses on a more direct relationship between producer and consumer.

5.2 Efficiency

The agroecosystem is still a fairly young one and they are still conducting trial and error in order to develop a more efficient system. There is a growing number of research focusing on the efficiency and sustainability of seaweed cultivation in Northern Europe with questions such as cultivation designs and locations (Boderskov et al., 2023; Marinho et al., 2015).

5.2.1 Growth cycles

Findings from Marinho et al. (2015) suggest that growing *Saccharina latissima* biannually, i.e., over two growing seasons, would be beneficial. The measured harvest was twice as much as *Saccharina latissima* grown over a single growing season as this would increase the harvest without increasing the operating cost. There are some issues with biannual harvesting when it comes to the analyzed agroecological system: The farmers had experienced few issues with biofouling. However, they did describe that if the seaweed was harvested too late in the summer, biofouling would decrease the quality of the biomass.

One of the main reasons for this identified by the farmer is the fact that many fouling organisms are not able to establish themselves over a single growing season. This means that the advantages of less labor in terms of biomass cultivated with the biannual harvesting might be outweighed by the disadvantages of increased labor spent on freeing the ropes from biofouling organisms or from putting the lines on land over the summer. This will require further research and will likely still be dependent on individual seasons.

Optimization of growth cycles will require further research and trial and error and, in most likelihood, the optimal growing cycle will depend on a variety of factors. As mentioned in section 4.7.1, waiting for two growing seasons may also enhance the seaweed lines resistance to biofouling. As the seaweed line is placed on the second growing season, it is already mature and therefore more resistant to biofouling. However, the rope is also exposed to fouling organisms for twice as long and therefore increases the ability for the organisms to establish themselves on the line. Putting the lines in land would reduce this exposure, but also increase the labor requirements. In most likelihoods, the type of fouling and its intensity would vary from season to season as could be seen in section 4.6.3 with case of *Ectoparus siliculosus*.

Another issue which was pointed out by Marinho et al. (2015) is the fact that a biannual growing cycle would reduce the ability for *Saccharina latissima* to combat eutrophication. The authors (ibid) found no enhanced biofilter efficiency and on top of this old frond biomass will be lost during the late summer which will also mean a loss for the potential removal of N and P.

Finally, leaving the crops longer at sea provides additional threats beyond biofouling. The farmers had already lost a significant amount of harvest in *Saccharina latissima* due to abnormally high-temperature waters over the spring in the previous growing season killing several crops. Increased biomass means an increase in loss if environmental factors become hostile to the crop.

The farmers do, however, not need to put all their eggs in one basket. An L2L system could be devised in which lines were harvested biannually but not at the same time. Thus, each growing season lines were put out for the purpose of growing over two growing seasons while lines who had grown for two seasons would be harvested. This would of course take at least two growing seasons to build. Another system could have mix of annually harvested and biannually harvested lines, reducing the threat of the biannual lines.

5.2.2 Cultivation systems

Boderskov et al. (2023) has provided evidence that using a layered cultivation system such as on nets can increase the harvested biomass. This however has the potential to pose a risk against certain marine mammals as has been pointed out by Campbell et al., (2019): The establishment of Kelp forests such as *Saccharina latissima* will attract a number of flora and fauna. This is generally considered beneficial as this can help revitalize biodiversity, however the establishment of ecosystems similar to stone reefs, which is marred by kelp forests, could attract porpoises which has the ability to get tangled into nets if this technique is used (Timmermann et al., 2022). A more stringent surveillance of the effect on marine ecology would be needed if nets were used in large scale in Danish waters.

5.3 Environmental impact

As outlined in the previous chapters, one of the primary advantages of seaweed farming is its low environmental impact, often having a net-positive environmental impact (Biris-Dorhoi et al., 2020). Although a detailed environmental examination, following for instance the nutrient uptake from the water, of the agroecosystem of the seaweed farm was beyond the scope of the research, we can still make inferences based on our examination of the system. This is particularly relevant as focusing on the sustainability of their product is one of the farmers' primary marketing strategies.

Researchers have pointed out that the environmental benefits of seaweed farming are often compounded by the fact that these marine farms are small in scale, thus the negative impacts are negligible (Campbell et al., 2019). The farmers have aspirations to expand their operation, and this creates the possibility of the farmers increasing their environmental impact both in positive and negative ways. The farmers have the opportunity to decrease the eutrophication of Danish waters, a goal set out by the Danish government. They also have the opportunity for carbon sequestration, particularly when seaweed is used as building materials. However, there are both positive and negative ways in which the biodiversity of the marine ecosystems will be affected. This is discussed in more detail below.

5.3.1 Marine Biodiversity

The effect of biodiversity by seaweed farming is a serious question. Mariculture is an agroecosystem that is not cultivated as separate from natural ecosystems as more traditional agroecosystems. This means that the species grown in seaweed farming can have far ranging consequences on the biodiversity of the coastal areas (Campbell et al., 2019). However, there is also an opportunity in regard to the impact of seaweed farming on biodiversity:

Seaweed in Denmark is currently not impacted by farming but is regardless in a dire situation. Issues such as global warming and stone fishing has put stress on native species in Denmark. Seaweed is difficult to cultivate in areas where they are not native, and cultivation can help protect the crops and the associated biodiversity. This does pose a problem for seaweed cultivation in Denmark considering the environmental changes with increased water temperature as well as the significantly reduced number of reefs in Denmark. This will likely reduce the areas in which native seaweed species can be cultivated in Denmark.

Effects on biodiversity from seaweed cultivation

One of the main questions of seaweed cultivation is the question of biodiversity. While seaweed is being planted in the ocean, providing ecosystem services, they are also quickly removed. It could thus be said that the seaweed forests are cut down almost as quickly as they are grown. In their paper, based on a literature review of seaweed cultivation, Forbes et al. (2022) found that not much research had been done on the effect on biodiversity from seaweed mariculture. They found that it could change the structure of the local ecosystem through changed nutrient cycling, but that this was understudied. That reflects the findings from Campbell et al. (2019) that the environmental risks from seaweed mariculture is understudied as well.

One benefit of biannual lines could be an increase in biodiversity as outlined above. Rather than staying in ocean for a single growing season it will stay there for two. It could thus attract species that like to habitat in and near seaweed forests. One of the main issues in the ability of seaweed to enhance the biodiversity of its growing site is the fact that it is planted and harvested in a span of less than a year, providing a less than optimal habitat for many animals (Forbes et al., 2022). If there is a more constant seaweed forest due to the more permanent cultivation system as outlined above, it could provide a more stable habitat for various species.

V2L systems could also provide a more stable source of ecosystem services as these cultivation systems leave the seaweed out indefinitely. While the bodies would regularly be removed it would still leave some of the plant to provide ecosystem services. This, however, will require more research.

Another possible biodiversity enhancement could come from the removal of nutrients in the ocean, preventing algae blooms. Forbes et al., (2022) has pointed out, seaweed mariculture could also enhance biodiversity through fouling organisms. While these organisms such as unwanted species of seaweed may be an annoyance to the farmer, they might be enjoyed by benthal species and other organisms and will also help to regulate nutrients and provide shelter. While biofouling is often weeded out, when the farmers noticed the *Ectoparus siliculosus* on the lines they simply chose to ignore it, thus it provided a more stable ecosystem services than the seaweed that was set to be harvested. While this does not necessarily highlight the benefit of seaweed mariculture, which seeks to avoid biofouling, it does highlight the complexity and need for more research.

While seaweed cultivation could have a negative impact on biodiversity it may also have a positive one if harvest can be diverted from wild stocks. If seaweed cultivation allows more wild seaweed to stay in the water, it could have an indirect benefit to coastal biodiversity. Particularly in the case of mechanical harvesting, which uses dredging methods which not only disturb seaweed ecosystems but also seagrass ecosystems (Mac Monagail et al., 2017).

While not an exact match, efforts to revitalize stone reefs removed by stone fishing has yielded positive results for biodiversity in Denmark (Helmig et al., 2020). The biodiversity-enhancing effects from stone reefs are not limited to the presence of seaweed. However, seaweed does provide the services of food, hiding spots and mediating nutrients, light and kinetic energy and this could be enhanced with a more permanent system (Forbes et al., 2022).

Gracilaria and invasive species

The introduction or role of invasive species in mariculture is a controversial subject. The farmers hoped to be allowed to grow *Gracilaria* despite its classification as an invasive species. Scholars have found that the introduction of invasive species is a possible environmental risk in marine farms (Campbell et al., 2019) However, the question of *Gracilaria* provides an interesting question on that front; It is an invasive species, but one that are thriving in Danish waters due to global warming. It is considered a species that will never leave the Danish waters by researchers (Thompsen et al., 2007). Thus, it is banned as a crop for cultivation but is still harvested wild by the farmers. Also, it is a healthy crop (Passos et al., 2021)

The temporal aspect to invasive species has long been a discussion amongst researchers and policy makers. An example is that *Mya arenaria* is believed to have been introduced in the Viking age while still being considered an invasive species (Staehr et al., 2020). *Gracilaria* has a much shorter history in Danish waters; it was first discovered in Danish waters in the mid-2000's and quickly established itself. *Gracilaria* has been successful in otherwise species-poor areas due to its hardiness and has quickly established itself to be dominant in some Danish coastal regions. *Gracilaria* has been shown to sustain growth in temperatures between 5-30°C and in varied saline and light environments (Thomsen et al, 2007).

The law banning it from cultivation in Danish waters and maybe even its role as an invasive species could be considered outdated. The farmers felt that it does not consider the current reality. As was pointed out by the farmers, some oyster species are now legal to be cultivated in Danish waters despite it also being classified as an invasive species. The hardiness of *Gracilaria* could provide for a more stable source of seaweed. This is also compounded by the effects of stone fishing which has had a detrimental effect on native seaweed species in Denmark. Species such as *Saccharina latissima* prefer colder environments and in the age of global warming, growing seaweed species that can survive the current realities may provide a necessary step for Danish seaweed mariculture.

5.4 Future marketing aspects of seaweed in Denmark

Some scholars argue that seaweed farming is going to increase in production, profit and interest in the coming years (Hafting et al., 2015). As this research has demonstrated, it is not hard to see why. Seaweed is both a source of nutrition and bioactive compounds and it can provide this without needing to take up land and without the need for nutritional input, at least in off-shore farming. As Hafting et al., (ibid) argues, many of the HVBC's require a high degree of control to ensure the quality of these compounds. It could therefore be theorized that a crossroad will emerge where off-shore seaweed farming will produce sea vegetables, bioremediation and relatively low-value bioactive compounds that does not need as much quality control while on-shore production will provide HVBC's in a more controlled environment.

Seaweed could find itself becoming a flex-crop. Flex-crop is a concept that highlights the flexibility and multiple uses of a crop. In all of recorded history, crops have been used in multiple roles, e.g., food, feed, fuel and fibers. Flex-crops is a concept that is developed in order to understand the new patterns of investment and its relation to the bioeconomy, which is broadly defined as the economy surrounding the use of biotechnology. It has expanded rapidly throughout the 2010's, spurred by a need for safe investment and green growth (Borras et al., 2016). This could increase the attractiveness of investment in seaweed cultivation, but also the attractiveness of using unsustainable and industrial methods to increase profits.

5.5 Limitations and further research

One aspect that has made the analyzed agroecosystem interesting, but also a limitation is the fact that seaweed mariculture and seaweed agroecosystems are new in Denmark. While this provides a useful snapshot of a developing agroecosystem it also means that this is an agroecosystem that is going to look very different in a few years after writing. The available interviewee was also one farmer from one farm. This means that perspectives were not available as other farmers may have other perspectives and priorities. However, currently the interviewed farm is the only major commercial seaweed framer in Denmark.

The limitation should encourage further research and monitoring as seaweed production expands in the future. Generally, the research on seaweed cultivation is in its infancy and much more research is needed. As the industry grows, the need for steering seaweed in a sustainable direction will be increasingly necessary. The methodology of agroecology, with its emphasis on the perspective and cooperation with farmers, allows for an ability to steer the development of sustainable seaweed farming in Europe. Seaweed farming has a great potential to provide healthy food that serves as bioremediation and revitalize biodiversity in coastal regions. However, there is also great potential for adverse effects if production becomes industrialized. Future research should focus on marketing, the social and political aspects and designing cultivation systems and finding locations so that seaweed farming can reach its potential while avoiding possible pitfalls.

6. Conclusion

This thesis has sought to answer the research questions *What are the current seaweed agroecosystems in Denmark?*, in which the thesis has found that seaweed agroecosystems in Denmark are sparse and emerging. Although these agroecosystems are not currently deeply integrated into mainstream foods in Denmark. The second research question: *What challenges are faced by seaweed farmers and what techniques are used to meet these challenges?* found the main challenges identified by the seaweed farmers were in terms of marketing and on the political side. While the farmers did face some perturbations, they saw that as part of the learning process and not a significant issue. The final research question: *What is future scenario for seaweed cultivation in Denmark and which increase is possible without compromising environment?* it was deduced that the health properties, eutrophication in the coasts and the current interest in seaweed made an expansion of seaweed production in Denmark and Europe very likely. How it will end up remains to be seen, but with determination from the consumers, producers and politicians, seaweed has the potential to be a potent tool in creating sustainable solutions in an otherwise stressed food system.

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Popular science summary

The global food system is in for one of history's biggest challenges: Not only does agriculture need to starkly reduce its emissions of CO_2, but also the runoff from fertilizer which often ends in rivers and oceans, creating an environment with too much nutrition that will harm the ecosystem. At the same time, to meet the food needs of a growing population estimated to be 9 billion by 2050, global food production needs to increase. These two, seemingly contradictory, challenges will require development of innovations and new knowledge based on sustainable practices. One potent tool in feeding the world without destroying it can be found in the ocean: seaweed.

Seaweed is useful because it is highly nutritious, containing proteins, dietary fibers and minerals. At the same time, it is grown in ocean, thus it does not have to compete with agricultural crops for space on the land. Simultaneously, since it is grown in the ocean, there is no need to add fertilizer as this has already been added by runoff from agriculture. In fact, due to it being able to absorb nutritional runoff from agriculture it is able to help restore coastal ecosystems. In addition, it may protect the coastal biodiversity through providing many services needed by local animals such as food and hiding places. However, to obtain the benefits of seaweed cultivation it must be developed in forms that work with respect and alongside the local ecology in which it finds itself.

This thesis sought to analyze the only major seaweed farm in Denmark in order to understand how the seaweed industry can be developed in a sustainable direction and what challenges are faced by seaweed farmers. It was observed that seaweed farmers have to learn as they go, since there is no tradition for seaweed farming in Denmark. However, as they have cultivated good connections with both local governments and universities, they are able to create a sharing knowledge economy that can help them develop their farming techniques. Their main issues are that the political landscape as Danish law is not built for seaweed farming and the economic and cultural landscape as there is not much tradition for eating seaweed in Denmark. Today, it is mainly restaurants that serve and make seaweed and the farmers hope that it will enter normal people's diets, however, there is still a long way to go.

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Appendix 1

Figure 7: Appendix 1: Top left: example of a red seaweed: Gracilaria (photo Moody, 2007) (GNU Free Documentation License). Top right: example of green seaweed Ulva Lactua (Photo Carter, 2020) (Creative Commons CC0 1.0 Universal Public Domain Dedication). Lower Left picture: example of brown seaweed: Fucus vesiculosus surrounded by Ectoparus siliculosus. Notice how the Fucus vesiculosus is anchored to a small rock that allows it to stay in the water and absorb nutrients through the water flow (photo L.S. Klausen). Lower right picture: Example of brown seaweed: Ectoparus siliculosus attached to larger rocks making up a dock in the Island of Amager near Copenhagen, notice how the seaweed is green despite being classified as a brown seaweed. (Photo: L.S. Klausen)

Appendix 2

First interview:

- How long have you cultivated seaweed? (*Hvor længe har du groet tang?*)
- How long have you been involved with the agroecosystem itself? (*Hvor lang tid har i været i gang med selve agroøkosystemet?*)
- What started the agroecosystem? (*Hvad startede agroøkosystemet?*)
- Academic background? (*Akademisk baggrund*)
- What makes you most satisfied? (*Hvad gør dig mest tilfreds?*)
- What do you cultivate and why (*Hvad gror du? Hvorfor?*)
- Are you getting support from academics and universities etc.? (*Får i støtte fra akademiske og universiteter og så noget?*)
- Seasons? (*Årstiderne?*)
- How often do you harvest? (*Hvor ofte høster i?*)
- How much maintenance is there? (*Hvor meget vedligeholdelse er der?*)
- What do you think is the hardest part of cultivating seaweed? (*Hvad syntes du er det sværeste ved at gro tang?*)
- Pests? (*Hvad med skadedyr?*)
- Have you considered pest management? (*Har i overvejet skadedyrsbekæmpelse?*)
- Have you had problems with competition from other plants? (*Har i haft nogen problemer med sådan konkurrence fra andre planter*)
- Have you used fertilizer (throughout the cultivation process)? (*Bruger i nogen form for gødning (i løbet af hele processen)?*)
- Where do you get your spores from? (*Frø/sporer, hvor får i det fra?*)
- Is seaweed season-dependent? How much do you plan? (*Er der specielle årstider i kan gøre det for forskellige tang? Er det noget i planlægger?*)
- Have the environment for seaweed changed since you begun cultivating? (*Har miljøet for tang skiftet i den tid du har groet?*)
- Do you have any plans or prognosis for the future? (*Har i nogen planer eller prognoser om hvordan fremtiden vil være?*)
- What do you do in order to keep the environment healthy? (*Gør i noget for at holde miljøet rundt omkring tang sundt?*)
- What do you think will be the biggest challenge next year? (*Hvad tror du bliver den største udfordring i det næste år?*)

- Do you do anything to keep yourself productively sustainable? (*Gør du noget for at holde jer produktiv bæredygtigt?*)
- Have you tried new techniques last year (*Prøvet nye teknikker i løbet af de sidste år?*)
- What about other forms of cultivation? (e.g. intercropping or on-shore) (*Hvad med andre groformer? (f.eks. intercropping eller on-shore)*)
- Have you considered changing marketing strategy? (*Har du ændret eller overvejet at ændre din marketingsstrategi?*)
- Value chains (*Værdikæder*)
- Do you dry seaweed yourselves? (*Tørre tang, er det noget i selv gør?*)
- Community supported agriculture?
- How will your agroecosystem look like in 10 years? (*Hvordan ser jeres agroøkosystemet om 10 år?*)
- Products (*Jeres produkter*)
- Network (*Netværk*)

Appendix 3

Interview 2:

- How did you learn how to cultivate seaweed? (*Hvordan lærte i at dyrke tang*)
- Have you considered expanding geographically? (*Har i overvejet at udvidde til andre områder geografisk*)
- Franchise
- What wild seaweeds do you harvest? (*Hvad høster i af naturligt voksende tang?*)
- How much do you make per 500m line? (*Hvor maget får i pr. 500m line?*)
- How often do you check your crops? (*Hvor ofte tjekker i jeres afgrøder?*)
- Season workers? (*Sæsonarbejdere?*)
- Overharvesting? (*Overhøstning?*)
- Fresh water (*Ferskvand*)
- Can carrying capacity match demand? (*Kan carrying capacity måle sig med efterspørgsel?*)
- Release of materials? (*Udledning af materiale?*)
- Recycling ropes (*Genbrug af reb*)
- Reaction from the community? (*Reaktion fra samfundet?*)
- Genetic diversity (*Genetisk diversitet*)
- Production pr line
- Cultivars that differs from what grows naturally? (*Afgrøder der er anderledes end de naturlige?*)
- Anchors? (*Anker?*)
- Knowledge on nutrition (*Viden om næringstoffer*)
- Heavy metals (*Tungmetaller*)
- Nutritional profile of the seaweed (*Næringstoffer i tangen*)
- Two-season growing period (*2-årig voksetid*)
- Permits (*Tilladelser*)
- Tools (*Værktøj*)

Appendix 4

Translated from: "Ja og så vil man selvfølgelig gerne tjene penge på det og så nogen ting, men som vi også hele tiden har sagt; så er CO2 beregningerne lige så vigtige som de økonomiske udregninger, altså hvis den ene ikke giver mening så gør vi det ikke, det skal ligesom følges hånd i hånd".

Appendix 5

Translated from: “vi vil bare gerne have at der også er andre virksomheder rundt omkring der ligesom kommer i gang med at dyrke [tang] så vi ikke er alene om ligesom at råbe op omkring det fordi det kan nogen gange godt være sådan lidt ensomt... så er der ikke så mange andre der ligesom er med til at råbe op omkring den her dagsorden og det gør bare at det tager lidt længere tid om at få folk gjort vant til tang som sådan.”

Appendix 6

Translated from: [Vi vil] bare gerne have at der også er andre virksomheder rundt omkring der ligesom kommer i gang med at dyrke [tang] så vi ikke er alene om ligesom at råbe op omkring det fordi det kan nogen gange godt være sådan lidt ensomt... og det gør bare at det tager lidt længere tid om at få folk gjort vant til tang.

Appendix 7

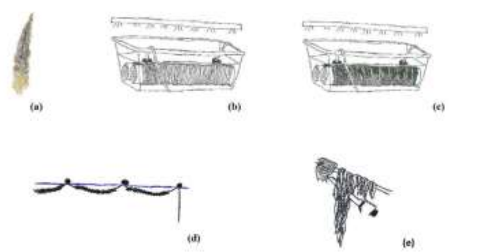
Fact sheet: Agroecological Mariculture: A case study of seaweed farming in Denmark

Liv Schantz Klausen

Problem: In Europe, seaweed cultivation is a new industry with many gaps in the required knowledge. Understanding seaweed agroecosystems and how they are formed can provide a useful source of understanding both how agroecosystems form, but also how they can be steered in a sustainable direction.

Seaweed is in essence an umbrella-term for several multi-cellular autotrophic species living in water. They are also referred to as macroalgae and are related to microalgae, which are their single-cellular cousins. Seaweed is usually divided taxonomically by color: red, green and brown. Red and green seaweeds are part of the plant kingdom while brown seaweeds are part of the chromista kingdom. They are not the only autotrophic species found in water, but they differ from other species by not having roots and absorbing nutrients from water flows through their bodies. Many species of seaweed are considered very healthy with a high amount of dietary fibers, proteins, vitamins and minerals. Seaweed is also usually a vital part of their local ecosystems.

Seaweed farming is a fairly new endeavor world-wide. The



A model of a seaweed cultivation system of sugar kelp. First fertile seaweeds are found from wild stocks (a). This is followed by the spores from the fertile seaweed being released into tubs containing rope where they will attach to the ropes. The ropes turn brown-green as they seaweed grows (b-c). Once the seaweed spores are ready, they are placed on ropes in the farm attached to buoys (d). When needed for harvest they are cut from the rope using a knife (e) Developed from interviews and inspection of the farm (artist: L.S. Klausen).

Fact-box: seaweed:

- Seaweed is also known as macroalgae, it is in the same family as microalgae.
- Seaweed has no roots and absorbs nutrients from the water flow through it body.
- The taxonomy of seaweed is usually divided into color: red, green and brown.
- Red and green seaweed are members of the plantae kingdom, brown seaweed is a member of the chromista kingdom.
- Most edible seaweeds are rich in protein, dietary fibers, minerals and vitamins.
- An important addition in many coastal ecosystems

Mature seaweed from the seaweed farm on the lines ready to harvest. (Photo: L.S. Klausen)

Main perturbations of the farmers:
Socio-economic:

- High prices for normal consumers
- Niche product
- Policies for seaweed are underdeveloped.

Natural

- Global warming
- Increase in invasive species.
- Biofouling on lines
- stone fishing reducing natural habitat for seaweed

harvesting of wild seaweed has been done throughout recorded history and is still the major source of seaweed production worldwide. However, in Asia, seaweed began to be cultivated in the 20th century. In Europe, where seaweed is not part of the staple diet, seaweed cultivation has only been conducted in the end of the 20th century, with many countries first beginning in the 21st century. Seaweed cultivation is conducted on lines that are placed in the water. In the most common type of seaweed cultivation, the first part of the seaweed's lifecycle is controlled in a laboratory setting and it is then placed on the lines in the ocean where it will grow to maturity. Other seaweed cultivation methods exist including vegetative and onshore methods.

The seaweed agroecosystem analysis was found in the northern regions of Sjælland, Denmark. They had been operating for seven years and cultivated seaweed for three of those. The ecological conditions of the Danish coasts have been deteriorating for a long time due to eutrophication, global warming and stone fishing amongst other issues. The seaweed farmers are the only major seaweed cultivators in Denmark and therefore had to learn through trial and error. They were, however, convinced that they had learned most beginners' lessons and hoped to expand their buisness. The main problem that they identified was therefore economic, political and cultural in scope. Since seaweed is not a part of staple Danish diets, neither the market nor institutions have been capable of providing the necessary framework that has allowed them to sell as much as they want. However, they have a lot of interest from restaurants.

In Conclusion, the development of seaweed agroecosystems has the potential to provide an environmentally friendly and source of food in an otherwise stressed food system. However, key knowledge gaps and institutional frameworks are still deterring seaweed farming from flourishing in Europe.

References:

For full list of refences, please see reference list in:

Klausen, L. S. (2023) *Agroecological Mariculture: A case study of seaweed farming in Denmark.* Second cycle, A2E. Alnarp: SLU, Dept. of Biosystems and Technology

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