Master's thesis

Trying to grow like a weed:
The impact of partial harvests on *Alaria esculenta* yield, quality, and cost

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Declaration

I hereby confirm that I am the sole author of this thesis and it is a product of my own academic research.

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Abstract

While seaweed aquaculture is generally promising from industry and ecological perspectives, most companies fail to become entirely profitable. This study aims to compare the impact of using two partial harvests to a single harvest on seaweed yield, biofouling, chemical composition, cost, and consumer preferences for *Alaria esculenta* farmed in the Faroe Islands. The study also aims to help identify ideal, cost-efficient harvesting methodologies that ensure the financial and ecological success of the industry. During the study, 50-meter-long lines were either trimmed in harvest 1 (June 2021) and entirely harvested in harvest 2 (August 2021, partial harvest), entirely harvested in harvest 1 (total harvest), or left unharvested during harvest 1 and 2 (control). Yield, biofouling, chemical composition, and economic analyses were compared between each trial.

Partial harvests did not significantly impact the harvest wet weight compared to a total harvest, and blade length decreased from harvest 1 (70-80 cm) to harvest 2 (46-57 cm). Biofouling cover in harvest 1 (1-4% cover) was signficantly lower than harvest 2 (7-8% cover) and showed a succession of epibionts from filamentous algae in harvest 1 to bryozoan in harvest 2. Biofouling likely reduced the growth of harvest 2 lines. Harvest 2 biomass was too fouled to be sold as human food, and harvest 1 had 3.5 times higher concentrations of bioactivity measurements (TPC) compared to harvest 2. However, all concentrations of potentially harmful elements peaked in harvest 1, potentially representing the bioabsorptive properties of *A. esculenta* without epibionts. Economically, average cost per kg (dry weight) seaweed was 1.4-1.7 times lower in the total harvest compared to the partial harvest. These results indicate that partially harvesting seaweed is not an effective method to increase yield and quality or reduce costs.

Developing good farming methods is essential for the environmental sustainability of seaweed farming. This study also indicates that harvest timing is more impactful than partially harvesting. Future studies should focus on analyzing yield, quality, and costs over time to optimize the harvesting time for specific locations.

Útdráttur

Á meðan lagareldi þangs lofar almennt góðu frá vistfræðilegum og iðnaðarsjónarmiðum mistekst flestum fyrirtækjum að verða arðbær. Þessi rannsókn miðar að samanburði á áhrifum þess að nota tvær hlutauppskerur miðað við eina uppskeru af þangafrakstri, lífmengun, efnasamsetningu, kostnaði, og vali neytenda á marínkjarna (*Alaria esculenta*) í þangbúskap í Færeyjum. Markmið rannsóknarinnar er einnig að skilgreina kjörnar, hagkvæmar uppskeruaðferðir sem tryggja fjárhagslegan og vistfræðilegan árangur vinnslunnar. Í rannsókninni voru 50-metra-langar línur annað hvort styttar að ofan í uppskeru 1 (júní 2021) og alveg uppskornar í uppskeru 2 (ágúst 2021, hlutauppskera), algerlega uppskornar í uppskeru 1 (heildaruppskera) eða skildar eftir óuppskornar í uppskeru 1 og 2 (viðmiðun). Afrakstur, lífmengun, efnasamsetning, og hagrænar greiningar voru bornar saman milli hverrar prófunar.

Hlutauppskerur höfðu ekki marktæk áhrif á blautvigt uppskerunnar samanborið við heildaruppskeru, og blaðlengd minnkaði frá uppskeru 1 (70-80 cm) til uppskeru 2 (46-57 cm). Lífmengunarþekja í uppskeru 1 (1-4% þekja) var marktækt lægri en í uppskeru 2 (7-8% þekja) og sýndi framvindu ásætulífvera frá þráðlaga þörungum í uppskeru 1 yfir í mosadýr í uppskeru 2. Lífmengun minnkaði sennilega vöxt uppskeru 2 lína. Uppskera 2 lífmassa var of spillt til að vera seld sem fæða fyrir menn, og uppskera 1 hafði 3,5 sinnum hærri styrk lífvirknimælinga (TPC) samanborið við uppskeru 2. Engu að síður toppaði allur styrkur hugsanlega skaðlegra þátta í uppskeru 1, og sýnir hugsanlega lífgleypni eiginleika marínkjarna (*A. esculenta*) án ásætulífvera. Fjárhagslega var meðalkostnaður á kg (þurrvigt) þangs 1,4-1,7 sinnum lægri í heildaruppskerunni samanborið við í hlutauppskerunni. Þessar niðurstöður benda til að hlutauppskera á þangi sé ekki virk aðferð til að auka afrakstur og gæði eða draga úr kostnaði.

Að þróa góða búskaparhætti er afar mikilvægt fyrir umhverfislega sjálfbærni þangbúskapar. Þessi rannsókn bendir til að tímasetning uppskeru hafi meiri áhrif en hlutauppskurður. Framtíðar rannsóknir ættu að beinast að greiningu á afrakstri, gæðum, og kostnaði með tímanum til að hámakra uppskerutíma fyrir tilteknar staðsetningar.

I dedicate this project to all my mentors, friends, and loved-ones. My work would not have been possible without each and every one of you.

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1 Introduction

Macroalgae, also referred to as seaweed, is a multicellular, photosynthetic protist that can form fruit, blades, leaves, or spheres (Bak, 2019). Most macroalgae grow on the shore in the intertidal or subtidal zone, but some can grow free-floating. Macroalgae can be grouped into three phyla: Rhodophyta (red algae), Chlorophyta (green algae), and Ochrophyta (brown algae). Approximately 10,000 marine macroalgal species have been identified (Bak, 2019). Seaweeds have historically been harvested for human consumption and are growing in interest (Ferdouse et al., 2018).

Interest in seaweed production across Europe and North America has been growing rapidly due to its versatile uses. While most seaweeds are grown to be eaten (Cottier-Cook et al., 2016), they are also produced as animal feed, biofuels, cosmetics, and pharmaceuticals (García-Poza et al., 2020). Seaweeds can be cultivated for use in the textile industry (Gregersen et al., 2019), and are used as nutrient fixers to remove finfish waste in integrated multitrophic aquaculture (IMTA) systems. Looking toward the future, Doumeizel (2020) believes that seaweed could reduce food insecurity, mitigate climate change, alleviate poverty, and support marine ecosystems. Using algae as a food source or a part of IMTA systems may become key for an expanding world.

Cultivating seaweeds provides numerous ecosystem services for the surrounding areas. Primarily, cultivating seaweeds removes carbon (CO_2) from its environment and sequesters it into biomass (Fernand et al., 2017). Seaweed aquaculture also creates artificial marine forests that provide nursery habitats for juvenile fish (Bak et al., 2018).

Although the seaweed industry has received recent attention, it has been expanding rapidly for the last 70 years. From 1950 to 2019, seaweed cultivation (by tonnage) increased 1000-fold (FAO, 2021). In 2019, seaweeds were the largest aquaculture product representing 29% of total aquaculture biomass. Red seaweeds (Rhodophyta) and brown seaweeds (Phaeophyceae) were the second and third most cultivated aquaculture species by weight in 2019, surpassed only by "carps, barbels, and other cyprinids" (FAO, 2021). As the seaweed supply increases, harvesting methods have changed. Wild harvested and cultivated seaweed quantities were equal in 1969 whereas 97% of seaweed sold in 2019 was cultivated (Cai et al., 2021).

While seaweed aquaculture is promising from industry and ecological perspectives, most companies fail to become economically sustainable. Some feasibility studies on commercial, kelp (brown seaweed) indicate that the industry is not profitable (Burg et al., 2016; Zuniga-Jara et al., 2016). However, some Chilean studies indicate that farms may become profitable after several years (Zuniga-Jara & Soria-Barreto, 2018) or profitable at sizes above 30 hectares (Camus et al., 2019). Understanding the economic sustainability of seaweed aquaculture, or its ability to create long-term economic growth, without compromising on environmental quality, is of high academic interest to advance the seaweed industry.

It is generally agreed that biofouling, or the unwanted growth of organisms on cultivation structures and biomass, is the largest barrier to seaweed production (Bak et al., 2018; Bannister et al., 2019; Dürr & Watson, 2010; Marinho et al., 2015). Biofouling reduces productivity on farms due to competition for light, space, and nutrients (Fitridge et al., 2012). Because kelp grows from the bottom of the frond, the oldest part of kelp blades is the top of the blade (Jennings & Steinberg, 1997; Park et al., 2008; Park & Hwang, 2012). Tips of blades often experience the highest amount of biofouling, and bases of blades generally show lower amounts of biofouling (Jennings & Steinberg, 1997; Park et al., 2008; Park & Hwang, 2012). A study by Zhang et al. (2012) found that 90% of annual blade production is lost at the tip of kelp due to breakage, likely due to impacts of biofouling. Prior studies have successfully improved seaweed harvests by removing the oldest part of the blades throughout the growing season (Bak et al., 2018; Gao et al., 2014; Levitt et al., 2002).

The seaweed industry has had consistent academic support and interest. It has the potential to reduce pollution in finfish farming, and generate new materials (García-Poza et al., 2020; Gregersen et al., 2019). However, there are significant financial barriers to entering the western seaweed industry that prevents the development of greater technologies and uses. It is integral to investigate sustainable, cost-effective methods for seaweed production. Bak et al. (2018) developed the proper methodology for multiple harvesting of *Alaria esculenta*, but self-seeding and errors impacted their analyses.Therfore, A cost assessment has not been completed on *A. esculenta*. This study aims to assess the practicality of multiple harvests for *A. esculenta* and should provide missing information from Bak et al. (2018).

Analyzing the biological effects of multiple harvests will generate greater industry knowledge on the best practices for seaweed harvesting and growing. If significant growth can be stimulated by an early-summer harvest, this will likely equate to significantly greater yields and lower costs. Moreover, the biofouling communities that grow on *A. esculenta* are not well documented in the Faroe Islands. Understanding methods of controlling biofouling and the biofouling communities that gather on fronds will advance biofouling management. Analyzing the economic effects of multiple harvests will identify if the methodology is viable for seaweed farmers. If biological and economic benefits are shown, this study could drive new best practices for seaweed farming.

1.1 Research Aims and Hypotheses

This project aims to analyze the yield, quality, and costs of the brown macroalgae *Alaria esculenta* in partial harvests compared to a single, total harvest. It examines if a second harvest will compensate for the material lost in the first harvest. The study identifies if biofouling, consumer preferences, presence of desirable chemical compounds, or presence of undesirable chemical compounds differs between partial harvests or a single, total harvest. The main question addressed is: How does the use of partial harvesting in the Faroe Islands affect the growth, quality, and economic sustainability of cultivated *Alaria esculenta*?

Specifically, the following aims hypotheses are tested:

Aim 1: To compare the yield of *A. esculenta* between partial harvests and the total harvest.
Hypothesis 1a:

- H_0: There is no difference in yield between the individual partial harvests and the total harvest.
- H_1: There is a significant difference in yield between partial harvests and the total harvest.

Hypothesis 1b:

- H_0: There is no difference in yield between combined partial harvests (partial harvest 1 + partial harvest 2) and the total harvest.
- H_1: There is a significant difference in yield between combined partial harvests and the total harvest.

Aim 2: To compare the quality of *A. esculenta* between multiple partial harvesting, control lines, and the total harvest

Hypothesis 2a:

- H_0: There is no difference in biofouling between partial harvests, total harvest, and control lines.
- H_1: There is a significant difference in biofouling between partial harvests, total harvest, and control lines.

Hypothesis 2b:

- H_0: There is no difference in chemical compounds in the seaweed growing on partial harvests, total harvest, and control lines.
- H_1: There is a significant difference in chemical compounds in the seaweed growing on partial harvests, total harvest, and control lines.

Aim 3: To compare the costs of growing and harvesting *A. esculenta* between multiple partial harvesting and the total harvest

- H_0: There is no difference in average cost per kg of algal biomass between combined partial harvests and the total harvest.
- H_1: There is a significant difference in average cost per kg of algal biomass between combined partial harvests and the total harvest.

1.2 Methodology and Data Collection

Primary data collection for this project occurred from June 29 to August 11, 2021, at TARI‘s seaweed farm in Kaldbaksfjord, Faroe Islands (Figure 3.1). Three harvesting treatments were used throughout this project: a total harvest (with complete removal of biomass on June 29, a partial harvest (with the removal of half the tissue on June 29 and complete removal of biomass on August 11), and control lines that were never harvested and used for comparison. The yield was measured through wet weight biomass as well as blade length, weight, and width. Quality was measured by total blade biofouling cover (%), biofouling cover (%) by individual biofouling organisms, grazing cover (%), vitamin content, undesirable mineral content, desirable mineral content, general nutrients, and bioactivity. Economic sustainability was measured through average cost per unit of biomass and total revenue.

1.3 Delineation of Scope

This study looks at the use of longline seaweed harvested using two methods: the traditional total harvest or partial harvests. Therefore, the results of this study directly apply to longline seaweed aquaculture.

Because only one study site (Kaldbaksfjord) was used during the duration of this project, the results from this study apply to seaweed farm management in the Faroe Islands. The Faroe Islands are known to have good conditions for the cultivation of *A. esculenta*. (Wegeberg et al., 2013). Environmnetal variables, such as availability of nutrients to the Faroe shelf, notably impact nutrient concentrations in fjords (Gaard et al., 2011). Due to differences in environmental conditions between farm sites, it is not clear if other geographic locations would experience the same results. In addition, seasonal variations, and durations of grow-out are outside the scope of this project as they can alter the ultimate result of the study.

1.4 Structure of Thesis

The structure of this manuscript includes six sections: Introduction, Background, Research Methods and Analysis, Results, Discussion, and Conclusions. The results from this study will be made available to seaweed industry members. This thesis format was approved by the University Centre of the Westfjord‘s Coastal and Marine Management Master‘s committee.

2 Background

2.1 State of the Seaweed Industry

Although there are over fifty countries that farm seaweed, over 97% of seaweed production came from Asia in 2019 (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). China, Indonesia, Japan, the Republic of Korea, and the Philippines are the top five producers by value (in descending order) with Chinese production accounting for nearly 60% of the global market (Ferdouse et al., 2018). Comparatively, Europe and the Americas accounted for only 1 percent of algae production each in 2019 (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). European and North American seaweed have less historical experience in algal cultivation, and their producers, therefore, experience higher costs than profits (Ferdouse et al., 2018). However, the geographic imbalance in seaweed production may indicate the potential for European and North American seaweed markets (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021).

Demand for seaweed has grown significantly with the advancement of the hydrocolloid industry. Fresh and dried seaweed is primarily consumed by East Asian and Japanese markets, but expansions of seaweed-based food products such as hydrocolloids (agar-agar, carrageenan, alginic acid) have largely increased demand in the European Union (EU) and the United States (US) (Ferdouse et al., 2018). Hydrocolloids are food and non-food industry products that can be used as substitutes for animal-based gelatin, caseinate, whey protein, soy protein, egg white protein, and chitosan. The seaweed hydrocolloid market was born in 1970, and ~300,000 tons were produced annually by 1990 (Cai, Lovatelli, Stankus, et al., 2021). Due to the expanded uses for hydrocolloids in the food and non-food industries, the production of seaweed hydrocolloids saw an exponential increase from 2007 to 2017 and has continued to rise since (Ferdouse et al., 2018). Seaweed hydrocolloids now make up approximately 40% of the hydrocolloid market which includes animal-based gelatin, soy proteins, and whey proteins. Carrageenan is the most popular seaweed hydrocolloid due to its versatile uses. Most commonly used as a gelling agent in food, demand for carrageenan in the EU and US is rapidly growing and is expected to continue growing (Ferdouse et al., 2018).

Seaweed hydrocolloids are also expanding with global halal markets. A Global Islamic Economy Report stated that the global halal market is expected to be worth 3 trillion USD by 2023 (Reuters & Standard, 2018). Hydrocolloids derived from plants are ideal for a halal diet, and some seaweed-producing countries, such as Thailand and Japan, are gaining halal certifications for their exports to gain market share (Ferdouse et al., 2018). Halal food standards comply with kosher and USDA food standards, so seaweed-based hydrocolloids carrying halal certifications hydrocolloids are ideal for many individuals with dietary restrictions (Ferdouse et al., 2018).

Although a massive quantity of seaweed is produced each year, few genera and species are brought to market. The increase in seaweed production during the past 70 years is primarily due to two genera of brown seaweed (*Laminaria/Saccharina,* and *Undaria)*, and three genera of red seaweed (*Kappaphychus/Eucheuma*, *Gracillaria,* and *Porphyra)* (FAO, 2021). Laminaria/Saccharina (kelp), *Undaria* (wakame), and *Porphyra* (nori) are primarily produced for human food whereas *Kappaphychus/Eucheuma* and *Gracillaria,* are generally cultivated for hydrocolloids. While few genera are primarily cultivated, there is a relatively small number of species brought to market. Thousands of seaweeds have been identified in the wild, but only 27 of the 443 known commercially viable species were cultivated in 2019 (FAO, 2021).

2.2 Seaweed cultivation methodologies

Wild harvesting of seaweed has been in decline because of overharvesting, and 97% of seaweed sold was cultivated in 2019 (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). Seaweed farming has steadily increased with the demand for seaweed products. In 2016, seaweed and seaweed products were traded for an estimated value of 10.6 million USD. It is projected that if a 10 percent yearly growth rate continues, seaweed‘s market value could reach 26 million by 2025 (Ferdouse et al., 2018).

Seaweeds, or macroalgae, dominate the algal market. In 2019, over 99.8% of algae cultivation was macroalgae, with the remaining being microalgal (Cai et al., 2021). However, the value for microalgae could be under-reported because microalgae are frequently produced for aquaculture hatchery feeds (Cai et al., 2021).

Seaweed farms can seed their spores onto textiles, nets, or spools of ropes (Rolin et al., 2017). In longline aquaculture, the method used in the present study, spores are seeded onto ropes, suspended horizontally near the water‘s surface, and held in place by structures such as anchors or buoys (Zhu et al., 2021; Mols-Mortensen et al., 2017). Farms are generally located in sheltered, nearshore locations where they are less expensive to access and provide appropriate light for photosynthesis (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). However, problems at the nearshore may complicate seaweed cultivation. In some areas, pollutants are too high to farm, or seaweed farmers compete with fish farmers, fishers, and other coastal development in the nearshore region (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). Furthermore, biofouling, or the growth of unwanted organisms on the blade of the seaweed, is typically worse on seaweeds grown in the nearshore due to the availability of light and nutrients (Bak et al., 2018).

Cultivation methods can be altered to alleviate the problems with nearshore longline cultivation. Many academics propose offshore cultivation as a new method for seaweed farming despite being much more expensive and difficult to access (Bak et al., 2018; Burg et al., 2016; Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). Burg et al. (2016) proposed adding seaweed cultivation to offshore wind energy structures, but note that seaweed yield or price must increase by 300% to become economically efficient. The present study investigates multiple partial harvests, a form of longline aquaculture occurring in the nearshore environment designed to reduce impacts of biofouling and increase yield.

2.3 Benefits of seaweed production

Seaweed farming has revolutionized sustainability in the human food and animal feed industries. Seaweed is a nutritious, low-impact food, sometimes referred to as „future food,“ that contains comparable or higher levels of calcium, zinc, vitamin A, and vitamin B12 when compared to animal-source foods (Augyte et al., 2021; Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021; J.-S. Park et al., 2021; Parodi et al., 2018). Seaweeds are a low-impact feed for animals and can reduce methane emissions in ruminants (Vijn et al., 2020). Seaweed that is not market-quality for human consumption can be used as a fertilizer. Nabti et al. (2017) found that when seaweeds are used as fertilizers, they observed stimulated seed germination, improved water and nutrient uptake in crops, enhanced shoot and root elongation, and remediation of pollutants in contaminated soil.

Several products can be made from seaweed. Augyte (2021) asserts that seaweeds can fill the global demand for biofuel in the next decades. Using biofuel, when replacing fossil fuels, can help mitigate climate change (Dave et al., 2013). Using the proteins and carbohydrates from seaweeds, algae-based plastics can easily biodegrade (Chia et al., 2020). Secondary metabolites and bioactive compounds in seaweeds are utilized in the food, pharmaceutical, and cosmetic industries as stabilizing agents, treat conditions such as allergies and heart diseases or protect skin against free radicals (Holdt & Kraan, 2011; Da Costa et al., 2017; Pimentel et al., 2018).

Seaweed aquaculture boasts numerous benefits for local environments and our broader climate. Seaweeds are known to assist with carbon capture and absorb nutrients in eutrophic waters (Muraoka, 2004; J.-S. Park et al., 2021). Assimilating massive quantities of nitrogen and phosphate, seaweed can mitigate hypoxia, treat wastewater, and control nutrient pollution (Racine et al., 2021). As they remove carbon dioxide from the water, seaweeds mitigate ocean acidification and provide regions of higher pH for calcifying organisms (Xiao et al., 2021). Seaweed farms, rather than wild seaweed, absorb wave energy (Alleway et al., 2019). Selecting shallow sites, planting a large farm, placing longlines in a shallow depth, densely growing seaweed, and selecting large and rigid species can increase wave attenuation (Zhu et al., 2021). Seaweed farms may be able to enhance marine biodiversity (Alleway et al., 2019; Naylor et al., 2021; Theuerkauf et al., 2022). Aquaculture structures can provide a habitat for non-cultivated species (Costa-Pierce & Bridger, 2002),

Seaweed production can also reduce the environmental impact of finfish aquaculture through integrated multitrophic aquaculture (IMTA). IMTA systems are complex aquaculture systems where seaweed or bivalves are grown in conjunction with fish and fishery species, acting as a natural ecosystem (Ferdouse et al., 2018). The interactions between cultivated species and their environment, including filtration rate and population dynamics, determine the success of IMTA systems (Granada et al., 2018). IMTA systems range from growing *Graciliaria* seaweed in shrimp or finfish ponds (Diatin, Effendi, and Taufik, 2020) to farming over 30 species (including kelp, scallops, oysters, abalone, and sea cucumbers) in over 100 km^2 area (Fang et al., 2015). IMTA systems have been praised for their potential to generate economic profits and plentiful environmental benefits, including bioremediation (Soto, 2009).

Ecologically, seaweed farms are said to provide numerous benefits to the surrounding ecosystems. Seaweed farms act as a habitat for fish and other marine organisms, providing substrate and shelter for a variety of wild marine organisms (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021; Costa-Pierce & Bridger, 2002; Naylor et al., 2021). Transient or resident fish can be attracted to longlines to eat biofouling organisms or live within the habitat (Augyte et al., 2021). Seaweed cultivation can also reduce overfishing by providing alternative livelihoods to coastal or fishing communities (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021).

2.4 Concerns surrounding seaweed production

2.4.1 Ecological

Arguably, biofouling is the largest challenge for seaweed cultivators. According to Dürr & Watson (2010), biofouling is one of the main barriers to efficient and sustainable seaweed production. Biofouling, or when unwanted organisms settle on natural or unnatural surfaces, increases the weight of seaweed which leads to increased breakage of tissue (Bannister et al., 2019; Dixon et al., 1981; Krumhansl et al., 2011). Blades may also tear due to increased drag from epibionts, or biofouling organisms (D'Antonio, 1985; Dixon et al., 1981). Specific organisms such as encrusting bryozoans (*Membranipora membrancacea*), tunicates, and hydroids can make kelp blades brittle, and damage their appearance (Førde et al., 2016; Rolin et al., 2017). Physiologically, some epibionts can lead to necrosis of kelp tissues, prevent spore release, and inhibit reproduction (D'Antonio, 1985; R. L. Fletcher, 1995; Peteiro & Freire, 2013; Saier & Chapman, 2004). Potentially covering large surface areas of blades, biofouling can limit photosynthesis (Hepburn et al., 2006)**.** Epibionts can grow on ropes or buoys used to farm seaweed, causing the infrastructure to sink to a deeper depth than desired and requiring costly cleaning (Marroig & Reis, 2011, 2016). Finally, biofouled fronds have lower market value, taste, and quality (Park & Hwang, 2012; Peteiro & Freire, 2013)**.** Low-quality fronds are used for non-food uses at best and discarded at worst (Rolin et al., 2017; Peteiro & Freire, 2013).

The hydrographic environment affects biofouling. Larval distribution of planktonic organisms varies based on topography (Alldredge & Hamner, 1980; Shanks & McCulloch, 2003). The overall larval pool limits the maximum amount of species available and is therefore affected by hydrographic systems (Herben, 2005). Bays with longer flushing time typically have greater species richness whereas bays with shorter flushing time have smaller species richness (Jessopp et al., 2007). To colonize on kelp, organisms must have a pelagic larval distribution or be highly mobile (Walls et al., 2016).

Biotically, kelp age, frond morphology, secondary metabolite production, and interactions between epibionts impact biofouling rates. Because kelp fronds grow from the base of their fronds, the tip of the blade is typically the oldest region (Jennings & Steinberg, 1997; Park et al., 2008; Park & Hwang, 2012). Frond tips typically have more biofouling than younger regions which may be due to an accumulation of epibionts over time or reduced biological activity over time (Jennings & Steinberg, 1997; Park & Hwang, 2012). The shape of kelp fronds affects biofouling, with a greater diversity of epibionts shown to settle on crinkle fronds versus smooth fronds (Jennings & Steinberg, 1997; Peteiro & Freire, 2013; W. J. Fletcher & Day, 1983). Kelps produce secondary metabolites that act as antifouling chemicals, limiting the settlement of fouling organisms (Al-Ogily & Knight-Jones, 1977; Weinberger, 2007). The concentration of secondary metabolites that are produced will impact the fouling on seaweed blades. Finally, ecological interactions, such as predation and competition, between epibionts impact the overall biofouling on seaweed blades. In a model, Marzinelli et al., (2011) found that a decrease of urchins living near artificial habitats, such as pilings, results in an increase of biofouling cover on the artificial structure. Førde et al. (2016) observed overgrowing and competition for habitat between two bryozoan species on kelp blades throughout the growing season.

Cultivators can take action to mitigate biofouling through specific management and husbandry practices. Seaweed can be grown in areas of high wave exposure (Peteiro & Freire, 2013; Rolin et al., 2017). However, growing seaweed in exposed sites can lead to further tissue damage (Rolin et al., 2017). Manual removal of epiphytes from infrastructure or seaweeds may be necessary for some regions but is very costly and labor-intensive (Hurtado et al., 2006; Marroig & Reis, 2016). To avoid seasonal epibiont blooms, seaweed lines can be deployed as early as possible and harvested before sea surface temperatures rise in spring or summer (Bak et al., 2018; Førde et al., 2016; Marinho et al., 2015; Park & Hwang, 2012). Some researchers recommend stocking individuals at a higher density to reduce biofouling, but this has not affected the species richness or composition of epibionts for *Alaria esculenta*, the focus species of this study (Bannister et al., 2019; Walls et al., 2017). Moving seaweed into deeper water has been proposed to both increase yield and limit biofouling for some species, but has also not been shown to limit biofouling for *A. esculenta* (Bruhn et al., 2016; Fei, 2004; Sulaiman et al., 2013; Walls et al., 2017). Cultivating seaweed at depth is also economically inefficient (Bak et al., 2018). Also, cultivators should select healthy and epiphyte free organisms for their seed stock as they may have stronger defense mechanisms (Hayashi et al., 2010; Hurtado et al., 2006).

Although seaweed is said to provide habitat services, the species settling on fronds are often non-native. Non-native species are typically characterized by a willingness to settle on artificial structures, and they typically reduce the overall biodiversity of an area through increased competition for resources, alteration of the environment, and predation (Chapman & Carlton, 1991; Holloway & Keough, 2002; Mack et al., 2000). Because non-native species settle different on artificial structures than natural reefs, shallow moving structures create new habitats and generally increase the dominance of non-native species (Connell, 2001; Dafforn et al., 2009; Glasby, 1999). Additionally, cultivation structures may enable „ocean sprawl“ by blocking the natural movement of some organisms or providing new pathways for the movement of organisms or resources (Bishop et al., 2017). Therefore, biofouling communities should be monitored to ensure that non-native epibionts are not colonizing seaweed blades or structures.

Biofouling is frequently considered a leading issue for seaweed cultivation, but few studies have identified financial costs associated with them (Lüning & Pang, 2003; Kim et al., 2017; Dürr & Watson, 2010; Bannister et al., 2019). Costs associated with biofouling are estimated to be approximately 5-10% of aquaculture production costs, equating to USD 1.5 to 3 billion in 2012 (Lane & Willemsen, 2004; Fitridge et al., 2012). Ranges in costs depend on species, locations, companies, and management approaches, and many of the economic impacts are unassessed (Bannister et al., 2019). Therefore, it is likely that the impacts of biofouling are underreported and may be underestimated (Fitridge et al., 2012).

Climate change will undoubtedly change the physiochemical ocean environment. However, the exact impacts of climate change are uncertain (Campbell et al., 2019). Potential challenges include increased pathogen spread, loss of biodiversity, and greater pest presence on farms (Mateo et al., 2020; Wade et al., 2020). Especially as farms increase in size to become more profitable, they face greater risks of pathogens, grazers, and biofouling (Buschmann et al., 2017). To mitigate challenges affiliated with climate change, many academics also recommend seed banking seaweed species (Augyte et al., 2021; DeWeese & Osborne, 2021; Wade et al., 2020). Seed banking will ensure that individuals can survive the coming challenges of climate change thanks to their natural genetic diversity.

2.4.2 Business

In general, seaweed is a low-value commodity. In 2019, the seaweed industry was worth only 5.4% of the USD 275 billion world aquaculture production value (Cai, Lovatelli, Stankus, et al., 2021). However, many aquaculture products have a low value, and only four species groups had a larger value than macroalgae. In 2019, “carps, barbels, and other cyprinids;” ”marine shrimps and prawns;” “salmon, trout, smelts;” and “crayfishes” were the top four aquaculture products by value (FAO, 2021).

IMTA systems can become profitable, but many are not economically sustainable. Attempting to market multiple products across multiple value chains, farmers often have difficulties selling lower-valued products (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). Farmers may be hesitant to change their business model to incorporate lower-valued products, such as seaweeds, especially if they must work harder to sell them (Troell, 2009). Additionally, IMTA systems work with either bivalves or seaweed farmed alongside finfish. If there is a market shift in the price for seaweed or bivalves, IMTA farmers often do not have the flexibility to change their stock because they must keep a specific value of filtering organisms for a well-functioning IMTA system (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). Cultivation infrastructure for one species can impact infrastructure for another species such as finfish cages attracting herbivorous fish to graze on seaweed (Campbell et al., 2019).

Not only is seaweed a low-value commodity, but the demand for seaweed products- other than hydrocollids- is uncertain outside of Asia. Generally, people outside of Asia have minimal exposure and preference for seaweed consumption despite its nutritional and health benefits (Burg et al., 2016; Golden et al., 2021). In Europe and North America, seaweed may be consumed as a niche or novel food, traditional food in coastal communities, environmentally low impact food, or micronutrient supplement (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021).

Because seaweed producers do not want to increase supply without increased demand, more work should be done to generate interest in seaweed consumption. Government agencies and nonprofits should work to promote seaweed consumption and overcome negative connotations that consumers have about aquaculture products (Augyte et al., 2021). By creating outreach and educational events that highlight the economic and environmental benefits of seaweed production in coastal schools or community colleges, management bodies can educate consumers on the benefits of growing and consuming seaweed (Augyte et al., 2021). In many areas across North America and Europe, the seaweed market is undeveloped (Naylor et al., 2021). Coastal managers have an excellent opportunity to involve stakeholders throughout the development of profitable and sustainable cultivations systems, increasing consumer trust and aquaculture sector value as an industry is born (Buschmann et al., 2017; Chopin & Tacon, 2021, 2021; J.-S. Park et al., 2021).

2.5 Species of Interest

Kelps are a diverse group of seaweed from the Order *Laminariales* (Guiry & Guiry, 2021). Each kelp species varies in size, morphology, life span, and habitat depending on its species or genera (Dayton, 1985; Kain & JM, 1979). Most kelps naturally occur in dense populations called beds, are fast-growing, and are considered to be comparable in productivity to tropical rainforests (Reed et al., 2006). Kelp species have been some of the first species to be cultivated in North America and Europe (Buschmann et al., 2017).

Biofouling impacts are affected by the age of *Laminariales*. Kelp species grow from a meristematic region at the base of the frond, so tips are the oldest part of the frond (Jennings & Steinberg, 1997; Park et al., 2008; Park & Hwang, 2012). Ages of fronds impact the biofouling rates of kelps because the oldest areas either accumulate more epibionts or have reduced secondary metabolite activity (Jennings & Steinberg, 1997; Park & Hwang, 2012).

Alaria species are from the Order *Laminariales* (Guiry & Guiry, 2021). *Alaria* is a common genus with fourteen species documented in the northern hemisphere (Kraan et al., 2000). Three *Alaria* species have been documented in the Northern Atlantic Ocean: *Alaria pylaii, Alaria grandifolia,* and *Alaria esculenta*. *Alaria esculenta* is commonly found growing in high wave exposure areas on the lower shore (Tyler-Walters, 2008). This kelp is commonly found across the North Atlantic and the Pacific Ocean and is native to the Faroe Islands (Bak, 2019; Irvine, 1982; R. Nielsen, 2001; Widdowson, 1971). Having multiple morphotypes depending on its location, there may be several intraspecific hybrids (Kraan et al., 2000). Growth rates are highest in April and May, slowing in June and July as the blades become damaged (Birkett et al., 1998; Tyler-Walters, 2008).

Alaria esculenta, also known as winged kelp or dabberlocks, is primarily grown for human consumption because of its rich sugar, vitamin, and protein concentrations (Marinho et al., 2015; Peteiro & Freire, 2013; Guiry & Blunden, 1991). Alaria esculenta is sometimes referred to as "Atlantic Wakame" because of its similarity to "true Wakame" (*Undaria pinnatifida*) grown in Japan, China, and South Korea (Yamanaka & Akiyama, 1993). Sometimes used in non-food industries, *A. esculenta* is also used for animal fodder, biochemical extracts such as cosmetics, and alginates (Bak, 2019; Walls et al., 2017). Kraan & Guiry (2001) found that *A. esculenta* has up to 42% alginic acid concentrations, a high percentage for brown seaweeds that makes it excellent for alginate production. Moreover, this species gained commercial interest because they produce large biomass, growing up to 10 cm/day (Druehl et al., 1988; Wegeberg et al., 2013).

Specifically, there are limited studies conducted on epibionts growing on *A. esculenta*. Walls et al (2017) conducted a study of the species composition and abundance of epibionts on Irish *A. esculenta*. Over two years, species richness increased with time and biofouling communities showed predictable trends of succession (Walls et al., 2017). First, filamentous algae dominated the community followed by bryozoans (Walls et al., 2017).

2.6 Faroe Islands

Conditions for *A. esculenta* cultivation are known to be good in the Faroe (Mols-Mortensen et al., 2017; Wegeberg et al., 2013). Nutrients and temperatures are generally steady throughout the growing season which provides stable growing conditions for seaweeds. The Marine Research Institute of the Faroe Islands has measured nitrate levels on the Faroese shelf since 1995, and it is well documented that sufficient nitrate is available throughout the year for seaweed growth (Faroe Marine Research Institute, n.d.; Gaard et al., 2011). Nitrate concentrations stay above 0 µM from May to September, ranging from 2.2 to 10.2 µM (Debes et al., 2008; Gaard et al., 2006; Hansen et al., 2005). Sea surface temperatures and salinity are generally consistent in the Faroe Islands, with a yearly range of 7 to nearly 11 °C and 35-35.2 salinity (ENVOFAR, 2017; Larsen et al., 2008). *Alaria esculenta* prefers full salinity (30-40) and can tolerate temperatures from -2 to 16 °C (Tyler-Walters, 2008).

The Faroe Islands produces the most brown seaweed in Europe. Producing 156 tonnes of brown seaweeds in 2019, the Faroe Islands ranked fifth in brown seaweed production behind China, the Republic of Korea, the Democratic People's Republic of Korea, and Japan (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). This small archipelago nation ranks above Norway and Spain for production despite representing less than one percent of global production of brown seaweeds (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). Only having a population of 53,000 people, the Faroe Islands have a notable impact on European seaweed production (Hagstova, 2021).

2.7 Partial harvest methodology

Most kelp species are harvested once. *Lamanaria* species grow quickly from January to May in Europe, and farmers commonly harvest the entire blade during their quick growing period (Bruhn et al., 2016; J. Zhang et al., 2012). Using this method, the entire farm has to be re-seeded after each harvest which results in high costs (Bruhn et al., 2016).

As a cost-effective alternative, some have proposed trimming kelp during their quick growing period and leaving their meristematic tissue so the seaweed can be harvested again. Conducting multiple partial harvests is expected to be less expensive and more efficient while taking advantage of the growing period. Cutting *Ecklonia maxima* 20-30 cm above their base was shown to significantly increase their harvest in South Africa (Levitt et al., 2002). In northern Japan, thinning Wakame (*Undaria pinnafida)* led to the generation of sporophytes with greater texture and quality (Gao et al., 2014).

Burg et al. (2016) economically analysed seaweed production in the North Sea and found that multiple harvests each year could improve its costs. The Faroe Island’s naturally consistent nitrate levels may allow kelp to regrow without older tissue (Bak et al., 2018; Gaard et al., 2011). Moreover, Zhang (2012) found that 90% of annual blade production of the kelp *Saccharina japonica* was lost at the blade tip due to breakage. Using multiple partial harvests where old tissue is removed may prevent tissue loss by damage.

Bak et al. (2018) trialed multiple harvests in the Faroe Islands with two species, *Saccharina latissima,* and *Alaria esculenta*. Over sixteen months, they were able to harvest four times without reseeding *S. latissima* and three-time without reseeding *A. esculenta*. Their results showed a preliminary increase in yield and decrease in costs per kilogram of *S. latissima*, but experienced seaweeds self-seeding onto *A. esculenta* lines which limited their analyses. The cost of *S. latissima* decreased by approximately 75% (€ 36.73 to € 9.27 per kg) likely due to the lower seawater temperatures and therefore lower rates of biofouling (Bak et al., 2018). This study aims to replicate the work of Bak et al. (2018) using *A. esculenta* to investigate multiple partial harvests in the Faroe Islands.

3 Research methods and analysis

3.1 Location

Fieldwork was carried out in the Faroe Islands, an archipelago located in the Northeastern Atlantic Ocean (Figure 3.1). All seaweeds were sampled from TARI's farm site (AA-02) on Kaldbaksfjord (Figure 3.2). TARI's farm produced two seaweed species, *Alaria esculenta* and *Saccharina latissima*. This work focused on *A. esculenta*.

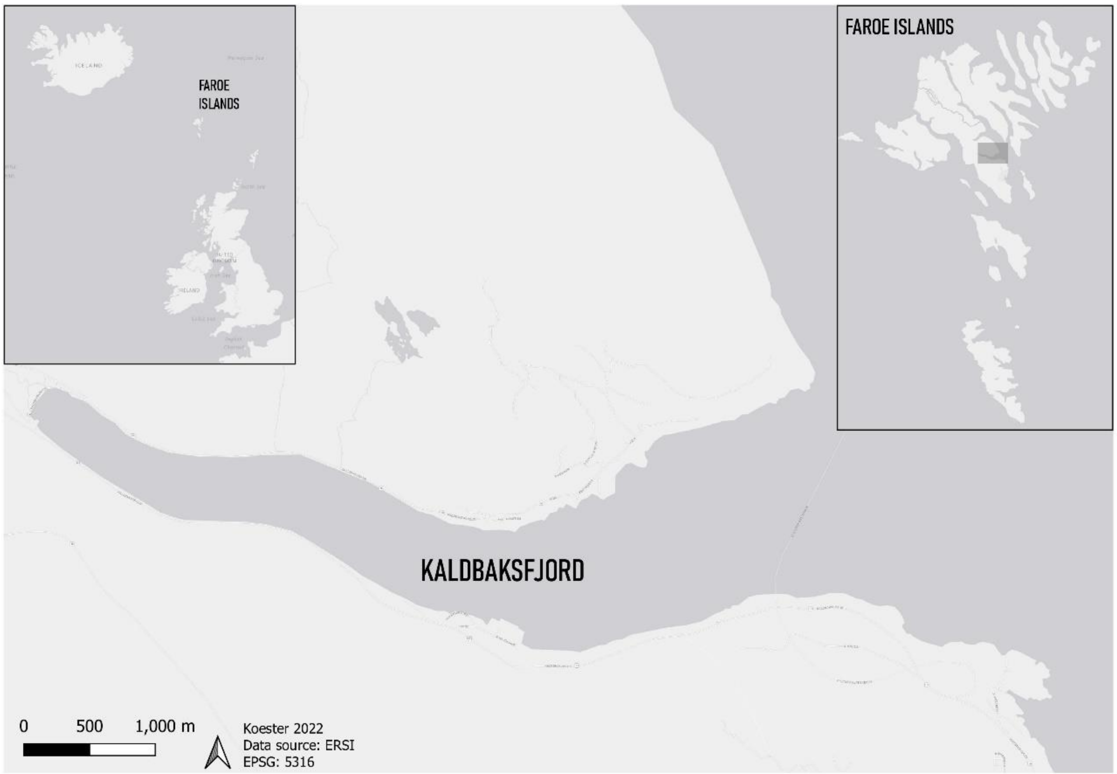

Figure 3.1 Map showing the cultivation location, Kaldbaksfjord, in the Faroe Islands. Kaldbaksfjord is highlighted on the map of the Faroe Islands (top-right).

Figure 3.2 Seaweed farm in Kaldbaksfjord as seen from the harvesting boat on August 11, 2021. Two buoys can be seen above the water supporting the long line.

Sea water nutrients at Kaldbaskfjord were sampled through a collaboration between TARI and Fiskaaling, the aquaculture research institute of the Faroe Islands. The seaweed farm site, AA-02, was included as one of the sampling sites.

Samples were collected from February to September 2020 and again from March to October 2021. During the 2020 sampling, water samples were taken at depths of 2, 4, 8, and 12 meters depth using a hand-held water sampler. In 2021, water samples were taken at the same depths and 35 m using a hand-held water sampler for the 2 m sample and Niskin bottles attached to a CTD (Figure 3.3) for the deeper samples. All water samples were collected in flasks, preserved with chloroform, and kept refrigerated until analysis.

The samples were analysed for nitrate concentration (µM) at Havstovan, Faroe marine research institute, on an autoanalyzer according to Grasshoff et al. (2009).

Figure 3.3 Fiskaaling research vessel. Niskin bottles in a rosette with an attached CTD (left) were used to sample water using the crane on board (right).

3.2 Seeding

Fertile *Alaria esculenta* individuals were collected from Kalbaksfjord on September 21, 2020. Spores were extracted from the fertile sporophylls (Figure 3.4) and seeded onto a 6 mm rope coiled around cylinders (Figure 3.5). Once seeded, the ropes were placed into tanks with seawater. LED lamps were used to generate an artificial 16 hours of light and 8 hours of darkness, and seawater was kept at a consistent temperature of 9 °C. To improve attachment success, there was no flow-through of water in the system for the first five days. After five days, the flow of seawater was turned on and the water volume was changed 6-8 times/day.

All seeding and hatchery processes were conducted by TARI at their hatchery in Nesvík.

Figure 3.4 Spore extraction from Alaria esculenta.

Figure 3.5 Seeding Alaria esculenta spores onto cylinders at TARI hatchery. Photo credit: Agnes Mols-Mortensen.

The life history developed from spore through gametophyte stage and to sporophyte stage and then the new sporophytes were given some time to increase in size before deployment. The ropes were deployed on January 15, 2021, at the TARI seaweed farm (AA-02) at roughly 4 meters depth in Kaldbaksfjord. Twenty-four 50m ropes seeded with *A. esculenta* were deployed on the farm. Eight of these lengths were used for the present study.

3.3 Sampling and Measurement

3.3.1 Harvests

Harvest 1 occurred on June 29, 2021, and harvest 2 occurred on August 11, 2021. Eight total lines of 50 m in length were used in the study. The lines were divided into total harvesting treatments, partial harvesting treatments, and control treatments. This study used three totally harvested lines (TH), three partially harvested lines (PH), and two control lines (C). C lines act as a comparison for blade characteristics. All data collected was quantitative.

All harvested tissue was collected and measured for its wet weight (ww). The totally harvested (TH) lines were harvested entirely during harvest one, removing all tissue from the ropes and cutting at the holdfast. The partially harvested (PH) lines were trimmed during harvest one (PH1), leaving the meristematic tissue for further growth. Approximately 5-15 cm of tissue was left on the basal part of the blade and the remaining tissue was trimmed as described in Bak et al. (2018). The PH lines were re-harvested during harvest two (PH2), and all tissue was removed from the ropes. Mesh plastic buckets were used to measure the seaweed biomass while harvesting. A handhold scale was used to collect the ww to the closest kg for all harvested lines (Figure 3.6**).** Control (C) lines were not weighed during analyses because they were used to compare blade characteristics over time.

Figure 3.6 Harvesting individuals at the holdfast into a mesh bucket during harvest 2. Photo credit: Mayleen Schmud

Using methods from Mols-Mortensen et al. (2017) to select samples, ten individuals from each line were cut at the holdfast (a total of 130 individuals after both harvests) and selected from varying areas of the line, placed in designated plastic bags, and kept in a cooler until analysis. Individuals from the control lines were samples in harvest one (C1) and harvest 2 (C2). Seaweed on the control lines was not weighed for biomass comparison.

3.3.2 Length, Width, Weight

All individuals were brought back to the laboratory at iNOVA for measurement. Each blade was measured for length, weight, and width using methods described in Mols-Mortensen et al. (2017). Blade length was measured from the tip to the bottom of the blade to the nearest millimeter. Blade width was measured across the largest parts of the blade to the nearest millimeter. Blade weight is measured to the nearest gram as wet weight.

3.3.3 Biofouling Analysis

All individuals were imaged for a biofouling analysis. A polystyrene cooler was used to photograph the individual blades (Figure 3.7). A hole was cut through the lid of the cooler to take photos using iPhone 7 Plus from a 29.5 cm distance. An 18 by 24 cm analysis frame was drawn into the inside of the cooler, and a 16 cm ruler was placed outside of the frame for calculating image pixels per cm (Figure 3.8).

Individuals were cut into three sections and photographed in three areas: the meristematic (bottom) region, middle section, and distal (top) region as described in Forbord et al. (2020) (Figure 3.8). If the individuals were too short, two photos were taken at the meristematic region and distal region. Occasionally, one photo would cover the entire individual.

After imaging, photos were imported to Coral Point Count with Excel Extension (CPCe) software to assess biofouling (Kohler & Gill, 2006). Photos in the first harvest were taken at 113.19 pixels per cm^2, and photos in the second harvest were taken at 118.31 pixels per cm^2 (accurate to one mm). To remove white space in the analysis, the outlined 18 by 24 cm analysis frame was shortened by 50% to a 9 by 12 cm analysis frame. Using similar methods to Forbord et al. (2020), 100 random points were assigned to the 9 by 12-inch analysis frame for each image. Biofouling organisms falling on the points were identified as the lowest taxonomic level.

Areas that did not include a biofouling organism, such as clean *A. esculenta* or white cooler space, were coded as *A. esculenta* or white space. Unidentifiable tissue, or tissue that was folded, creased, or had a biofouling organism on the opposite side, was coded as *A. esculenta*. Grazing areas were specifically coded as damage and identified by interior tears of the algal blade. Grazing damage was intended to represent damage done by organisms such as the snail species *Lacuna vincta* when they were not visible or represented in the analyses.

Figure 3.7 Polystyrene cooler used for imaging. The distance from the top to the bottom of the cooler is 29.5 cm. Seaweed individuals were placed in plastic bags (pictured on the left) in a cooler until ready for analysis.

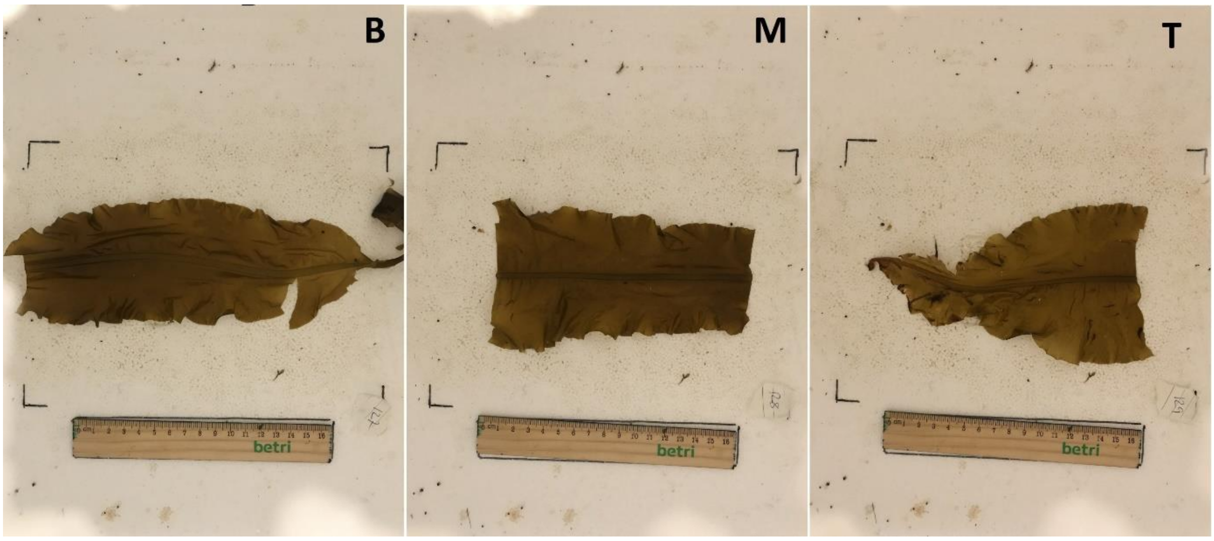

Figure 3.8 Sample biofouling image from harvest one. An 18 by 24 cm photo frame was drawn to help orient the seaweed blade correctly, a 16 cm ruler was placed within the image frame for scaling, and the image number was written in the corner.

Epibiont cover (%), frequency of epibionts, biofouled area (%), grazing (%), taxa richness, Shannon Wiener Diversity Index (H’), and Shannon Wiener Evenness Index (E) were calculated to assess the biofouling impact by treatment. Epibiont cover was calculated for each treatment by averaging the number of epibionts present in every 100 random points.

The frequency (f) of epibionts in images represented the number of photos the organisms appeared in for each harvest treatment. The biofouled area was calculated by summing each number of biofouling organisms out of 100 random points. All grazed areas out of 100 random points were averaged for each harvest treatment. All averaged values included a standard deviation. Analyses were completed from August 5-24, 2021.

3.3.4 Quality Analyses

To assess the quality of the seaweed, the seaweed samples were analysed chemically for heavy metal content and protein content in a commercial laboratory. While harvesting, 45L coolers were filled with tissue from each harvesting treatment and dried in commercial facilities. These samples were cut at the holdfast and kept in separate coolers. Samples were dried the day after harvesting in commercial facilities and kept in whole-blade form (Figure 3.9). Lot numbers were assigned to each sample to distinguish which harvest the material came from.

All sensory analyses were arranged to occur at the Sensory Laboratory at iNOVA where a tasting panel of experts is trained to analyze tastes, flavor profiles, color, and texture (iNOVA, n.d.). Samples from the first harvest control (C1) and partial harvest (PH1) were combined with samples from the second harvest control (C2) and partial harvest (PH2) respectively and compared to the total harvest (TH). Because the tissue in harvest 2 was too fouled for human consumption, the samples could not be analysed adequately.

For the chemical analysis, samples were shipped to labs that utilize standard methods. Three samples were sent to each lab: combined harvest 1 (including total harvest, partial harvest 1, and control 1); partial harvest 2 (PH2); and control 2 (C2). A combined harvest 1 sample was used in analyses due to budget and time constraints under the assumption that all seaweed grown in the same geographic area that was planted and harvested at the same time should display similar chemical contents.

Figure 3.9 Seaweed dried for quality analyses in full-blade form. Lot numbers distinguish the type of harvesting treatment that the blade received.

Three external labs were used to collect quality analysis data. Outsourcing through Thetis, a commercial Faroese lab, analyses were completed for vitamin B, C, and E; minerals P, Ca, Mg, Cu, Zn, Cr, Mo, Cd, organic and inorganic Ar; and the general nutrients fat, carbohydrates, protein, fiber, sodium, ash, salt. The national food institute of Denmark (DTU) provided bioavailability metrics and amino acid concentrations. Of the amino acid results, the 10 total essential amino acids (ΣEAA) were included in the results. The bioactivity metrics total phenolic content (TPC) and (1,1-diphenyl-2-picrylhydrazyl) (DPPH) method was detected spectrophotometrically using standard methods described in Kressig (2021). The Swedish University of Agricultural Sciences (SLU) provided alginate (% dry weight (dw)) concentrations using standard methods. All results from Thetis (vitamins, minerals, and general nutrients) were completed once per sample. Results from DTU and SLU (bioactivity and alginate) were duplicated, and their figures were represented as averages (± standard deviation). Chemical analyses were described and assessed with percent difference comparisons.

3.4 Statistical Analysis

During statistical testing, each dependent variable regarding yield and quality were compared against the harvest treatment, or the independent variables. Wet weight was analyzed by comparing all wet weights to each other and comparing a combined partial harvest wet weight to the total harvest. Blade length, blade width, blade weight, biofouling cover, individual organism cover, and grazing pressure were analyzed by harvest treatments to show changes in the blade size or biofouling impacts over time.

All data were compiled into Microsoft Excel and R (version 4.0.3) for statistical testing (R. Core Team, 2020). Aggregate functions in R were used to calculate descriptive statistics such as standard deviation and averages of dependent variables. The function ggplot 2 was used to produce figures unless stated otherwise (Wickham, 2016). The linear model (lm()) function in R was used to compare differences between the means of yield or quality measurements by their harvest treatments. Depending on the levels of the independent variable, this function performs a t-test (2-level) or an ANOVA (> 2 levels). After completing the linear model, post hoc (Tukey's Honest Significant Difference (HSD)) tests were conducted on any significant three-way linear models as a multiple comparison test because it conservatively evaluates all pairs for the largest differences (Abdi & Williams, 2021).

The chemical analyses data could not be statistically analysed in a similar way to the data mentioned above; because most of the tests were completed only once, there were not enough data points to complete ANOVA tests.

3.5 Economic Analysis

Economic analyses were completed on the total harvest and partial harvests. Data was collected on the cost of cultivation rigs, growth lines, materials for growing, deployment, growth lines, hourly vessel operations offshore, and hourly labor costs in collaboration with TARI. Information on the number of growth lines, the number of hours spent on inspections, the number of inspections, the number of hours spent harvesting, and the expected depreciation of growth lines and rigs by years was also recorded. Company records and invoices were used when available, and best approximations were provided by seaweed cultivators as needed.

All economic calculations were based on Bak et al. (2018). All calculations were completed twice to describe the TH and PH.

Equation 1

$$NR = TP - TC$$

With:

NR= net revenue
TP = total profit
TC= total costs

Net revenue (NR) of seaweed was used to assess the economic benefit when using a TH or a PH (Equation 1). Total profit (TP) and total costs (TC) were used to determine NR.

Equation 2

$$TP \ = \Sigma SW * \ MP$$

With:

Σ SW = seaweed (kg) dry weight (dw)
MP = market price per kg in DKK

To calculate yield of seaweed (Σ SW), the wet weight (ww will be converted to dry weight (dw) using a 10:1 ratio). Invoices from September 2020 – September 2021 sales were used to estimate how many dw seaweed kg will be sold at each market price (MP). Total profit (TP) in DKK is the gross benefit received by the seaweed farm at each market price (Equation 2).

Specific information on revenue was not available for the 2021 harvest because it had not been sold yet. Using data from the 2020 harvest, predictions were made on the quantity of seaweed that would sell in each market. During a non-biofouled harvest, it was estimated that 19.3% of dry weight (dw) seaweed was sold as end-consumer food (or packaged dried products), 14% were sold as food ingredients to restaurants, and 66.7% were sold as animal feed. When seaweed was overly biofouled, 100% of blades were disposed of in composting facilities for a fee. The sum of each volume multiplied by their price is the total profit (Equation 3).

Equation 3

$$TC = CAPEX + OPEX$$

With:

CAPEX = Capital expenditures
OPEX = Operational expenditures

Equation 4

$$CAPEX = (CR + M)\,(N_Y)^{-1} + (CL * N_L * l)$$

With:

CR = cost of rigs (CR),
M = materials used
N_Y = number of years in use
CL = cost of seeded lines
N_L = number of lines
L = lenth of lines

Hatchery costs are not considered because they are considered equal among the two treatments.

Equation 5

$$OPEX = OC * N_H$$

With:

OC =Operational costs
N_H = number of harvests

Equation 6

$$OC = (VC + LC)((I_h * N_I) + (H_h * N_h))$$

With:

VC = hourly vessel costs

LC = hourly labor costs

I_h = Hours spent inspecting

N_I = Number of inspections

H_h = Hours spent harvesting

N_h = Number of harvests

4 Results

4.1 Nitrate concentrations in Kaldbaksfjord

Nitrate concentrations varied notably during 2020 and 2021. During both years, nitrate concentrations were highest in the winter, declined in the spring, and began fluctuating throughout the summer (Figure 4.1). Nitrate concentrations plummeted by May during both years at all depths except for the 35m samples in 2021 (Figure 4.1). During each month in the summer, nitrate at 4m depths, the depth of the seaweed lines, frequently reached 0 µM and then increased concentrations. A similar pattern was seen in all samples taken at 2-12 m depths. Although there were relative dips in nitrate concentrations during harvest 1 (June 27) and harvest 2 (August 11), nitrate concentrations in Kaldbaksfjord rarely sustained values of 0 µM throughout the summer.

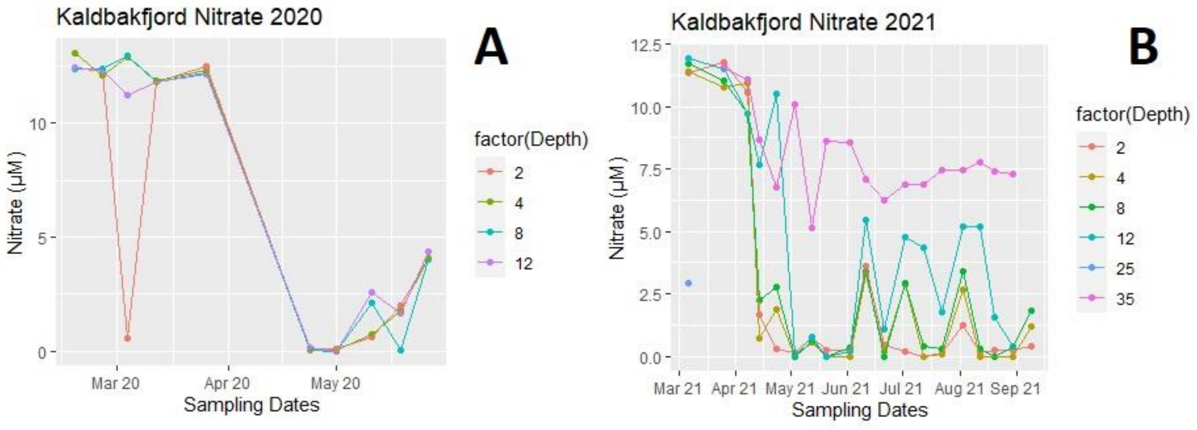

Figure 4.1 Nitrate (µM) concentrations at different depths in Kaldbaksfjord from (A) February 18 to May 27, 2020, and (B) March 21 to September 9, 2021.

4.2 Yield analysis

4.2.1 Wet weight

The average weight of *Alaria esculenta* was 49 kg in the total harvest, 24 kg in partial harvest 1, and 30 kg for partial harvest 2 (Figure 4.2). The total harvest had a significantly larger mass ($p<0.01$) compared to weights from partial harvest 1 and partial harvest 2 (Figure 4.2). PH1 and PH2 did not have a significant difference in wet weight ($p=0.32$). When combined, the total mass of the partial harvests was 54 kg (Figure 4.3). When compared with the mass of the total harvest, there was no statistical difference between combined partial harvests and the 49 kg total harvest (p=0.48).

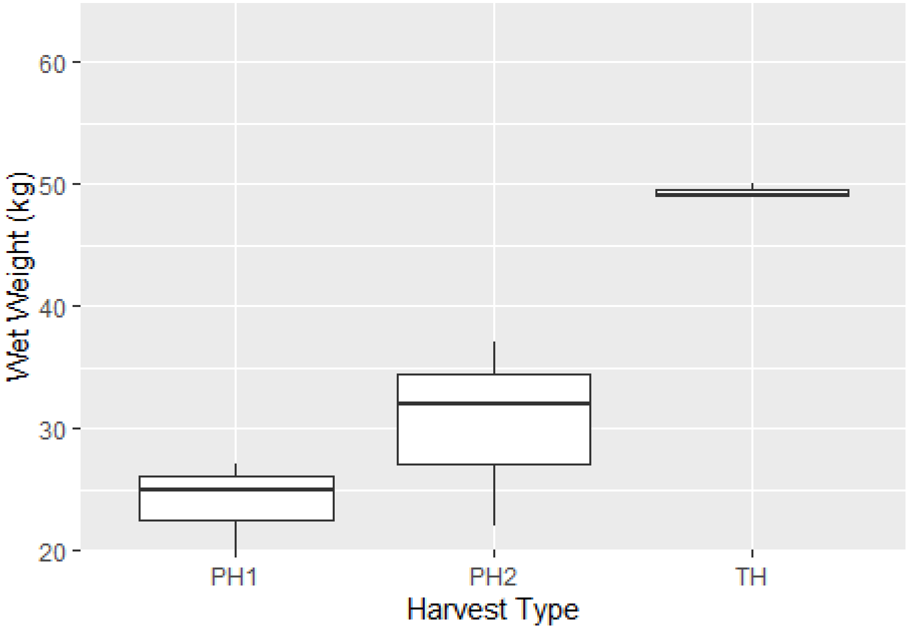

Figure 4.2 Boxplot of the wet weight compared between partial harvests 1 (PH1), partial harvest 2 (PH2), and the total harvest (TH) of the yield of Alaria esculenta (n=3 in each treatment). PH1 and PH2 were smaller than the TH (p<0.01).

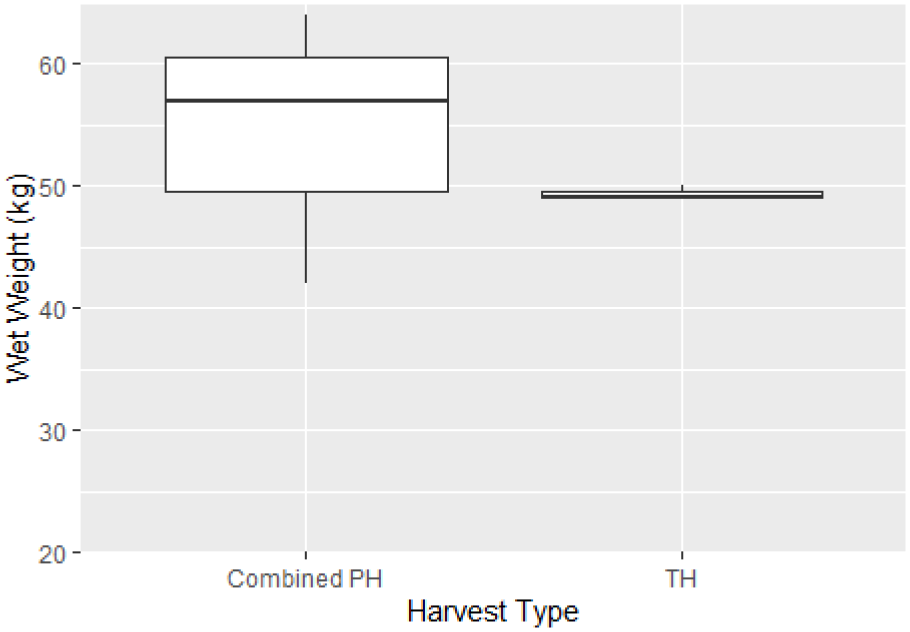

Figure 4.3 Boxplot of wet weight compared between combined partial harvests (PH) (harvest 1 and 2 summed) and total harvests (TH) of Alaria esculenta (PH n=6, TH n=3). There was no difference in wet weight between the combined PH and the TH (p=0.48).

4.2.2 Length, width, weight

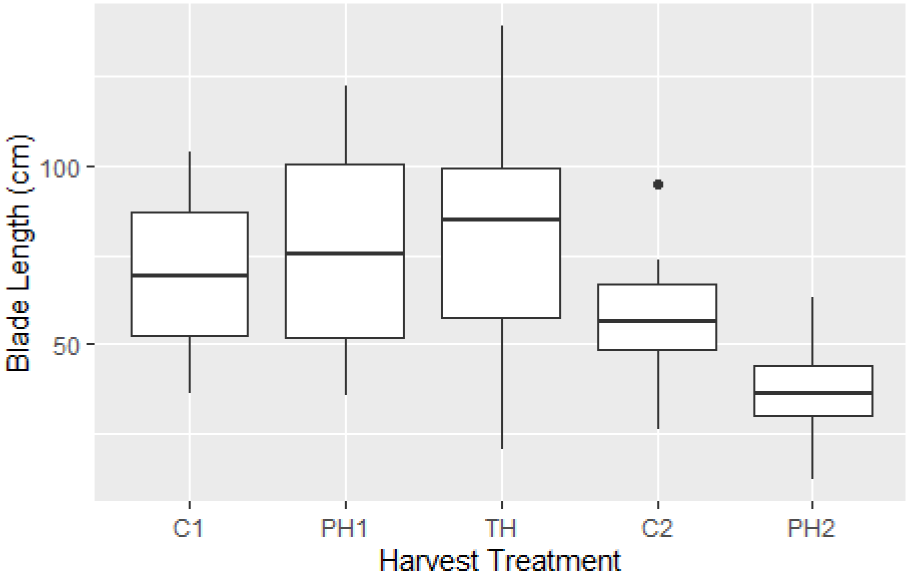

Figure 4.4 Boxplot of blade length compared among all harvest treatments. A significant difference in blade length was seen between the first and second partial harvest (PH1 vs PH2, p<0.01) as well as the second control and partial harvest (C2 vs PH2, p<0.05)).

Blade length showed a negative trend from harvest 1 to harvest 2 (Figure 4.4). During harvest 1, seaweed blades grew to an average length of 80 cm in the total harvest, 76 cm in partial harvest 1, and 70 cm in control 1 (Figure 4.4). In harvest 2, seaweed blades grew to average lengths of 36 cm in partial harvest 2 and 57 cm in control 2 (Figure 4.4). There was a significant difference between harvest 1 and 2 for the partial harvest ($p<0.01$) and the control ($p<0.05$) treatments. Average blade lengths from PH1 (76cm) were approximately double those of PH2 (36 cm). During harvest 2, blade length in partial harvest 2 was significantly smaller than control 2 ($p<0.05$). In harvest 2, average control values were approximately 1.5 times larger than partial harvest values.

Blade width ranged between 12 cm and 14 cm on average (Figure 4.5). The difference in blade width was not significant between any harvest trials ($p>0.05$). Blade weight ranged from 30 g to 45 g on average (Figure 4.6). Blade weight was not statistically different between any harvest trials ($p>0.05$).

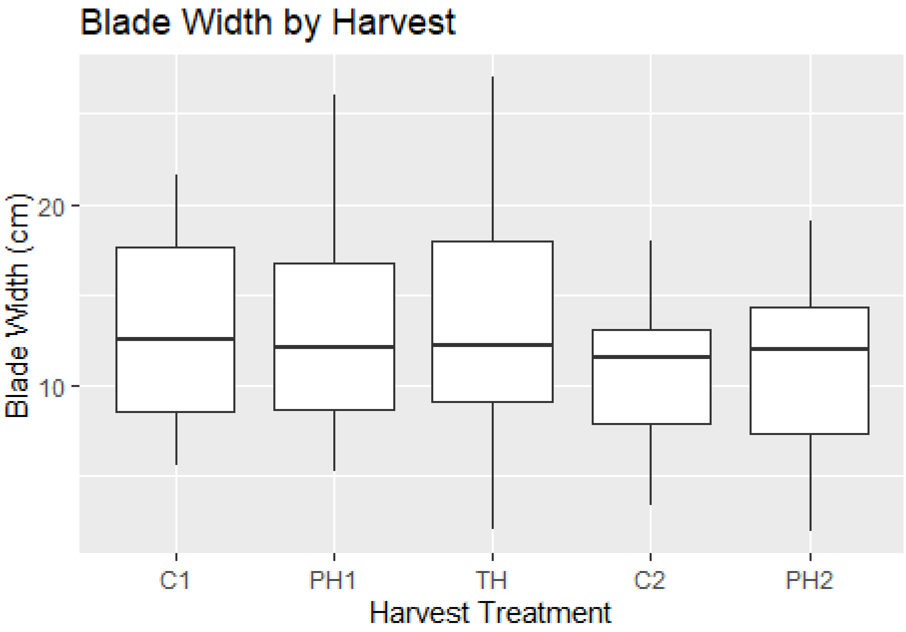

Figure 4.5 Boxplot of blade width by harvest treatment.

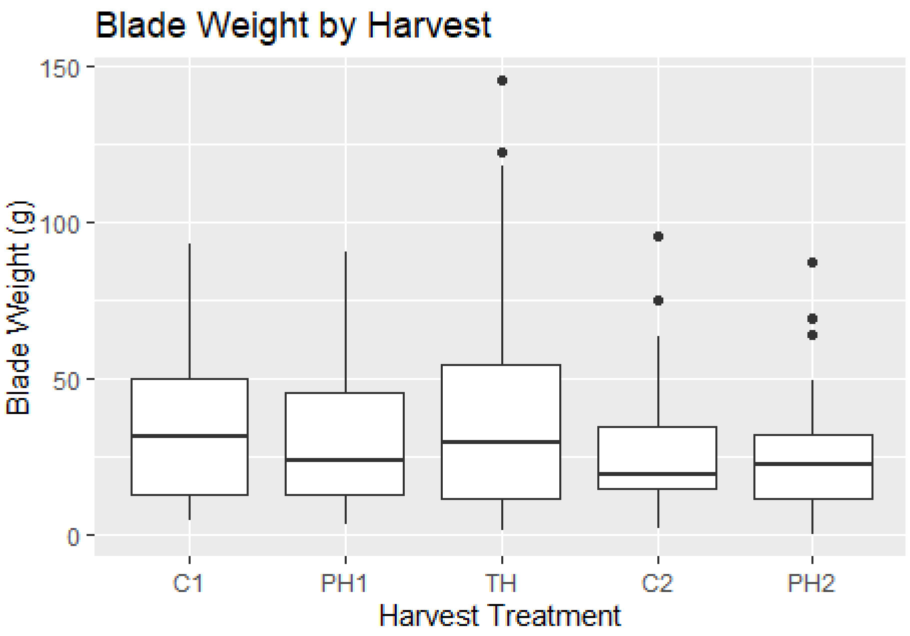

Figure 4.6 Boxplot of blade weight by harvest treatment.

4.3 Biofouling analysis

Table 4.1 Average percent cover ± SD of blade-area of Alaria esculenta covered by different epibionts and frequency (F) of epibionts at two different harvest dates, June 19 and August 11.

	Harvest 1						Harvest 2			
	Control 1 (n=56)		Partial Harvest 1 (n=81)		Total Harvest (n=82)		Control 2 (n=55)		Partial Harvest 2 (n=65)	
Epibiont Taxon	Cover (%)	F	Cover (%)	F	Cover (%)	F	Cover (%)	F	Cover (%)	F
Bryozoan	0	0	0.01 ± 0.11	1	0.02 ± 0.16	2	7.60 ± 13.93	26	6.72 ± 13.09	27
Hydroid	0	0	0	0	0.02 ± 0.16	2	0	0	0.02 ± 0.12	1
Filamentous Algae	2.36 ± 5.32	18	1.04 ± 2.05	28	4.10 ± 11.02	31	0	0	0.18 ± 1.37	2
Tunicata	0	0	0	0	0	0	0.02 ± 0.13	1	0	0
Lacuna vincta	0.05 ± 0.23	3	0.05 ± 0.22	4	0.07 ± 0.26	6	0.36 ± 0.73	14	0.11 ± 0.68	7
Thoracica	0	0	0	0	0	0	0.02 ± 0.12	1	0	0
Bivalvia	0	0	0	0	0	0	0.05 ± 0.23	3	0	0
Asteroidea	0	0	0	0	0.01 ± 0.11	1	0.02 ± 0.13	1	0	0

There was a shift in biofouling organisms from harvest 1 to harvest 2 (Table 4.1). Initially, filamentous algae were the dominant biofouling organism, with 41 colonies present, occurring in over 35% of all images in the first harvest. Later, in harvest 2, filamentous algae were replaced by Bryozoa and occurred in over 44% of all images. Bryozoan cover (%) was significantly higher in partial harvest 2 and control 2 compared to partial harvest 1 and control 1 ($p<0.001$). Filamentous algae cover was highest in the total harvest treatment, significantly outweighing all samples from harvest 2 ($p<0.001$) and partial harvest 1 ($p<0.05$).

Less common epibionts were present in both harvests including Hydroids, Asteroidea, and *Lactuna vincta* (Table 4.1). Hydroids and Asteroidea were present in >1% of images overall and did not show any trends in cover. *Lacuna vincta* cover was greatest in control 2 in comparison to harvest 1 and partial harvest 2 ($p<0.01$). Having its highest average cover in the second harvest, *L. vincta* frequency was 200% higher in control 2 compared to the partial harvest 2.

Three taxa, Tunicata, Thoracica, and Bivalvia, were only present in control 2 (Table 4.1). Tunicata and Thoracica appeared once, and there was no statistical trend in their cover. However, bivalve cover was statistically significant in control 2 in comparison to the first harvest sample and the second partial harvest ($p<0.05$).

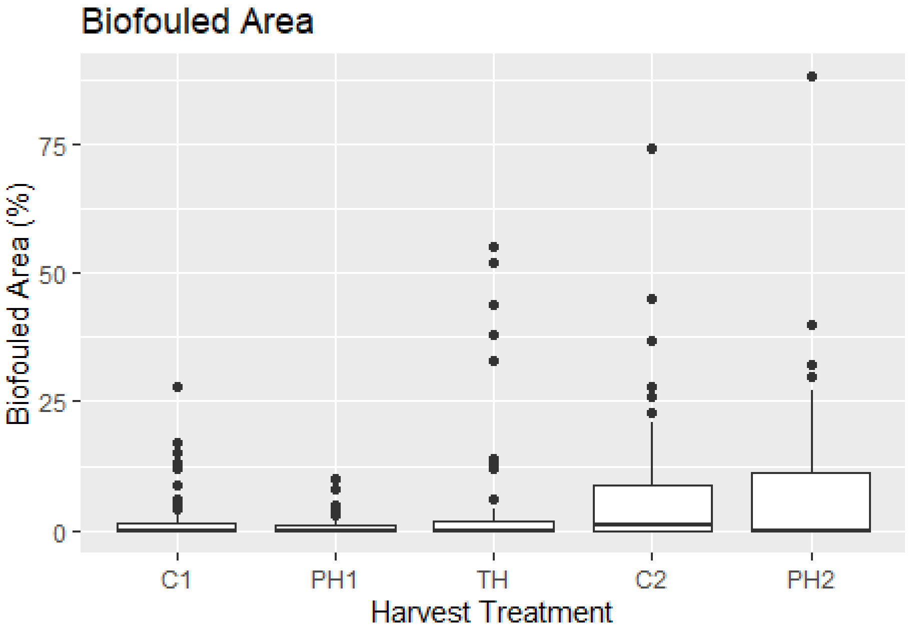

Figure 4.7 Proportion of the blade area covered by animals and plants.

The average biofouled area varied from 4% in the total harvest, 1% in partial harvest, and 2% in control 1 (Figure 4.7). In the second harvest, the biofouled area increased to 7% in partial harvest 2 and 8% in control 2 (Figure 4.7). There was no difference in biofouled area during harvest 1 ($p>0.05$). Biofouling increased significantly from control 1 to control 2 (p<0.05) and partial harvest 1 to partial harvest 2 (p<0.01). Partial harvest 2 and control 2 had no difference in biofouled area.

All samples experienced a range in grazing, with each mean being smaller than the standard deviation (Table 4.2). On average, grazing cover was less than 1% in harvest 1 (Table 4.2). In harvest 2, average grazing cover ranged from 2-4% (Table 4.2). Grazing cover (%) did not differ during harvest 1 (p>0.05). Partial harvest 2 and control 2 had greater grazing cover than partial harvest 1 and control 1 respectively (p<0.01). During harvest 2, grazing in control 2 was greater than partial harvest 2 (p<0.001).

Table 4.2 Average (± sd) biofouled area (%), grazing cover (%), taxa richness, and Shannon Wiener Diversity index (H') for each harvesting treatment. Averages were calculated using the number of images taken (n) for each harvesting treatment which varied depending on the number of experimental lines or the length of seaweed harvested.

	Harvest 1		Harvest 2		
Biofouling metrics	Control 1 (n=56)	Partial Harvest 1 (n=81)	Total Harvest (n=82)	Control 2 (n=55)	Partial Harvest 2 (n=65)
Biofouled Area (%) ± sd	2.41 ± 5.33	1.10 ± 2.07	4.23 ± 10.99	8.07 ± 13.79	7.03 ± 13.09
Grazing Cover (%) ± sd	0.27 ± 0.65	0.16 ± 0.46	0.59 ± 1.37	4.35 ± 4.53	1.98 ± 2.98
Taxa richness	2	3	5	6	4
Shannon Wiener Diversity Index (H')	0.107	0.194	0.158	0.271	0.216
Simpson's Diversity Index (p)	0.044	0.108	0.062	0.112	0.085

Measurements of the biofouling community such as Shannon Wiener Diversity Index, Simpson's Index, and taxa richness were greatest for control 2 (Table 4.2). Likewise, Shannon Index, Simpson's Index, and taxa richness were all lowest for control 1. While Shannon Index values were lowest during harvest 1 and highest during harvest 2, Simpson's Index values did not show the same trend, with the second-highest Simpson value occurring in partial harvest 1 (Table 4.2).

4.3.1 White Space and *Alaria esculenta* Coding between harvests

The cover (%) of white space and *Alaria esculenta* showed opposite trends during harvest 1 and harvest 2. When comparing white space cover, or areas analysed on images without data, between harvests, there was no difference within harvest 1 ($p>0.05$) or within harvest 2 ($p>0.05$) (Figure 4.8). Control 2 and partial harvest 2 images had a greater cover of white space compared to control 1 ($p<0.01$) and partial harvest 1 ($p<0.05$) respectively. There was no difference in *A. esculenta* cover during samples within harvest 1 or harvest 2 (Figure 4.9). However, *A. esculenta* cover values were significantly lower in Control 2 and partial harvest 2 compared to control 1 and partial harvest 1 ($p<0.01$). Therefore, harvest 1 showed less white space and more *A. esculenta* cover whereas harvest 2 showed more white space and less *A. esculenta* cover.

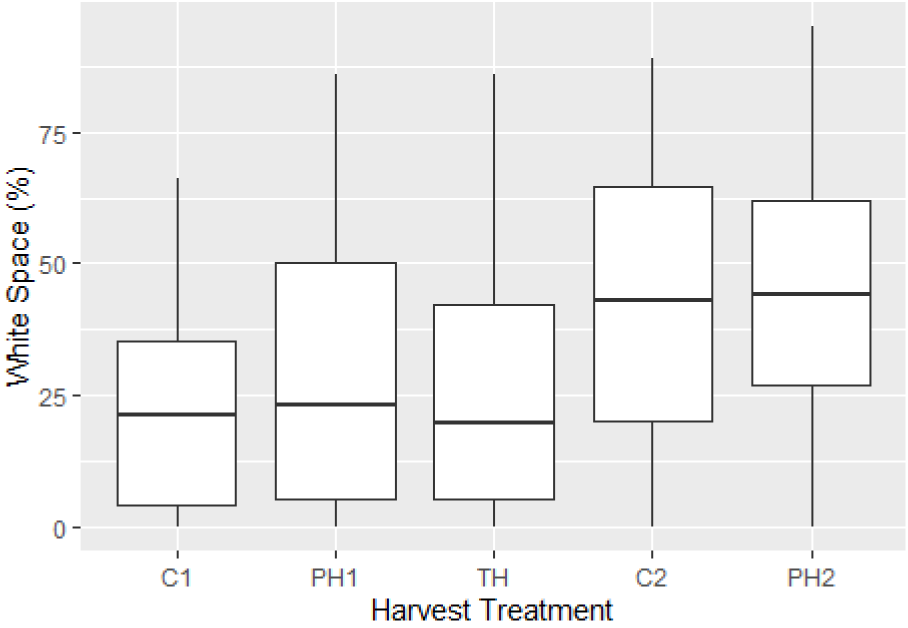

Figure 4.8 Boxplot of white space cover (area of the image frame without Alaria esculenta or epibionts) by harvest treatment. White space significantly increased in the second harvest (C2 and PH2) compared to images in the first harvest (C1 and PH1, p<0.05).

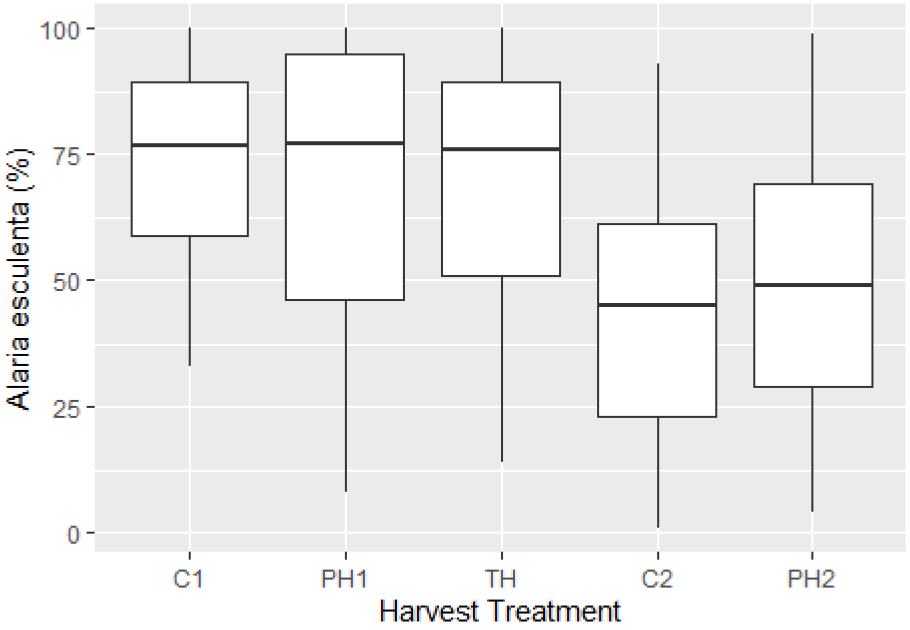

Figure 4.9 Boxplot of Alaria esculenta cover by harvest treatment. Alaria esculenta cover decreased in the second harvest (C2 and PH2) compared to the first harvest (C1 and PH1, p<0.01).

4.4 Quality Analysis

4.4.1 Sensory Panel

A sensory panel could not be conducted with the harvested samples. Samples from harvest 2 displayed heavy biofouling and were therefore deemed unsuitable for food markets. Therefore, because the partial harvest 2 and control 2 samples were unsuitable, no analyses could be completed.

4.4.2 Chemical Analyses

Table 4.3 Concentration of organic arsenic, inorganic arsenic, and cadmium found in Alaria esculenta, harvested on June 29 (Harvest 1) and August 11(Partial Harvest 2) compared with the control harvested on August 11. All values are in mg/kg dw.

Potentially harmful mineral	Harvest 1	Partial Harvest 2	Control 2
Arsenic (organic)	51.50	51.10	45.40
Arsenic (inorganic)	0.99	0.52	0.64
Cadmium	3.70	4.59	3.45

Concentrations of potentially harmful minerals were highest in harvest 1 (Table 4.3). Organic arsenic stayed relatively consistent from harvest 1 to partial harvest 2, decreasing 11% in control 2. Contrarily, inorganic arsenic peaked in harvest 1, nearly double the size of harvest 2 values. Cadmium increased ~ 25% from harvest 1 to partial harvest 2 and decreased ~15% from partial harvest 2 to control 2.

Harvest 1 samples showed the highest concentrations of manganese and calcium (Table 4.4). Manganese in harvest 1 was over 20% greater than control 2 and 28% greater than partial harvest 2. Calcium decreased over 60% from harvest 1 to other harvest samples.

Table 4.4 Concentration of iodine, manganese, calcium, iron, copper, magnesium, molybdenum, and zinc found in Alaria esculenta, harvested on June 29 (Harvest 1) and August 11(Partial Harvest 2) compared with the control harvested on August 11. All values are in mg/kg dw.

Beneficial mineral	Harvest 1	Partial Harvest 2	Control 2
I	283	262	261
Mn	4.71	3.35	3.71
Ca	29,600	11,800	11,100
Cr	0.40	0.35	0.30
Fe	103	104	122
Cu	1.29	2.74	2.73
Mg	7,760	10,600	9,750
Mo	0.55	0.78	0.54
Zn	17.70	27.40	19.00

Magnesium, molybdenum, and zinc peaked during partial harvest 2 (Table 4.4). Magnesium increased 37% from harvest 1 to partial harvest 2 and decreased ~9% from partial harvest 2 to control 2. Molybdenum was over 42% greater in partial harvest 2 compared to harvest 1 and control 2. Zinc peaked during partial harvest 2, increasing 54% compared to harvest 1 and 44% compared to control 2. Iron peaked in control 2, with values over 17% greater than partial harvest 2 or harvest 1. From harvest 1 to harvest 2, copper concentrations increased approximately 200%.

Average bioactivity measurements, total phenolic concentration (TPC), and DPPH (measured through EC_{50}) showed an inverse relationship (Table 4.5). TPC was ~72% greater in harvest 1 compared to other samples. Conversely, EC_{50} was ~80% lower in harvest 1 compared to other samples.

Table 4.5 Average (± standard deviation) of DPPH radical scavenging activity (EC_{50}) and total phenolic concentration (TPC) found in Alaria esculenta, harvested on June 29 (Harvest 1) and August 11(Partial Harvest 2) compared with the control harvested on August 11.

Bioactive compound	Harvest 1	Partial Harvest	Control 2
DPPH (± sd) (µg GAE/ g dw)	0.273 ± 0.002	1.361 ± 0.08	1.387 ± 0.016
TPH (± sd) (mg/extract mL)	59.35 ± 1.64	16.22 ± 0.13	15.93 ± 0.79

Table 4.6 Concentration of vitamins B1, B2, B12, E, and C found in Alaria esculenta, harvested on June 29 (Harvest 1) and August 11(Partial Harvest 2) compared with the control harvested on August 11. B12 values are in µg/kg. All other values are in mg/kg dw.

Harvest	Harvest 1	Partial Harvest 2	Control 2
B1	-	1.47	0.63
B2	-	4.08	2.94
B12	-	2.91	0.944
E	-	19.2	19.8
C	90.5	130	197

Harvest 1 had the lowest concentration of vitamins (Table 4.6). Concentrations of vitamin B1, B2, B12, and E were too low to detect in harvest 1 biomass. When comparing samples within harvest 2, partial harvest 2 had the highest concentration of B vitamins. Most notably, partial harvest biomass had ~63% greater B1 values and ~68% greater B12 values than control 2 (Table 4.6). Conversely, E and C peaked in Control 2. vitamin E was only 3% different between partial control 2 and partial harvest 2. However, vitamin C values were ~34% larger than partial harvest 2 and ~54% largest than harvest 1 (Table 4.6).

Total essential amino acids (Σ EAA) were highest in the second harvests (Table 4.7). Control 2 and partial harvest 2 samples had ~20% and ~18% more Σ EAA compared to harvest 1 respectively. Partial harvest 2 and control 2 were only 2% different on average. Alginate concentrations were significantly different between each treatment, peaking in harvest 1 ($p<0.05$, Table 4.7).

Table 4.7 Concentration of fat, carbohydrates, protein, fiber, sodium, ash, water, salt, alginate, and total essential amino acids (ΣEAA) (mg/g dw)) found in Alaria esculenta, harvested on June 29 (Harvest 1) and August 11(Partial Harvest 2) compared with the control harvested on August 11.

Nutrient	n	Unit	Harvest 1	Partial Harvest 2	Control 2
Fat	1	g/100g dw	0.59	0.65	0.67
Carbohydrates	1	g/100g dw	19	10.5	13.6
Protein	1	g/100g dw	12.7	17.7	14.1
Fiber	1	g/100g dw	35.1	28.3	34
Sodium	1	g/100g dw	3.07	5.1	3.82
Ash	1	g/100g dw	22.9	32.7	26.4
Water	1	g/100g dw	9.67	10.1	11.2
Salt	1	g/100g dw	7.68	12.8	9.55
Alginate (± sd)	4	% DW	22.36 ± 1.78	14.34 ± 0.55	17.83 ± 2.81
Σ EAA (± sd)	4	mg/g dw	29.00 ± 2.32	34.78 ± 1.08	35.51 ± 1.90

Beneficial nutrients (denoted as fat, carbohydrates, protein, fiber, sodium, ash, salt, and alginate) primarily peaked in harvest 1 or partial harvest 2 (Table 4.7). Harvest 1 showed the highest concentrations of carbohydrates and fiber. Notably, Harvest 1 carbohydrate content was ~45% more than partial harvest 2 and ~28% more than control 2. Fiber concentrations were only ~3% different between harvest 1 and control 2, but harvest 1 had ~19% more fiber than partial harvest 2. Alginate peaked in harvest 1, declining ~18% to partial harvest 2 and 14% in control 2 on average.

Partial harvest 2 showed the highest concentrations of protein, sodium, ash, and salts (Table 4.7). Partial harvest 2 protein concentrations were ~39% greater than harvest 1 and ~14% greater than control 2. Ash concentrations in partial harvest 2 were ~30% greater than harvest 1 and ~19% greater than control 2.

4.5 Economic Analysis

Table 4.8 Profit equations and values for Total Harvest and Partial Harvest of Alaria esculenta. All monetary values are in DKK.

	Equation	Total Harvest	Partial Harvest
Total meters of growth line	-	150	150
Total yield (kg ww)	-	148	163
Total yield (kg dw)	kg ww * 10%	14.8	16.3
Profit from biomass sold as food (end consumer)	2000 DKK/kg dw * kg dw	5,713	2,779
Profit from biomass sold as food (ingredients)	250 DKK/kg dw * kg dw	518	252
Profit from biomass sold as animal feed	100 DKK/kg dw * kg dw	987	480
Losses from biomass composted	-50 DKK/kg dw * kg dw	0	-455
Total profit	-	7,218	3,056

Total harvest profits were over 2 times that of the partial harvests (Table 4.8). While there was lower total biomass, more of the total harvest could be sold as end-consumer food products or ingredients to restaurants. None of the total harvest needed to be composted whereas the entire second harvest of the partial harvest needed to be composted. While each harvest had the same capital expenditures or was grown on the same line setup, the operational expenditures were ~1.6-2 times greater in the total harvest than partial harvest. Costs of harvesting were 4 times greater in the partial harvest compared to the total harvest. Total costs were 1.5-1.8 times greater in the partial harvest than the total harvest.

Neither harvest treatment was unable to break even (Table 4.8), but the total harvest had more appealing revenues and costs per kg (dw) (Table 4.9). Despite both values being negative, total revenue is 2.2-4.6 times less in the partial harvest than in the total harvest. Average costs per kg (dw) of seaweed were over 1.4-1.7 times greater in the partial harvest than the total harvest. Overall, the total harvest of seaweed exhibited fewer costs and greater profits than the partial harvest.

Table 4.9 Cost, revenue, and average cost equation and values for the Total Harvest and Partial Harvest of Alaria esculenta. All monetary values are in DKK.

	Equation	Total Harvest	Partial Harvest
Material cost	2,916.66 DKK cost/line * 3 lines =	8,750	8,750
Number of years materials can be used		5-10	5-10
Material cost/year	Material cost / number years	1,750 – 875	1750 – 875
Total number of lines		3	3
Costs of seeded lines/year	0.5 DKK/m * 50 m lines * n lines	75	75
Capital expenditures	Material cost/year + Cost seeded lines/year	950 – 1,825	950 – 1,825
Hours of inspection		6-12	8-16
Cost of inspections	(1,000 DKK vessel costs + 350 DKK labor costs) * hours of inspection	8,100 – 16,200	10,800 – 21,000
Hours of harvests		1.5	6
Cost of harvests	(1,000 DKK vessel costs + 350 DKK labor costs) * hours of harvests	2,025	8,100
Operational expenditures		10,125 – 18,225	19,900 – 29,700
Costs	Captial expenditures + Operational expenditures	11,075 – 20,050	20,850 – 31,525
Total revenue	Profit - Costs	-3,857 – -12,832	-17,794 – -28,469
Average cost per kg seaweed (dw)	Costs/total yield (kg dw)	748 – 1,355	1,279 – 1,934

5 Discussion

5.1 Nitrate and Kaldbaksfjord

Kaldbaksfjord appears to be an excellent location for multiple partial harvests. Nitrate stayed above at 0 µM throughout the growing season, going further (Figure 4.1). Nitrate is often the limiting nutrient for macroalgal primary productivity, making it an essential component to consider when regrowing biomass (Moss, 1969). *Alaria esculenta* are known to be effective at nitrogen uptake and can store nitrate from early in the growing season for future use (Tyler-Walters, 2008). Because Kaldbaksjford, similarly to other areas of the Faroe Islands was shown to have nitrate available throughout the growing season, the regrowth of partially harvested blades was not limited by nutrients (Debes et al., 2008; Gaard et al., 2006; Hansen et al., 2005). Moreover, during events when nitrate briefly reached 0 µM, *A. esculenta* can use stored nitrate to continue primary production. These results support the findings of á Norði et al. (2011) where nitrate concentrations fluctuated throughout the growing season in Kaldbaksfjord from 2006 to 2007. Nitrate is known to vary within Kaldbaksfjord, depending largely on the input of nutrients from outside the fjord (á Norði et al., 2011; Gaard et al., 2011).

5.2 The yield of partial harvests

Since the weight of the partial harvests, when separate or combined, did not statistically exceed total harvest weights, partial harvests did not increase *Alaria esculenta* yield (Figure 4.3, 4.4). Blade length decreased from harvest 1 to harvest 2, indicating that the biomass lost tissue over time (Figure 4.4). In particular, blade length was greater in the control than the partial harvest, indicating that the partial harvest was unable to regrow (Figure 4.4).

This decline in yield is predictable. Biomass typically decays in late summer due to erosion and biofouling impacts (Rolin et al., 2017). Biofouling and the additional weight of epibionts likely led to a decrease in wet weight and blade length throughout the second harvest. This phenomenon is very common in kelps where biofouling organisms increase the weight of the blade and severely tear blades or dislodge them from the macroalgae entirely (Bannister et al., 2019; D’Antonio, 1985; Dayton, 1985; Rolin et al., 2017; J. Zhang et al., 2012).

Although *A. esculenta* wet weight and blade length decreased from harvest 1 to harvest 2, blade width and weight remained consistent throughout all harvests (Figure 4.6). Blade width indicates that all *A. esculenta* blades grew to the same relative size, but biofouling impacts reduced their length. Blade weight was likely compensated by the addition of epibionts, despite the breakage of blade tips.

This study is the first of my knowledge to analyze *Alaria esculenta* using partial harvests. Prior studies have shown success with partially harvesting *Saccharina latissima*, but *A. esculenta* may be more prone to breakage or biofouling (Bak et al., 2018; Rolin et al., 2017). *Saccharina latissima* may also be more tolerant of blade removal or loss of photosynthetic area compared to *A. esculenta*.

5.3 Biofouling

There was a clear succession in the epibiont community from harvest 1 to harvest 2. Initially, filamentous algae dominated followed by bryozoans (Table 4.1). This species progression has been documented in other epibiont communities. For example, Walls et al. (2017) observed a succession of epibionts on *Alaria esculenta* in Ireland where filamentous algae were dominant in April followed by bryozoan (*Membranipora membrancea*) in May and June. Likewise, Forbord et al. (2020) documented a community shift from filamentous algae to bryozoan on *Saccharina latissima* in Norway. These community changes are representative of the four stages of succession discussed in Wahl (1989) where fouled surfaces are first covered with biofilms and eventually are settled by spores.

As the biofouling community changed, biofouling cover increased significantly. All samples in harvest 2 had a significantly higher fouled area than harvest 1 samples (Figure 4.7). Furthermore, all samples from harvest 1 had significantly less cover of white space and greater cover of *Alaria esculenta* (Figure 4.8, 4.10). Bryozoan covered greater percentages of blades than filamentous algae. This trend is expected, as biofouling is influenced by abiotic factors. As temperatures and light increase in the late spring and summer, epibionts typically increase in cover (Walls et al., 2017). Higher sea surface temperature (SST) has been correlated with hydroid and copepod infestations on kelps (Park et al., 2008; Park & Hwang, 2012). Therefore, bryozoan likely took advantage of the warmer temperatures in the later growing season.

While partial harvesting did not prevent the succession or cover of biofouling organisms, it appeared to impact the grazing and cover of *Lacuna vincta* gastropods. *Lacuna vincta* is a common grazer of *Alaria esculenta* and causes considerable damage to the tissue (Fralick et al., 1974; Krumhansl & Scheibling, 2011). Grazing and *L. vincta* cover were greater in harvest 2 compared to harvest 1 (Table 4.1, 4.2). However, grazing and *L. vincta* cover were lower in partial harvest 2 compared to control 2. Therefore, it is likely that the partial removal of blades successfully removed larvae of *L. vincta* from seaweed fronds and prevented grazing-related tissue damage during a second harvest. *Lacuna vincta* is a notorious grazer of kelp species, and their grazing can cause significant losses of kelp biomass (Fralick et al., 1974; Krumhansl & Scheibling, 2011). The timing of *L. vincta* on *A. esculenta* fronds can be predicted, appearing later in the growing season (Walls et al., 2017). Although partial harvesting limited the presence of *L. vincta* tissue damage, it was not represented in overall biofouling cover nor yield measurements. Therefore, this impact seems to have little benefit to the seaweed industry.

Taxa richness of epibionts did not show a clear pattern during the harvest treatments (Table 4.2). While total biofouled area increased from harvest 1 to harvest 2 (Figure 4.7), taxa richness peaked in control 2 followed by total harvest and partial harvest 2 (Table 4.1). Walls et al. (2017) found that epibiont species richness increased on *A. esculenta* blades each month of their study. Typically, one expects that greater light availability and sea surface temperatures will lead to more epibionts; these variables affect settlement, reproduction, and dispersal over time (Førde et al., 2016; Park & Hwang, 2012, 2012; Walls et al., 2017). Several factors could contribute to differences in taxa richness for harvest 1. Discrepancies in taxa richness could represent naturally occurring differences in epibiont distribution. These differences could be due to the physical distribution of larvae in Kaldbaksfjord and the placement of each seaweed line (Jessopp et al., 2007). Also, taxa richness may have varied throughout harvest 1 due to sampling errors. Harvest 1 samples were analysed in the order that they gain taxa richness, and some taxa may have been recognized as the analyses progressed. Therefore, some taxa may have been unidentified in control 1 or partial harvest 1. Finally, image analysis may have limited the ability to distinguish different taxa from one another. It was difficult to identify epibionts to their species-level strictly by their photograph. Rolin et al. (2017) experienced similar difficulties with identification via image analysis.

Nonetheless, image analysis was an effective method to monitor the change in biofouling pressure and epibiont community over time and with harvesting methodologies. Multiple specimens could be analysed from each harvest without any significant costs. After images were taken, analyses could be completed at any time. However, image analyses should not be used for studies requiring precise species identification.

Mobile organisms were documented during biofouling analyses, but they were not a part of this study. In particular, *Caprella mutica* was very common on harvest 2 samples. *Caprella mutica* is an invasive arthropod that entered European waters anthropogenically (Ashton, 2006)**.** Commonly found on artificial structures, such as aquaculture equipment, several researchers suggest that *C. mutica* use these structures to establish populations in new areas faster than they could in natural habitats (Adams et al., 2014; De Mesel et al., 2015). Invasive species compete with native species, displace native species into less favorable habitats, and can cause extinctions (Hill & Lodge, 1999). Because *C. mutica* was found on *A. esculenta* blades later in the season, partial harvest and control lines likely acted as artificial structures for their colonization. Aquaculture producers frequently pause production in a region or undergo a fallow, to minimize disease and pest pressure (Werkman et al., 2011). It may be in the interest of seaweed producers to remove cultivation equipment from the water in a fallow period to limit habitat for *C. mutica* and other invasive species.

Future studies should better investigate grow-out season length and the presence of mobile species to ensure that seaweed farms are not providing substrate for invasive species. If seaweed farmers have a long grow-out period for their species, monitoring for invasive species should be conducted to limit the spread of non-native species and assess if a fallow period would be beneficial. Because seasonality seems to have the largest impact on biofouling rather than partially harvesting, future studies should also focus on determining the ideal time for harvesting to maximize yield and quality of tissue. Future studies could attempt trials of harvests throughout the growing season to identify the onset of sea surface temperature increases and the subsequent epibiont blooms. Ideally conducted in regional areas, this knowledge would guide the most efficient use of resources throughout the growing season.

5.4 Quality Analyses

Overall, seaweed from harvest 1 was suitable for human consumption and had desirable values for select chemicals analysed. Several sought-after compounds such as calcium, TPC, carbohydrates, fiber, and alginate were highest in harvest 1 (Table 4.4, 4.5, 4.6). All analyses were conducted on dried biomass and whatever was living on it. To best represent the chemical profile of the biomass if it were brought to market, epibionts were not removed from the seaweed before chemical analyses. Therefore, all samples from harvest 2, including partial harvest 2 and control 2, include significantly more epibionts than the samples from harvest 1. Quality analyses from harvest 2 likely represent the chemical profile of the dominating epibiont, bryozoan.

Inorganic and organic arsenic was highest in harvest 1 (Table 4.3). The highest values of organic arsenic are within the ranges that have been documented in Greenlandic *Alaria esculenta* by Kreissig (2021). The Australia & New Zealand Food Standards Code denotes that seaweed must contain no more than 1 mg/kg of inorganic arsenic, but other food regulatory institutions have not regulated inorganic arsenic (Food standards Australia New Zealand, 2013). While the UK has created regulations on total arsenic in food at 1mg/kg, this limit excludes seaweeds. The samples with the highest concentrations of inorganic arsenic were all below 1 mg/kg (Table 4.3). Several countries, including the UK and Canada, also have regulations discouraging the consumption of hijiki seaweed (*Sargassum fusiforme*) for its high arsenic levels and potential health risks (Food standards Australia New Zealand, 2013). The inorganic arsenic concentrations of *A. esculenta* should be montiored to ensure that it is safe for human consumption.

Epibionts and age may have affected the bioapsorbtion of arsenic in *A. esculenta.* Most arsenic absorbed by brown seaweeds is stored as arsenosugars, a less toxic form of inorganic arsenic to humans (Taylor & Jackson, 2016). The epibionts living on control 2 lines may not absorb arsenic at the same rates as *Alaria esculenta* tissue. Moreover, Ronan et al. (2017) found that inorganic arsenic concentrations increased from meristematic regions toward the blade tip in kelp species. Control 2 lines may have lost older tissue, or tissue at the tip, over time which could lead to decreased inorganic arsenic concentrations.

Cadmium concentrations were high for each harvest, peaking in partial harvest 2 (Table 4.3). All values exceed those found in Greenlandic *A. esculenta* (Kreissig, 2021). Partial harvest 2 values were over two times the cadmium concentrations found in French *A. esculenta* in Stévant et al. (2018). High cadmium levels have been reported in seaweeds sold in Europe (Almela et al., 2006; Besada et al., 2009). Cadmium exposure is associated with several negative health impacts such as bone and renal diseases, but there is no direct evidence for seaweed consumption is associated with negative physiological impacts (Järup, 2002; Cheney, 2016). The partial harvesting process may have led to greater bioabsorption of cadmium.

Differences in cadmium absorption may be due to differences in alginate concentration and tissue structures between treatments. Davis et al. (2003) outlined the role of cell-wall carbohydrates and their role in heavy metal absorption in fucoid species, noting that alginate concentration is linked to cadmium absorption. However, alginate concentrations were highest in harvest 1, and concentrations of alginate were slightly higher in partial harvest 2 than in control 2 (Table 4.6). Declining alginate over time has also been observed in Schiener et al. (2015) where alginate concentrations from June to September in *A. esculenta*. Stévant et al. (2018) suggest that differences in alginate structure could affect overall cadmium concentration. Partially harvest seaweed may have altered alginate chemical structures between partial harvest 2 and control 2 harvests, but that is outside the scope of this study.

Iodine concentrations were relatively stable between harvest treatments. All samples were under 300 mg/kg dry weight, a relatively low value in comparison to other seaweed species. For example, European *Saccharina latissima* can contain up to 6500 mg/kg dry weight of iodine (Stévant et al., 2018). It is recommended that adults consume 600 µg iodine/day, but there are no regulations regarding maximum level of iodine in seaweed or other food products (Nielsen et al., 2020). *Alaria esculenta* may be an effective source of iodine as a supplement where consumers could use it as a seasoning without the fear of overconsuming their daily consumption level.

Alginates provide numerous biochemical applications for seaweeds and benefits for human health. Food and non-food industries chemically extract alginates from seaweed to use as stabilizers in the food and non-food sectors (Cai, Lovatelli, Stankus, et al., 2021). Zhang et al. (2021) summarize in a literature review that products from alginate have antimicrobial, anticancer, anti-inflammatory, antioxidant, and immunostimulatory characteristics. Alginates will readily decompose into organic matter, also making seaweeds ideal for fertilizers (Nabti et al., 2017). Alginate in harvest 1 was similar to previously documented concentrations, dipping in harvest 2 (Davis et al., 2003; Stévant et al., 2018). Thus, partially harvesting seaweed did not benefit the creation of alginates and limits the biochemical applications of *A. esculenta*.

Protein concentrations shifted with changes in the biofouling community. Total essential amino acids increased with time, representing the addition of epibionts in samples as the seaweed became fouled (Table 4.6). This pattern has been observed by Mols-Mortensen et al. (2017) where *Saccharina latissima* grown in May or June had a greater essential amino acid score and protein concentrations than fouled biomass grown in July or August. Similarly, *Saccharina latissima* grown in Norway experienced greater protein concentrations with bryozoan blooms in late summer (Forbord et al., 2020). However, *A. esculenta* protein concentrations decreased from March to July in Schiener et al. (2015). In the present study, protein concentrations were highest in partial harvest 2 and lowest in control 2 (Table 4.6). Therefore, control 2 experienced the highest essential amino acid scores and the lowest protein concentrations. The difference in the biofouling community between control 2 and partial harvest 2 may account for the differences in protein concentration.

Antioxidant levels were highest in harvest 1. TPC values from harvest 1 were over 16 times the values of Greenlandic *Alaria esculenta* found in Kreissig (2021). Decreasing in harvest 2 samples, partial harvest 2 and control 2 were over four times greater than Greenlandic *A. esculenta*. It is well-known that brown seaweeds have large amounts of phenolic compounds that act as antioxidants (Sappati et al., 2019).

TPC and DPPH radical scavenging activity, measurements of antioxidant activity, had an inverse relationship. The unit, EC_{50}, is the concentration of a substance needed to generate a 50% antioxidant effect against free radicals (Chen et al., 2013). Therefore, the lower the EC_{50} value, the higher the potency. DPPH was lowest in harvest 1 and increased during harvest 2 (Table 4.5). This indicates that antioxidant scavenging abilities were stronger in harvest 1 than in harvest 2. This agrees with TPC values or total antioxidant concentration values. DPPH values for harvest 1 are approximately half and harvest 2 values are approximately four times that recorded in Greenlandic *A. esculenta* (Kreissig, 2021). Regarding TPC and DPPH, this study may have shown particularly large antioxidant concentrations or scavenging abilities in Faroese-grown *A. esculenta* or encountered a lab error. Future studies should confirm the TPC and DPPH values from this study. Because antioxidants determine the quality of proteins, confirmed values could guide the industry on what species to farm for food or extract antioxidants from. Food and cosmetic industries often use seaweed antioxidants to replace synthetic antioxidants in their products (Ronan et al., 2017). *Alaria esculenta* may make an excellent replacement for synthetic antioxidants.

Although harvest 1 contained copious amounts of antioxidants, the samples had the lowest quantities of vitamin B, C, and E (Table 4.6). The increase of bryozoan in harvest 2 likely led to an increase in B, C, and E vitamins. Seaweeds have been shown to have healthy amounts of vitamin B and B_{12} (Phaneuf et al., 1999). B vitamins peaked in partial harvest 2, likely representing the chemical composition of its epibionts compared to control 2. Vitamins C and E are well-known to have antioxidant properties (Bendich et al., 1986; Burton & Traber, 1990; Yamauchi, 1997). Bryozoan may have high antioxidant properties, shown through the concentrations of vitamin C and E, that were not represented through TPC or DPPH. Supplementation of vitamin C and E is of interest to the pharmaceutical industry to reduce the impacts of free radicals (Sitorus & Anggraini, 2017). Moreover, deficiencies in micronutrients such as calcium, iron, zinc, vitamin B12, and vitamin C lead to the death of approximately 1 million people annually (Micha et al., 2020). If biomass is too heavily fouled, it usually cannot be used for human consumption and may be thrown away (Rolin et al., 2017). Heavily fouled tissue could be used for supplements in the future, particularly if they contain high quantities of bryozoan. Future studies should investigate the creation of marine supplements from fouled seaweed biomass and its potential role in the health-foods market.

Most quality analyses were not duplicated due to financial constraints. Apart from TPC, DPPH, Alginate, and essential amino acids, all quality analyses were conducted once per sample. Because duplicates were not used, it is difficult to tell if discrepancies in values are due to sampling errors. For example, samples used in a partial harvest may have been more regionally fouled than samples used in control 2 for specific tests. Without understanding the chemical composition of the entire sample, or across a blade surface, it is difficult to better understand the chemical processes occurring within partial harvests.

5.5 Economic efficiency of partial harvests

Economic analyses solidify that partially harvesting is not an effective harvesting method for seaweed farmers. Despite producing more biomass overall than the total harvest, partial harvests yielded less profit for their harvests (Table 4.8). Partially harvested seaweed also had greater costs due to double the harvesting time, requiring more attention to detail (Table 4.9).

Neither harvest treatments were economically sustainable, with costs outweighing the profits in both treatments (Table 4.9). However, the costs in this study were estimated to be higher than they may be. Values used in operational expenditures were conservative, using the highest wage rates and fuel rates that TARI could pay. TARI also uses second-hand aquaculture equipment for their grow-out materials, often obtaining them at very low costs. This study used prices for new equipment to estimate the capital expenditures for better comparison between other studies. Costs for hatchery and seeding processes were not included in this study because they were the same for each treatment.

Optimistically, this study included costs to compost fouled biomass at a biogas facility to eventually turn it into a liquid fertilizer (Table 4.9). Although fouled seaweed is not currently being composted into fertilizer, kelps are known to be a good fertilizer shown to improve soil conditions (Nabti et al., 2017). In the future, fouled biomass could be composted and made into a marketable fertilizer. If a market was established, this relationship could prevent the waste of fouled biomass, generate energy, and produce a high-quality liquid fertilizer for residents. Some salmon aquaculture facilities use their mortalities to produce commercial fertilizers, and a similar approach could be used with waste biomass produced on seaweed farms (Lo et al., 1993). A Faroese salmon aquaculture company, Bakkafrost, currently operates the biogas facility in the capital (Tórshavn) called Førka, producing energy and liquid fertilizers with their mortalities (Bakkafrost, 2019). Roughly 500 DKK could be spent to digest biofouled seaweed in Førka, but this relationship has not been established yet. Therefore, partial harvest profits could be roughly 500 DKK higher, but this does not offset profit differences with the total harvest.

There is a known market for biofertilizers with room for expansion and improvement (Nabti et al., 2017). Moreover, there is a potential for heavily fouled biomass to be converted into nutirtional supplements or other products. Utilizing waste from the seaweed aquaculture process could improve the profits and economic sustainability of the industry.

Profit values were estimated, using previous sales records to indicate the percentage of harvest sold to consumers, restaurants, and livestock farmers (Table 4.8). These values are the best estimate of profits received by the current harvest, but they can easily vary with tastes and preferences or regional demand. If local restaurants change their menus to include more *Alaria esculenta* on their menu, or if consumers gain interest in seaweed products, less biomass would be diverted to feed, and profits would increase.

Because many of the values in the economic analyses were based on assumptions from prior harvests, future studies should focus on completing full economic audits. Collecting data over several years, determining the longevity of cultivation structures, assessing the efficiency of hatcheries, and evaluating the market would generate a much-needed insight. These analyses could guide future research on creating more efficient seaweed farms, producing new harvesting methodologies, or finding a way to connect with consumers. Most importantly, these studies can guide the industry into methodologies for becoming more economically sustainable.

5.6 Partial harvests and lumpfish

Partial harvests were unsuccessful in producing food-quality seaweed, but they may be beneficial for non-food uses of seaweed. Preliminary research and industry trials are placing living seaweed lines inside salmon cages as a substrate for lumpfish cleaner fish. Lumpfish (*Cyclopterus lumpus)* is an alternative method to manage sea lice in the salmon aquaculture industry, feeding off specific parasites living on the fish (Powell et al., 2018). Facing high mortalities within salmon pens, artificial and living lumpfish shelters allow the fish to settle and rest (Imsland et al., 2015; Vedvik, 2021). Living seaweed shelters for lumpfish are used in salmon aquaculture pens in the Faroe Islands. The shelters are called AkvaNest and produced by TARI. *Lacuna vincta* grazing can be a challenge to the longevity of the AkvaNest (Mols-Mortensen, personal communication August 2021). Partially, harvesting the seaweed from living lumpfish shelters may be an effective method to reduce the grazing pressure from *L. vincta*, prolonging the life of the AkvaNest.

5.7 Future of *Alaria esculenta*

Alaria esculenta has good potential to sell on the European market. European seaweed cultivation has previously focused on *Saccharina latissima* due to its hearty yields (Handå et al., 2013). However, this study illustrated that *A. esculenta* iodine concentrations are significnalty less than *S. latissima.* Minor iodine defeciencies or over consumption of iodine can lead to severe thyroid disorders (Smyth, 2021). Because of its lower iodine concentrations, it may be easier to advertise *A. esculenta* as an iodine supplement as consumers can eat more *A. esculenta* in a single serving, leading to larger quantities of consumption. Seaweed producers may be interested in growing a product that can be more heavily consumed, such as *A. esculenta*, compared to *S. latssima* over time. Despite having a positive nutritional profile, the *A. esculenta* industry is likely limited by the cost of production. Establishing more economically efficient methods will be vital for the future success of *A. esculenta*.

5.8 Policy recommendations

The seaweed industry is young, and policymakers can play a large role in establishing the economic success of the industry. Cai, Lovatelli, Stankus, et al. (2021) recommend the combined efforts of policymakers, industry members, academia, and stakeholders to foster the three A’s – making seaweed aquaculture “acceptable, available, and affordable.” Collaborative programs will be integral in increasing demand for seaweed products, gaining the trust of the public, and establishing best practices for the industry moving forward. Local food systems are known to be a stable markets, but stakeholders' cooperation is necessary to develop long-term dietary changes (Cai, Lovatelli, Aguilar-Manjarrez, et al., 2021). Potential programs could include outreach and educational events for coastal communities such as cooking courses, online industry training, and K-12 curriculum development (Augyte et al., 2021). Third-party labels, certifications, and increased regulations can also be established to develop trust with consumers. Augyte et al. (2021) recommend that state and federal agencies work with academics to create regulatory frameworks and sustainability certifications. New food safety standards would help consumers make informed choices about local products and uphold positive reputations for seaweed companies (Augyte et al., 2021).

6 Conclusions

Findings in this study highlight the impacts of biofouling on *Alaria esculenta* from June (harvest 1) to August (harvest 2). Partially harvesting seaweeds during each harvest did not mitigate the impacts of biofouling. All samples collected in harvest 2 had lower blade lengths, bioactivity measurements, and revenue. Harvest 2 also had greater biofouling cover and costs. Seasonal changes in sea surface temperature likely led to an increase in biofouling, leading to tissue damage (Førde et al., 2016; Park & Hwang, 2012, 2012; Walls et al., 2017). All *A. esculenta* collected in harvest 2 (partial harvest 2) was so fouled that it could not be sold as human food, dramatically reducing profits and revenue.

Based on the results, two key future studies should be conducted. First, yield, biofouling (including mobile organisms), chemical composition, and potential profit should be analysed for *A. esculenta* harvested each week from May to August. This study will determine the ideal harvesting time for *A. esculenta* based on the yield and quality of seaweed. Understanding the timing of harvests is integral for limiting waste, generating the highest revenues, and avoiding seasonal biofouling blooms. Investigating the presence of mobile and sessile biofouling organisms will also determine if non-native organisms, such as *Caprella mutica* utilize cultivation lines as artificial structures to establish their populations. A parallel study or the same study could also investigate the benefit of a fallow period on *C. mutica* or other non-native organisms‘ populations. Seaweed farmers of all species should ensure that their cultivation lines are not supporting the establishment of non-native species in their region. Because larval pools, nutrient availabilities, and sea surface temperatures vary widely amongst different fjords or locations, this study should be replicated by any seaweed harvester looking to optimize their harvest.

Secondly, an analysis should be conducted on the market potential for supplements or fertilizers from heavily fouled *A. esculenta* and other seaweeds. Because seaweed farmers frequently dispose of their heavily fouled seaweed, and they have been found to have high concentrations of beneficial nutrients, beneficial products could be produced from industrial waste. Moreover, supplements and fertilizers could naturally add nutrients to soils or provide essential nutrients to malnourished populations. This study should include the feasibility of producing supplements or fertilizers from *A. esculenta*, interest from consumers, and potential limitations.

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Háskólasetur Vestfjarða
University Centre of the Westfjords

Appendix A

Research ethics training and clearance

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This letter certifies that Jennifer Koester has completed the following modules of:

(X) Basic ethics in research
(X) Human subjects research
(X) Animal subjects research

Furthermore, the Masters Program Committee has determined that the proposed masters research entitled **How to Grow Like a Weed: The Economic and Environmental Effects of Seaweed Partial Harvesting in the Faroe Island**s meets the ethics and research integrity standards of the University Centre of the Westfjords. Throughout the course of his or her research, the student has the continued responsibility to adhere to basic ethical principles for the responsible conduct of research and discipline specific professional standards.

University Centre of the Westfjords ethics training certification and research ethics clearance is valid for one year past the date of issue unless otherwise noted.

Effective Date: 18 June 2021
Expiration Date: 18 June 2022

Prior to making substantive changes to the scope of research, research tools, or methods, the student is required to contact the Masters Program Committee to determine whether or not additional review is required