Master's thesis

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Norwegian University of Science and Technology
Faculty of Natural Sciences
Department of Biology

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The Effect of Cropping on Growth Yield in *Saccharina latissima*: a Norwegian Case Study

Master's thesis in Ocean Resources
Supervisor: Kjell Inge Reitan
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Abstract

Seaweeds, such as *Saccharina latissima*, have become very attractive for human applications due to their nutritional value in human food and animal feed, as well as their qualities as ingredients in cosmetics, pharmaceuticals, and nutraceuticals. Their applications in human industries have led to an increased pressure on wild stocks, and a need to upscale kelp cultivation. Partial harvest through cropping has been investigated by studies in the Faroe Islands (Bak et al., 2018), Shetland Islands (Rolin et al., 2017) and South Africa (Levitt et al., 2002), as a way to increase biomass yield without having to reseed, in other words, increasing the total biomass from each plant obtainable in one cultivation season. The present study investigated the seasonal biomass yield of S. latissima in one season for two different deployments, October 2021 and January 2022, as well as regrowth rates after cropping in April, June and both April and June 2022. The results showed that cropping in April led to a regrowth of 113.41% 113.06% in the October deployment, and 144.46% and 125.75% in the January deployment. Cropping in June did not result in regrowth. The highest biomass yields were found for the treatments cropped once in April with a biomass yield of 2098 kg in the January deployment and 2034 kg in the October deployment, which was more than double the biomass from Control (833 kg for October and 721 for January). The qualitative seasonal pattern of bryozoan fouling was also investigated, and was found to be negligible until June, but severe in July and August. The present study recommends future studies to investigate biofouling on cropped treatments as well to determine whether cropping could decrease biofouling levels. Future studies are also advised to include an economic aspect to determine whether the extra biomass gained through cropping would compensate for the costs of multiple harvests. Further investigation on whether cropping would result in more un-fouled biomass than non-cropped biomass is still needed, as this could add to the potential economic benefits from cropping as a cultivation strategy. The results of this study show that cropping can increase total biomass yields for one growth season, compared to conducting just one full harvest in spring, as is typical for the Hitra-Frøya region (Førde et al., 2015), where this study was conducted.

Sammendrag

Tare er svært viktige i det marine økosystemet, blant annet som primære produsenter gjennom fotosyntese, som habitat for andre marine organismer, og på grunn av deres evne til å ta opp næringsstoffer fra omgivelsene. Arter som for eksempel *S. latissima* har også vist nyttige kommersielle egenskaper i mat og dyrefôr, samt som ingrediens i farmasøytiske- og kosmetiske produkter. Disse egenskapene har ført til en økt etterspørsel, som har skapt et stort press på de naturlige tare bestandene. Det er derfor et behov for økt taredyrking for å møte denne etterspørselen. Å utføre flere høstinger i løpet av en sesong har blitt foreslått som en effektiv metode å øke biomasse i taredyrking på. Dette kan gjøres ved å beskjær plantene 20 cm ovenfor meristemet (hvor vekst cellene blir produsert), og la den nederste planten være igjen. Ved å la den nederste delen av planten med meristemet bli igjen vil dette skape en mulighet for gjenvekst, og dermed økt biomasse uten å plante flere ganger på én sesong, og kan dermed også redusere produksjonskostnadene. Dette prosjektet undersøkte gjenvekst, og biomasseutbytte av *S. Latissima*, samt begroing av mosedyr og snegler. Resultatene viser at beskjæring i april, etterfulgt av full høsting i juli, fører til høyere biomasse utbytte sammenlignet med kun én høsting i juli, for planter satt ut i både oktober og januar. Resultatene viser også at begroing var ubetydelig tidlig i sesongen, men svært utbredt i juli og august. Beskjæring kan potensielt redusere begroing, ved å la nytt, friskt vev vokse frem, og føre til mer biomasse av økt kvalitet. Tare uten begroing kan brukes til produkter av høyere kvalitet, og kan dermed medføre økt økonomisk gevinst. Dette ble ikke undersøkt i denne studien og det anbefales derfor at fremtidige studier undersøke om den taren som er beskåret has mindre begroing sammenlignet med taren som kun er høstet én gang på slutten av vekstsesongen. Det vil også være nyttig for videre forskning å inkludere et økonomisk aspekt for å fastslå om den økte biomassen fra beskjæringer kompenserer for ekstra kostnader ved flere høstinger. Denne studien støtter resultater fra tidligere studier (Levitt et al., 2002; Rolin et al., 2017; Bak et al., 2018) som stadfester at beskjæring kan øke den totale biomassen av tare i løpet av én sesong, sammenlignet med én innhøsting på slutten av sesongen.

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1.Introduction

1.1 Macroalgae

Macroalgae are photosynthetic organisms divided into three main groups based on their photosynthetic pigments, storage food products, cell wall components, fine structure of cell, and flagella (Sahoo and Seckback, 2015); Chlorophyta (green algae) with chlorophylls a and b, Rhodophyta (red algae) with chlorophylls a and d, and Phaeophycea (brown algae) with chlorophylls a and c. All groups have chloroplasts, and therefore photosynthetic capacity which makes them essential as primary producers in the marine environment (Littler and Littler, 2011). There are three functional groups of macroalgae: algal turfs, upright macroalgae and crustose calcareous algae (El- Manawy, 2008). They are fundamental in the marine ecosystem and provide energy for higher trophic levels, and function as ground pillars of marine food webs (Steneck et al., 2002; Hurd et al., 2014). Brown algae, also commonly referred to as kelp or seaweeds, belong to the upright macroalgae group (Pereira and Cotas, 2020) and are dominated by fucoxanthin carotenoids. They also have alginates in their cell walls, which can be extracted for commercial use in emulsifiers, anticoagulants, textile, and rubber.

Abiotic factors such as light, temperature, and salinity typically affect species composition, distribution, and physical performance of kelp (Brown et al., 1997; Hurd et al., 2014; Brodahl, 2018). Light is essential for photosynthesis and determines growth and productivity (Brodahl, 2018). Temperature and salinity affect nitrogen content, which is the limiting factor of growth and reproduction, colder temperatures have been linked to higher nitrogen content, while higher temperatures lead to lower content (Brown et al., 1997; Brodahl, 2018). As these factors, and other abiotic factors affect biochemical composition and create nutritional quality changes of kelp throughout the season, this also affects grazing activity, and commercial value. Therefore, abiotic factors need to be considered when cultivating seaweed.

1.2 *Saccharina latissima*

Saccharina latissima is a fast-growing seaweed belonging to the class *Phaeophyceae* (brown algae), and order *Laminariales*. This species is native to the Norwegian coastline, and between 25-50% of the world´s *S. latissima* grows in Norwegian waters (Moy et al., 2006). *S. latissima* has a seasonal growth pattern with strongest growth in spring when new tissue is formed in the meristem at the base of the blade. In summer the growth stops, and the plant produces spores for reproduction (Moy et al., 2006). Growth is influenced by other factors than season, such as latitude, environmental conditions, life stage and blade size (Zhang et al., 2012; Kerrison et al., 2015). Larger plants generally have a higher rate of tissue loss compared to growth rate which makes them more fragile and easily torn apart by wind-and wave action when they are at their largest in summer and autumn (Parke, 1948; Saunders and Metaxas, 2008; Andersen et al, 2011; Nielsen et al., 2014).

1.2.2 Commercial value of cultivation

Seaweeds have been used for human consumption and feed in aqua- and agriculture due to their nutritional profile, they have high content of fiber, and minerals, as well as high contents of Omega-3 fatty acids (Holdt and Kraan, 2011; Ferdouse et al., 2018). Ferdouse et al. (2018) reported that 82% of macroalgae produced globally was used for human consumption, 12,2% for cosmetics, and pharmaceuticals, 2,9% used for animal feed, and 2,6% for fertilizers in agriculture. Seaweeds are attractive as ingredients in cosmetics and pharmaceutical products due to their vitamins, pigments, and antioxidants (Ferdouse et al., 2018). Furthermore, species with high nitrogen content are considered very nutritious, as nitrogen are the building blocks of proteins and promotes growth (McShane et al., 1994; Fleming, 1995a; Angell et al., 2016), and are therefore attractive for the food-and feed industries.

S. latissima is commonly harvested for its alginates (Christie et al., 1998; Guiry and Morrison, 2013), and increasingly harvested for its use in production of food and biofuels (Kraan, 2013; Kerrison et al., 2015). The wide range of applications have led to a high demand and pressure on wild kelp populations from manual and mechanical harvesting, promoting an increase in kelp cultivation. Several cultivation techniques have been developed, such as cultivating sporophytes directly on spools and transferring them to longlines or droppers, and cultivating kelp directly on nets and textiles. However, more studies are needed to optimize cultivation and harvesting techniques to further improve cost-effectiveness and production.

Seaweed cultivation has many advantages such as carbon sequestering, nutrients removal, and coastal protection of erosion (Arkema et al., 2013; Charrier et al., 2017; Araùjo et al., 2021). Contrary to other aquaculture species such as fish and mussels, kelp do not need external resources, because they only rely on sunlight and nutrients (N and P) already present in seawater water to grow (Hurd et al., 2014). Seaweed farms can also serve as nurseries for several fish species, and provide several ecosystem services (Buschmann et al., 2017; Buck et al., 2018). Seaweed cultivation has also been suggested as part of the solution towards reaching the United Nation´s sustainability goals (SDGs), related to climate change and sustainable exploitation of life below water, due to their ability to sequester carbon and take up nutrients.

All the positive aspects related to seaweed cultivation has made it the fastest-growing aquaculture production and it is expected to double between 2015 and 2025 (Cottier-Cook et al., 2016; Buschmann et al., 2017; Ferdouse et al., 2018). Ferdouse et al. (2018) reported that 32.4 million tons of seaweed (fresh weight) was produced per year globally, with Asian countries producing the majority of the seaweed biomass. As much as 99% of Asian seaweed production comes from aquaculture, compared to 12% for European seaweed production (Charrier et al., 2017; Araújo et al., 2021). Despite the great potential for seaweed production in European countries, the European seaweed industry has stagnated in recent years due to the large pressure on wild stocks, and cultivation challenges such as the lack of cost-efficient technology (Vincent et al., 2020)

1.3 Cropping

The traditional method of seaweed harvesting is done by conducting one harvest of the full plant at the end of the growth season (Zhang et al., 2012 Bruhn et al., 2016), followed by reseeding before the next harvest. One method which is suggested to increase biomass yields for one growth season and possibly reduce cultivation costs, without the need to reseed, is conducting multiple partial harvests by cropping (Rolin et al., 2017). Cropping is done by cutting off a part of the plant but leaving the meristem behind for potential regrowth. The meristem is located at the proximal end of the plant, and is where the growth hormones are located, cropping above this point will therefore enable the kelp to regrow (Shmitz and Lobban, 1976; Levitt et al., 2002). This cultivation strategy has been investigated by studies in the Faroe Islands (Bak et al., 2018), the Shetland Islands (Rolin et a., 2017), and South Africa (Levitt et al., 2002).

Cropping has proven to increase total biomass yields of *Alaria escuelenta* (Bak et al., 2018), *Ecklonia maxima* (Levitt et al., 2002), and *S. latissima* (Rolin et et al., 2017). In a study that was conducted over two growth seasons at an exposed location in the Faroese Islands, cropping was found to increase *S. latissima* yields from the first harvest to the third, however, by the fourth harvest the yield decreased (Bak et al., 2018). Levitt et al. (2002) looked at regrowth of *E. maxima* after cropping fronds 2, 10, 20 and 30 cm from the meristem and found significant regrowth and increased biomass yields when cropping 20-30 cm from the meristem (Levitt et al., 2002). They concluded that cropping every four months was an efficient strategy to achieve the required commercial yield from smaller areas, compared to doing only one full harvest.

A study in the Shetland Islands found that *S. latissima* significantly regrew after being cropped 19cm above the meristem in both May and June/July, with highest regrowth rates in May (Rolin et al., 2017). They also found that cropped plants had a net increase of 10cm, while uncropped plants had a net loss in length of 2 cm (Rolin et al., 2017). These results indicate that cropping earlier rather than later in the growth season could be more beneficial, and that it can increase length also later in the season compared to uncropped plants. It has also been suggested that cropping can enable large-scale kelp cultivation and decrease the total costs of *S. latissima* per kg dry weight from €36,73 to €9,27 (Bak et al., 2018), compared to the common harvesting method where the entire blade is cut off at the end of the growth period (Bruhn et al., 2016; Zhang et al., 2012). The studies mentioned from South Africa, the Faroe Islands, and the Shetland Islands, show great promise in terms of using cropping as a strategy to increase biomass yields of kelp and decrease production costs, however none of the studies compared the total biomass yield in one season between cropped and uncropped plants.

1.4 Biofouling

Although there are many advantages with seaweed cultivation, it also has its challenges, and one of them is biofouling. Biofouling is the settlement of other marine organisms, typically filamentous algae, bryozoans, hydroids, tunicates, and herbivorous invertebrates on the kelp (Scheibling and Gagnon, 2009; Andersen et al., 2011; Moy and Christie, 2012). Biofouling has been related to seawater temperature (ST), where higher temperatures lead to increased fouling of e.g., the bryozoan *Membranipora* membranacea on *S. latissima* (Saunders and Metaxas., 2007; 2009a; Scheibling and Gagnon, 2009; Saunders et al. 2010; Matsson et al., 2019). Biofouling of a species with calcium carbonate skeleton such as *M. membranacea*, that forms large, sheet-like colonies, creates a barrier between the kelp and the sunlight and nutrients, thereby reducing photosynthesis and growth (Andersen et al., 2011). In addition, high levels of sheet-like biofouling can make the plants more fragile and vulnerable to wave- and wind action, and lead to losses of biomass of up to 100% (Krumhansl et al., 2011). Biofouling is often found on the oldest parts of the blade, the distal ends, as biofouling organisms accumulate over time (Jennings and Steinberg, 1997; Matsson et al., 2019).

Several studies have shown that species such as *S. latissima* degrade towards the end of summer and autumn, both in wild and cultivated populations, indicating that harvest is likely more beneficial in spring/early summer (Saunders and Metaxas, 2008; Andersen et al., 2011; Førde et al., 2015; Parke, 1948; Saunders and Metaxas, 2008; Nielsen et al., 2014; Rolin et al., 2017). It has been suggested that as the waters get warmer due to climate change, the outbreak of fouling organisms such as bryozoans may arrive earlier and be larger than before, which will likely increase decay and breakage of the kelp (Saunders and Metaxas, 2008; Scheibling and Gagnon, 2009; Park and Hwang, 2012). Kelp with high levels of biofouling are not attractive as food grade for human consumption, mostly due to aesthetic reasons, but have other commercial values such as animal feed, and biochemical extraction (Ferdouse et al., 2018). This has given rise to several suggestions for biofouling prevention, such as harvesting the biomass early in the season, before the heaviest biofouling period begins, or having seaweed farms at more exposed locations which could make settlement of fouling organisms harder (Peteiro and Freire, 2013). Importantly, the biofouled kelp still has wide ranging applications such as feed in aqua- and agriculture (Førde et al., 2015; Ferdouse et al., 2018), biofouels (Jiang et al., 2016), and ingredients in cosmetics, pharmaceuticals, and nutraceuticals (Ferdouse et al., 2018).

1.5 Ash and dry matter content

An important factor to consider in seaweed application is ash content, which describes the mineral content in the kelp (Schiener et al., 2015). Ash content is approximately 30% in kelp of the order *Laminariales*, such as *S. latissima*, compared to 1-10% in terrestrial plants (Grohmann and Bothast, 1994; Lynd, 1996). The ash consists of minerals like Na, K, Ca, Mg, S and Si, in addition to trace metals such as Fe, Zn, Mn, and Cu (Ross et al., 2008). Ash content in kelp have been reported to make up more than 50% of its dry weight (Moss, 1952), and *S. latissima* have been found to contain 80% more metal ions than other brown seaweed like *Laminaria hyperborea* and *L. digitata*. According to Schiener et al. (2015) K and Al are two elements strongly associated with ash content, and they also found that carbohydrate levels reached a maximum in combination with low ash- and water content. Kelp has highest water content during the winter, where it can reach up to 85% of the biomass, this decreases throughout the season and reaches the lowest values in summer (Adams et al., 2011). Seasonal variations in chemical composition of *Laminariales* have been reported, where different components peak at different times during the growth season, e.g., K content have been reported to double in the winter compared to the summer in *L. digitata* (Adams et al., 2011). It is important to understand these seasonal variations to determine the best harvesting window and applications, and to avoid undesirable components in the harvested biomass.

1.6 Aim of the study

With increasing demands of seaweed for human applications there is a need for optimalisation of the cultivation process, and to find the most efficient and economical method to cultivate kelp such as *S. latissima*.

The main aim of this study was to investigate the potential of cropping as a useful harvesting strategy to increase obtainable biomass within one growth season. For this, the seasonal growth of *S. latissima* was monitored in a sheltered site at Skarvøya, Hitra. Two deployments were made, October 2021 and January 2022, representing early and late stages of the deployment window in Mid-Norway region (Nilsen, 2018). The seaweeds of both deployment groups were then cropped once (April or June) or twice (April and June) in the season and regrowth rates were then verified. Complimentary to this work, the seasonal pattern of biofouling was observed during the experimental period, and samples taken for determination of ash and dry weight.

The project consists of three sub-objectives:

- To investigate the growth of *S. latissima* during one growth season and the effect of cropping time: April, June or April and June. Regrowth rates are measured in terms of length, width, and biomass.
- To compare total biomass yields of cropped and uncropped treatments in one growth season of the two deployments.
- To determine biofouling pattern during the experimental period, for the two deployments, as well as dry weight and ash.

The hypothesis is that cropping of kelp, once or multiple times, during one season will stimulate the plants to regrow, without the need to reseed. Thereby getting an increased biomass yield, compared to harvesting once at the end of the growth period.

2. Method

2.1 Study site

The cultivation experiment was conducted at SINTEF´s seaweed research location (figure 1), a sheltered site, with an average depth of 20-25m.

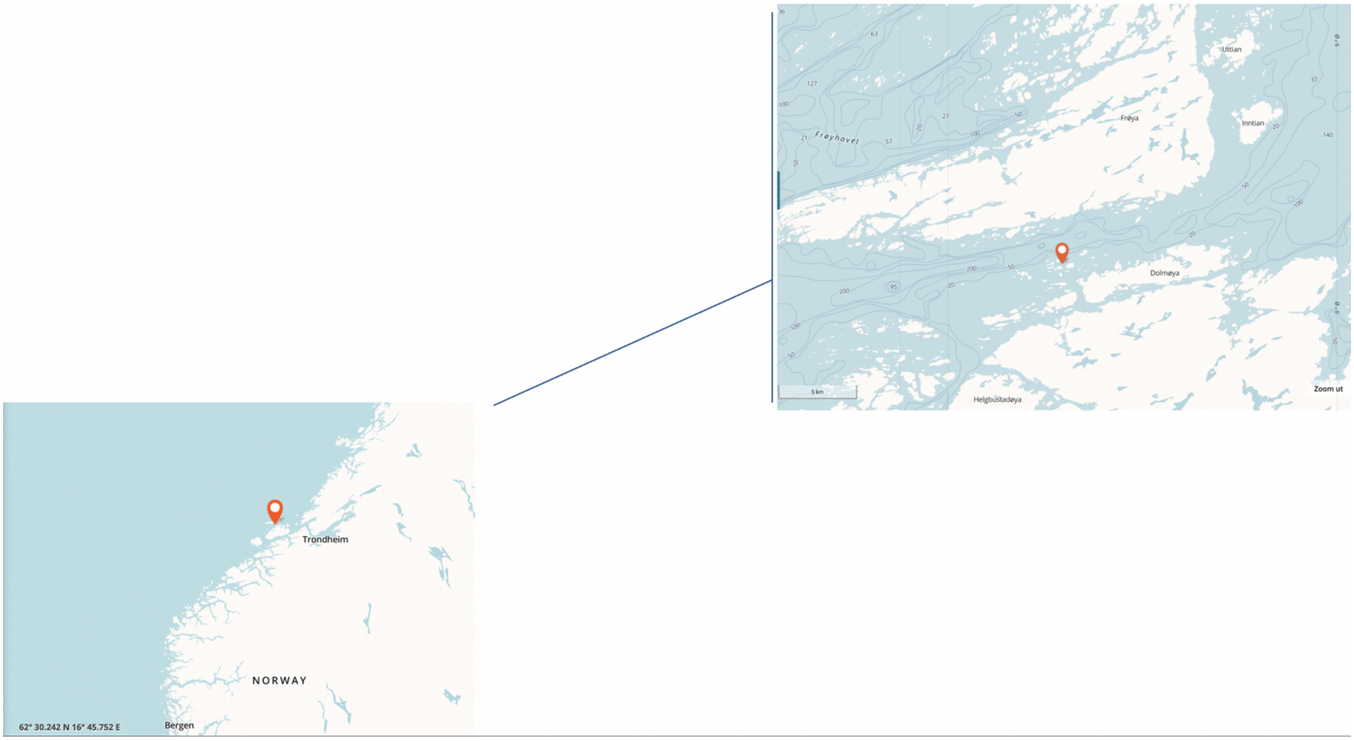

Figure 1. Study site near Skarvøya which is located between the islands Frøya and Hitra (63,650517°N, 8,650533°E) (BarentsWatch, 2023).

2.2 Seedling production

For this study, a total of 28 seeded ropes of 10 m each were obtained from Seaweed Solutions AS and deployed in October 2021 and January 2022.

2.3 Seaweed site set-up

Figure 2 shows the seaweed site set up which was submerged to 2-3 m to avoid impact from boat propellors, and to allow more maneuverability in the site. Both deployments had one treatment that was used for control, which was not cropped (Control), one treatment that was only cropped in April (Crop April) and one treatment that was cropped once in April and again in June (Crop A+J). In addition, the January deployment also had a treatment that was cropped once in June (Crop June). Each treatment had four seeded ropes (figure 2).

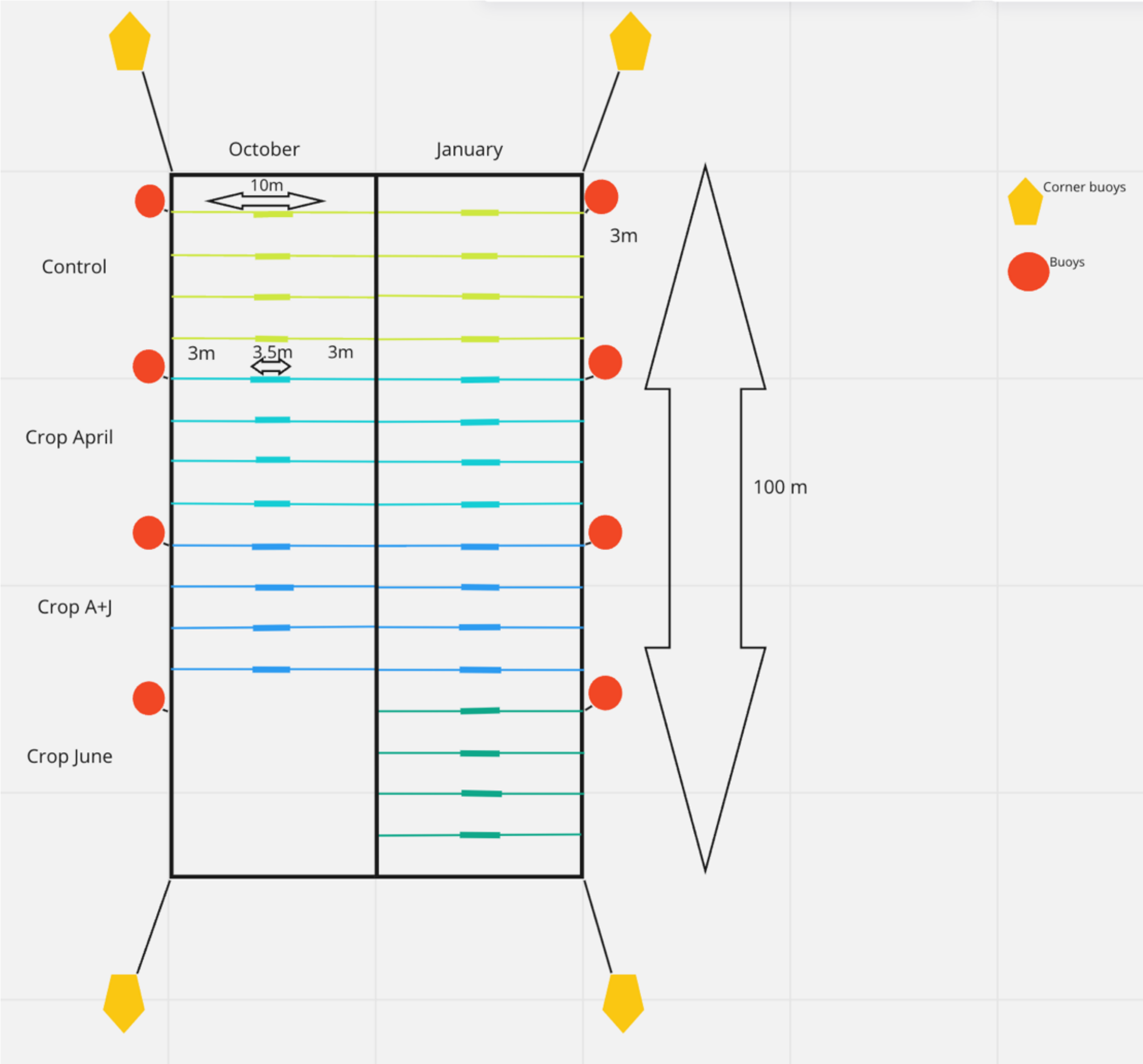

Figure 2. A schematic of the seaweed site set up. The three 100 m longlines were held up by a series of buoys and large corner buoys and anchored to the seafloor with mooring blocks. Ropes seeded with S. latissima *were deployed 10 m apart, horizontally between the longlines. The 3.5 m in the center of these ropes were seeded and is represented with a thicker line, leaving 3 m of unseeded rope on each side.*

2.4 Data collection in the field

2.4.1 Registration of environmental parameters

On the first day of each monitoring trip CTD data and water samples were collected. The CTD data was collected using Saiv SD204.

2.4.2 Growth and biomass of the seaweed

The fieldwork was conducted from March to August 2022, with two one-day trips in March, and from April there was one two-day monitoring trip per month. All seeded ropes were weighed with a handheld scale. If there were pieces of kelp that fell off these were weighed in a bucket and added to the total weight of the replicate (before crop). In addition to fresh biomass measurements, 10 individual plants from every seeded rope in each treatment were randomly taken for measurements of length, width (at the widest part of the blade), and stipe (140-280 plants each monitoring trip), then frozen at -20°C.

“Crop April” and “Crop A+J” from each deployment were weighed and measured, then cropped, and weighed again after cropping. In June for both deployments and August for the October deployment only 5 plants were taken for measurements, due to time- and weather constraints. The cropping was done by two people holding each end of the rope, keeping it tight so that the third person could cut the plants. A rough cropping was conducted of all plants with a knife, leaving around 15-20 cm of the meristem behind. Similarly, in June, the “Crop June” treatment from the January deployment was weighed, cropped, and re-weighed. The percent recovery was subsequently calculated for all cropped treatments. From each monitoring trip 50 plants were collected and divided into five sample bags (10 plants per bag).

Once back on land, 1-3 plants from each of the five sample bags were laid out on a white waterproof sheet next to a folding rule and photographed (using an iPhone 12). The pictures were taken at an angle as close to 90° as possible, and later analyzed for bryozoan coverage using a qualitative scale.

2.5 Sample preparation and analyses

Three plants from each deployment and each monitoring day were selected for qualitative biofouling analysis. A range between 1-5 was used to differentiate the different levels of fouling by bryozoans, as demonstrated in table 1. In addition, the presence of snails was determined by “P” (present) or “A” (absent). The results were put in a table including both deployments and each monitoring, from March to August.

Table 1.The level of bryozoan fouling from 1-5, and how they are defined. 1 being the lowest level of fouling, and 5 the highest.

1	Negligible fouling
2	Small colonies start to appear (dots)
3	Small colonies visible and starting to grow (<1cm)
4	Mid-large colonies (>1cm)
5	«take over» of significant parts of the blade

In the lab, collected samples were divided into subsamples, for determination of dry weight and ash. The seaweed was taken out of the plastic bag, and allowed to thaw slightly, for about 5-10 minutes in room temperature, and then cut with scissors into smaller pieces. A small aliquot of mixed pieces, representative of the plant overall, was placed into pre-weighed crucibles and weighed with a fine scale balance (Mettler Toledo AG204 Delta Range) for determination of fresh (wet) weight. Next, the samples were dried in an *** oven at 60°C for 24h or until constant weight, to determine dry weight, and combusted at 600°C in a **blast furnace for determination of ash content.

2.5.1 Statistical analyses and figures

Skewness and kurtosis test was performed to determine normal distribution. When samples were N<50 the null hypothesis was that the data was not normally distributed, making the data normally distributed if the Z-value fell inside the range -1.96 and +1.96. When samples were 50 > N < 300 the data was normally distributed when the Z-value fell inside the range -3.29 and +3.29, when N > 300 the data was normally distributed when absolute skewness value was between -2 and +2, and kurtosis value was between -7 and +7. One-way analysis of variance (ANOVA) was performed when normal distribution was found, to determine significant difference in mean biomass (kg), and potential harvested biomass, between monitoring dates, before and after cropping. Kruskal Wallis test was performed when normal distribution was not found. All statistical analyses were carried out in IBM SPSS Statistics (version 29.). Graphs and tables were created in Microsoft Excel (version 16.72) and SPSS Statistics (version 29).

3. Results

3.1 Temperature and salinity

Sea water temperature was quite stable between sea surface level and 25 m depth (figure 3A), but had a steady increase with time during the experimental period from approximately 5,5°C in March to 13,5° in August (figure 3B). Figure 4A shows that salinity changed little with depth. Salinity also barely changed over time and ranged from 32 to 34 ppt during the experimental period, with highest values in April and lowest in August (figure 4B). The weather on sampling days varied between sunny, overcast, and overcast with sunny intervals, but little precipitation.

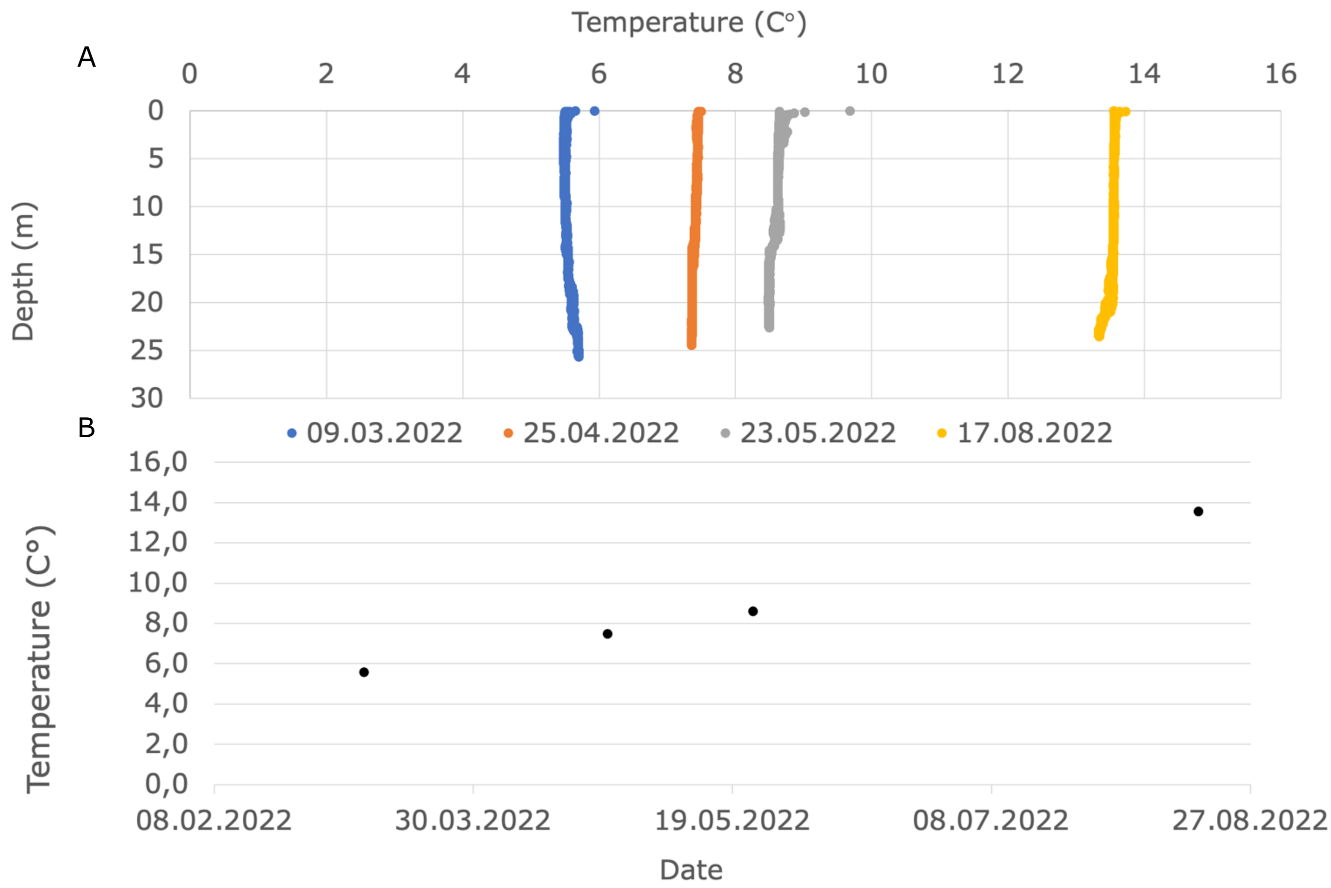

Figure 3. A) Temperature over depth from the monitoring trip in March, April, May, and August. Data from June and July are absent because they were collected with a Manta ± multisensory platform from Eureka, which experienced some issues that made the data unattainable. B) Temperature (averages ± SD) over time during the experimental period, data for June and July were also unattainable here.

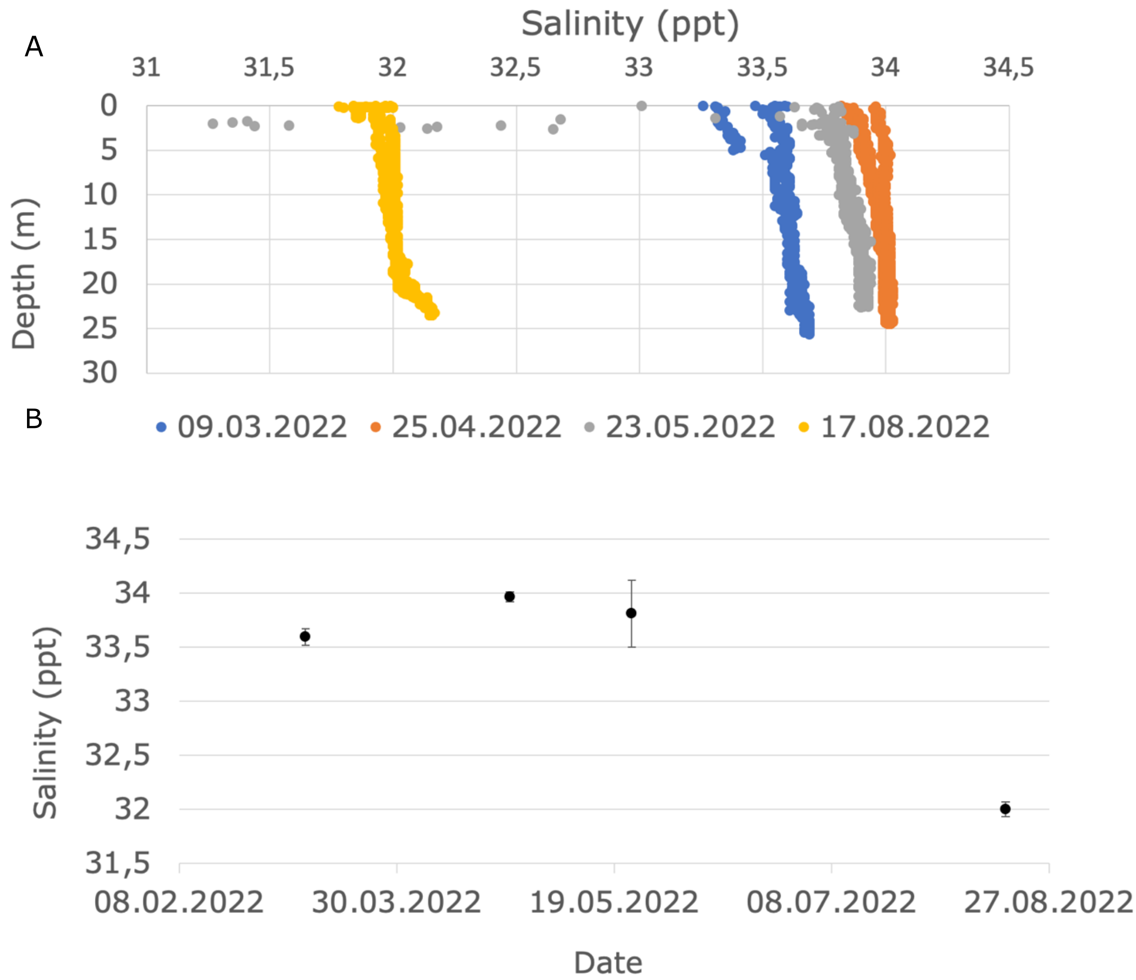

Figure 4. A) Salinity over depth from the monitoring trips in March, April, May, and August. B) salinity over time (averages ± SD) during the experimental period. Data from June and July are absent because they were collected with a Manta ± multisensory platform from Eureka, which experienced some issues that made the data unattainable.

3.2 Growth and cropping

3.2.1 Biomass

Both deployments follow the same growth pattern with an increase in growth from March to June, then from July to August there is a rapid decrease (figure 5 and 6). There was no statistically significant difference in average weight between the two deployments at any point in the growth season for the Control treatment ($p > 0.05$).

For the October deployment the highest average biomass was 9.49 kg m^{-1} in June for the Control treatment, for Crop April the highest biomass yield was 8.23 kg m^{-1} in July, and for Crop A+J the highest biomass was in June at 7.25 kg m^{-1} (figure 5). For the January deployment the highest yield was found in July for Crop April at 8.48 kg m^{-1}, followed by 8.19 kg m^{-1} for Control in June, and 7.64 kg m^{-1} for Crop April in July (figure 6).

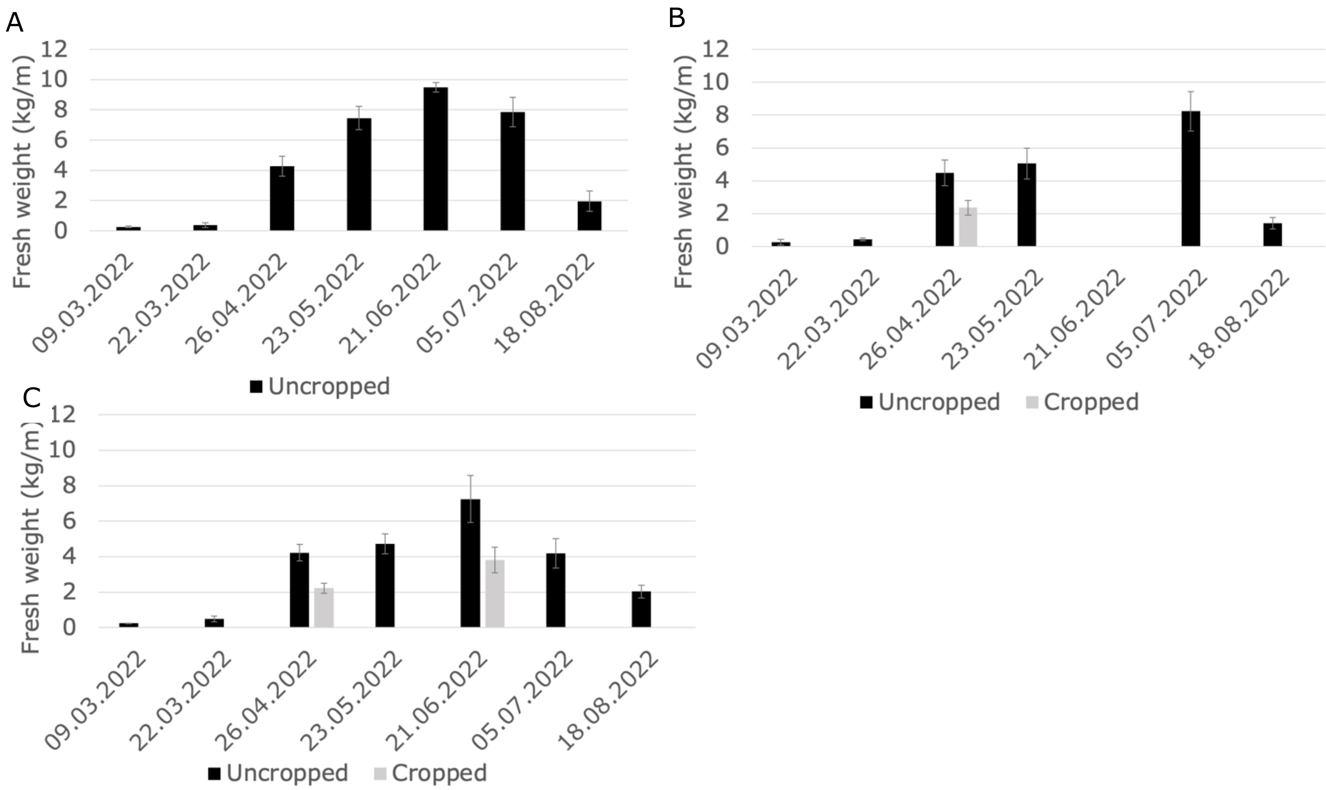

Figure 5. Averages ± SD of S. latissima *biomass for all treatments during the experimental period for the October deployment, divided into panels A, B, and C. A represents Control, B represents Crop April, and C represents Crop A+J. In panel B data for the monitoring trip in June is missing due to weather-and time constraints. The black bars symbolize the uncropped biomass, the grey bars symbolize the biomass after cropping, from the same monitoring trip.*

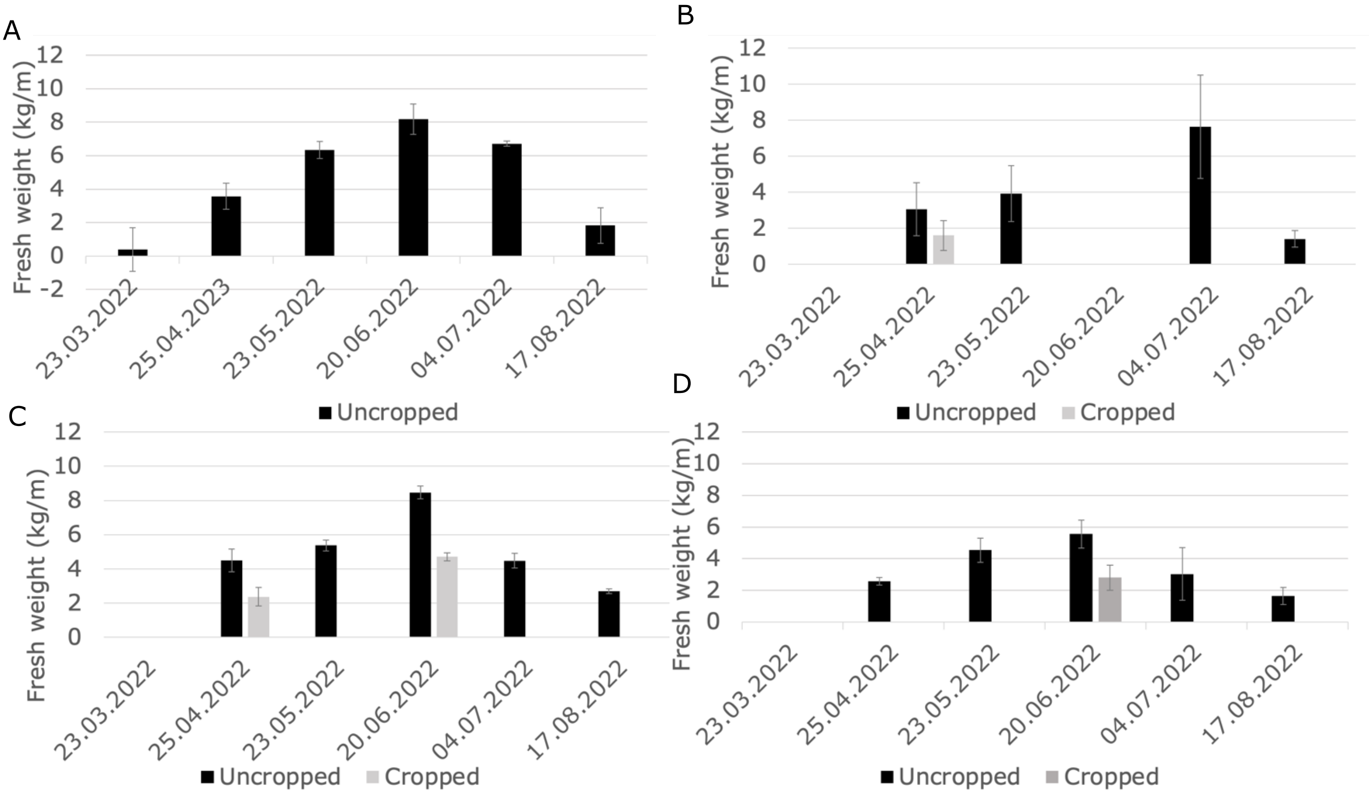

Figure 6. Averages ± SD of S. latissima *biomass for all treatments during the experimental period for the January deployment, divided into panels A, B, C, and D. A represents Control, B represents Crop April, C represents Crop A+J, and D represents Crop June. The black bars symbolize the uncropped biomass, and the grey bars symbolize the biomass after cropping, from the same monitoring trip.*

For the October deployment, Figure 7 shows that *S. latissima* in the Crop April treatment had a regrowth of 113.41% of the uncropped biomass, one month after the first cropping. A one-way ANOVA confirms that there was no significant difference in the biomass of *S. latissima* in April before cropping, and the biomass one month after cropping (in May), F (1) = .887, p = .383. Crop A+J had a regrowth of 113.06% one month after the first cropping. A one-way ANOVA confirms that there was no statistically significant difference between the weight of the biomass in April before cropping and in May, one month after cropping, F (1) = 1.9, p = .217. Crop A+J was cropped again in June, but barely had any regrowth. A one-way ANOVA determined that there was a statistically significant decrease in biomass from June (before cropping) and July (after cropping), F (1) =15.33, p = .008.

For the January deployment, Figure 7 shows that Crop April had a regrowth of 144.46% of the uncropped biomass, one month post-cropping. A one-way ANOVA determined that there was no statistically significant difference between the biomass in April, before cropping, and the biomass in May, one month after cropping, F (1) = .652, p = .450. Figure 7 also shows a regrowth of 125.97% in the Crop A+J treatment one month after the first cropping. A one-way ANOVA determined that there was no statistically significant difference in biomass (kg/m) wet weight in April and May for Crop A+J in January deployment, F (1) =5.59, p = .056. After the second crop, biomass of Crop A+J declined. A one-way ANOVA determined that there was a statistically significant difference in biomass (kg/m) wet weight between June and July for Crop A+J in the

January deployment. F (1) = 193.35, $p < .001$. Similarly, the biomass of Crop June one month after the crop also declined. The negative values in figure 7 indicate no regrowth, but rather a loss of biomass. A one-way ANOVA determined that there was a statistically significant difference between biomass in June and July, F (1) = 7.203, p = .036.

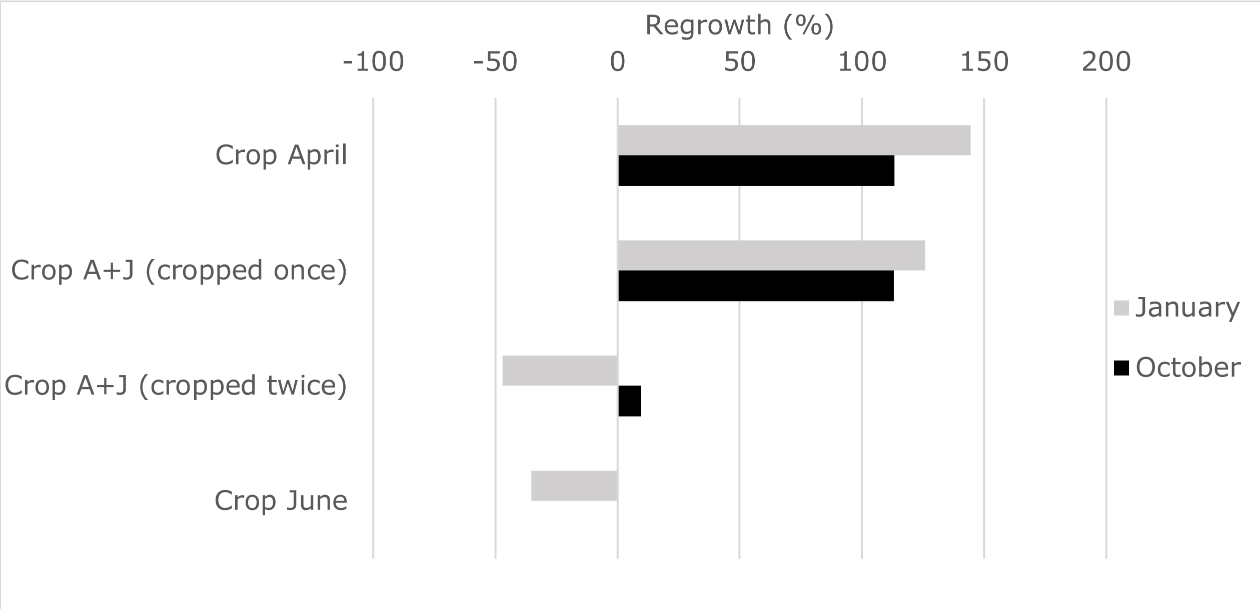

Figure 7. Percentage regrowth of S. latissima *one month after cropping for all groups in both deployments. Crop April and Crop June has one bar for each deployment, while Crop A+J has two bars because this group was cropped in both April and June. The black bars represent the October deployment, and the grey bars represent the January deployment.*

3.2.2 Length and width

Blade length increased from March to June for Control in the October deployment (figure 8) and the January deployment (figure 9). For Control in the October deployment there was a statistically significant difference in average lamina length between monitoring trips during the experimental period, Kruskal Wallis (with post-hoc, Bonferroni) H (6) = 150.093, $p < .001$. There was a significant difference in length between the second monitoring in March (32.83 cm) and June (94.6 cm) ($p < .001$), followed by a significant decrease from June to August (54.28 cm) ($p < .01$). For Crop April in the October deployment (figure 8) there was a statistically significant difference in average lamina length between monitoring trips during the experimental period, Kruskal Wallis (with post-hoc, Bonferroni), H (5) = 95.261, $p < .001$. Figure 8 shows that lamina length for Crop April followed the same pattern with similar lengths as Control from the first monitoring in March to the first crop in April. There was a significant difference in length from 69.65 cm in April to 44.94 cm in May (< .001). No data was collected in June for this treatment. Lamina length in August was significantly lower than July, with 43.11 cm compared to 66.97 cm ($p < .001$) (figure 8). For Crop A+J in the October deployment there was a statistically significant difference in average lamina length between monitoring trips during the experimental period, Kruskal Wallis (with post-hoc, Bonferroni), H (6) = 121.628, $p < .001$ Crop A+J followed the same pattern as Crop April with similar lengths, from March to June. Crop A+J was cropped a second time in June and had significantly lower lamina length in July with 31.97 cm compared to 66.22 cm in June ($p < .001$). Lamina length increased from July to August (figure 8), but not significantly.

For Control in the January deployment there was a statistically significant difference in average lamina length between monitoring trips, highlighted by a one-way ANOVA test of variance (with post-hoc test, Bonferroni), F (5) = 43.549, $p < .001$. Lamina length was significantly higher in June (85.6 cm) compared to March (32.87 cm) ($p < .001$). In August, lamina length had decreased to 50.59 cm, which was significantly lower than in June ($p < .001$). For Crop April in the January deployment there was a statistically significant difference in average lamina length between monitoring trips during the experimental period, Kruskal Wallis (with post-hoc, Bonferroni), H (3) = 100.672, $p < .001$. There was no data collected in March or June for this treatment. Lamina length was significantly lower in May with 36.52cm compared to 71.2 cm in April ($p < .001$). Lamina length increased from May (36.52 cm) and was significantly higher in July (56.99 cm) ($p < .001$). In August, average lamina length had decreased to 35.86 cm, significantly lower than average length in July ($p < .001$). For Crop A+J in the January deployment there was a statistically significant difference in average lamina length between monitoring trips during the experimental period, Kruskal Wallis (with post-hoc, Bonferroni), H (4) = 116.015, $p < .001$. Lamina length was significantly lower in May (42.42 cm) compared to April (78.85 cm) ($p < .001$). From May to June lamina length increased to 61.4 cm, which was significantly higher than average length in May ($p < .001$). In July, average length had decreased to 29.19, significantly lower than average length in June ($p < .001$), and from July to August there was an increase to 37.76 cm, significantly higher than average length in July ($p = .004$). For Crop June in the January deployment there was a statistically significant difference in average lamina length between monitoring trips during the experimental period, Kruskal Wallis (with post-hoc, Bonferroni), H (4) = 111.612, $p < .001$. There was a slight increase from 66.21 cm in April to 72.2 cm in June, but not significantly. In July, lamina length was significantly lower (34.86 cm) than in June ($p < .001$), followed by an increase to significantly higher lamina length in August (43.62 cm) ($p = .018$).

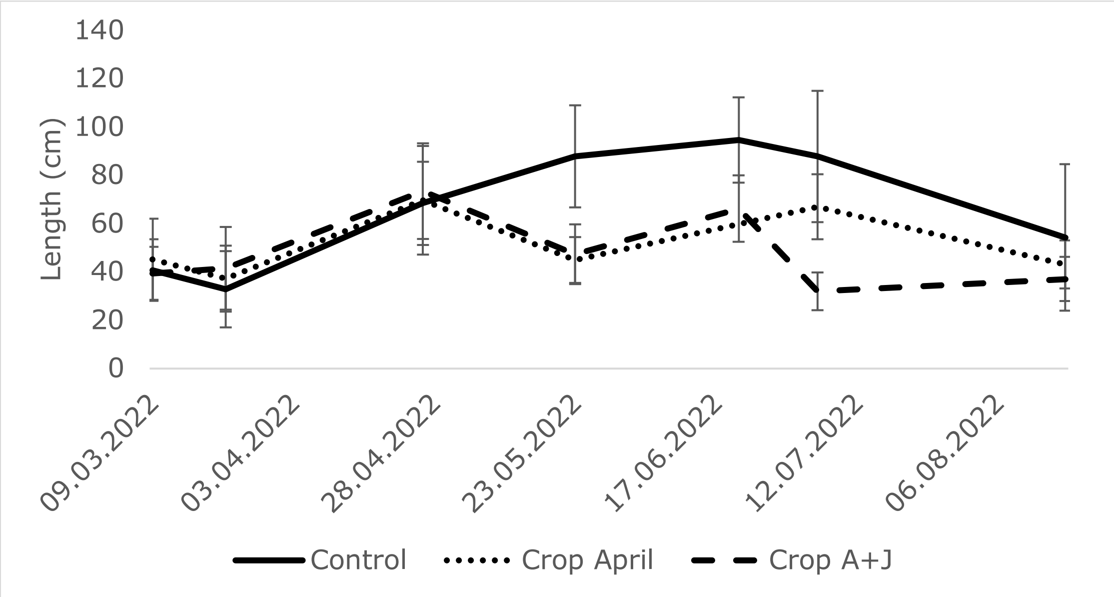

Figure 8. Seasonal growth in blade length of S. latissima *from the October deployment (averages ± SD). All groups were monitored twice in March, and from there on, once a month until August. An exception was Crop April which was unavailable in June, due to weather conditions. For the control group in June, there was one replicate missing, so this group has only three replicates instead of four. Only three replicates from each group were measure in August due to time limitations. Ten plants from each replicate were measured, but this was reduced to five in June and August, due to time limitations and challenging weather conditions.*

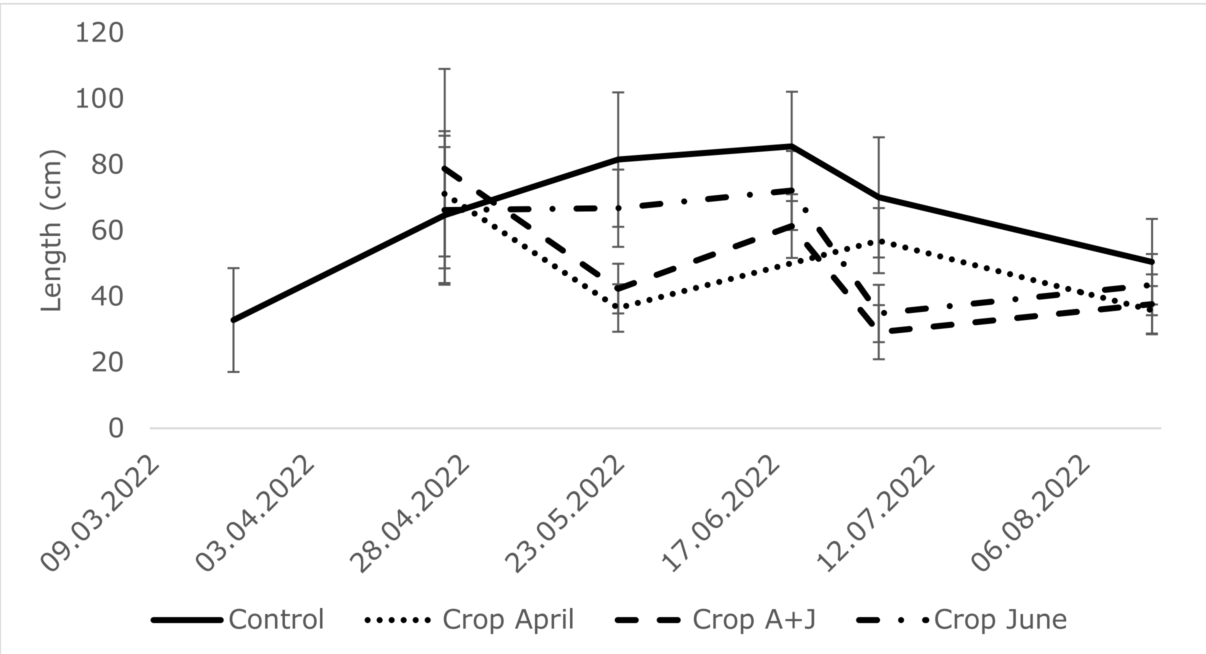

Figure 9. Seasonal growth in blade length of S. latissima *from the January deployment (averages ± SD). All groups were monitored once a month from April to August, except Crop April which was unavailable in June, due to challenging weather conditions. Control was monitored twice in March to check status of the seeded ropes.*

Width increased from March to April for all treatments in the October deployment (figure 10) and the January deployment (figure 11). For the Control treatment there was a statistically significant difference in average lamina width between the monitoring trips during the experimental period, highlighted by a one-way ANOVA test of variance (with post-hoc, Bonferroni), F (6) = 51.668, p < .001. Average width starts with a similar pattern as lamina length with significantly lower width for the second monitoring (March II, 13.38 cm) in March compared to the first (March, 7.9 cm) monitoring (p = .025). Average width increased significantly from March II to 32.57 cm in June (p < .001), followed by a slight decrease in August (24.72), but not significant.

For Crop April there was a statistically significant difference in blade width between the monitoring trips during the experimental period, determined by a one-way ANOVA (with post-hoc, Bonferroni), F (5) = 42.266, p < .001. There was a statistically significant lower blade width in the second monitoring trip in March (March II, 9.65 cm) compared to the first (March, 14.96 cm) (p = .021). There was no data collected in June. Blade width increased and reached 27.42 cm in July, significantly higher than March II (p < .001), followed by a slight decrease in August (22.6 cm), but not significant. For Crop A+J there was a statistically significant difference in blade width between the monitoring trips during the experimental period, one-way ANOVA (with post-hoc, Bonferroni), F (6) = 42.457, p < .001. There was a slightly lower lamina width in the second monitoring trip in March (March II, 10.59 cm) compared to the first (March, 12.97 cm), but not significant. From March II to May blade width increased, and reached 28.12 cm, significantly higher than March II (p < .001). Followed by a decrease to 21.24 in August, significantly lower than width in May (p = .012).

Figure 11 shows the seasonal growth in lamina width for the different treatments in the January deployment. In March, data was only collected for the Control treatment. For Control there was a statistically significant difference in average lamina width between the monitoring trips during the experimental period, one-way ANOVA (with post-hoc, Bonferroni), F (5) = 38.583, p < .001. There was a statistically significant increase from 7.9 cm in March to 22.2 cm in June (p < .001), then a slight decrease by 2 cm in July, followed by an increase to 22 cm again in August, these changes were not significant.

Crop April had a statistically significant difference in lamina width between the monitoring trips during the experimental period, Kruskal Wallis test of variance (with post-hoc, Bonferroni), H (3) = 12.335, p = .006. Lamina width was significantly lower in May (17 cm) compared to April (20.46 cm) (p = .018), followed by an increase in July to 19.7, significantly higher than May (p = .004), and a statistically significant decrease from July to August (16.92 cm) (p = .011). For Crop A+J lamina width stayed quite stable throughout the experimental period, and no statistically significant changes in average width was found, Kruskal Wallis test of variance (with post-hoc, Bonferroni), H (4) = 5.899, p = 0.207. For Crop June there was a statistically significant difference in average lamina width between the monitoring trips during the experimental period, Kruskal Wallis test of variance (with post-hoc, Bonferroni), H (4) = 28.124, p < .001. There was an increase in width from April to June, where plants in June were significantly wider than in April, 17.47 cm compared to 20.12 cm, (p = .004). There was no statistically significant difference in width between June and July, p = .132. There was a statistically significant increase from July to August (p= .054).

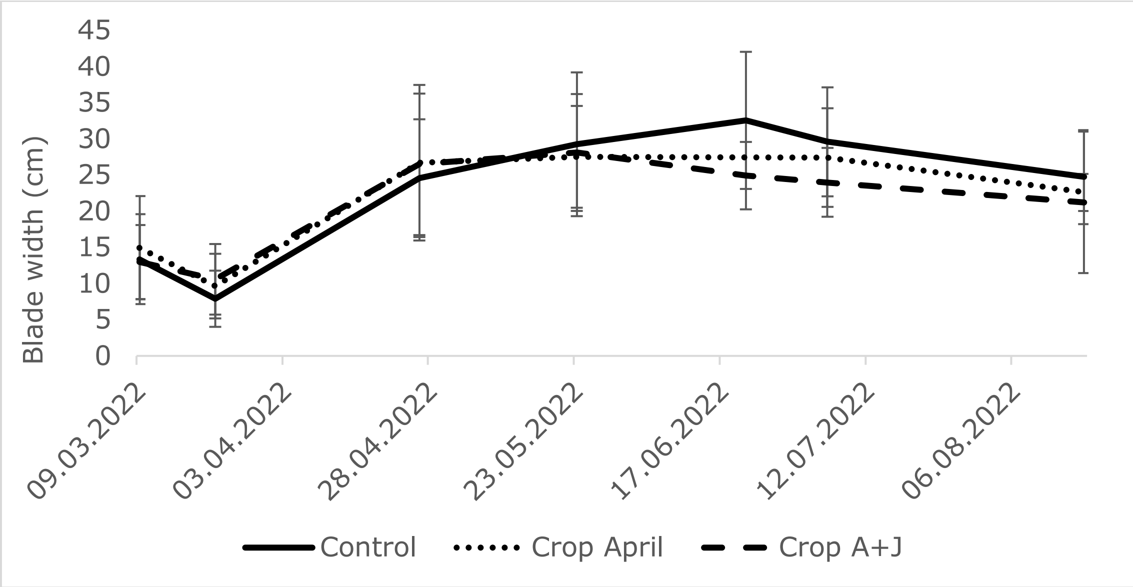

Figure 10. Seasonal growth in blade width (averages ± SD) of S. latissima *from the October deployment. All groups were monitored once a month from March to August, except for Crop April which was not monitored in June due to challenging weather conditions. Control was measured twice in March why? In June there was one replicate missing for Control. In August only three replicates of each group were measured due to time limitations. Ten plants from each replicate were measured, but this was reduced to five in June and August due to time limitations.*

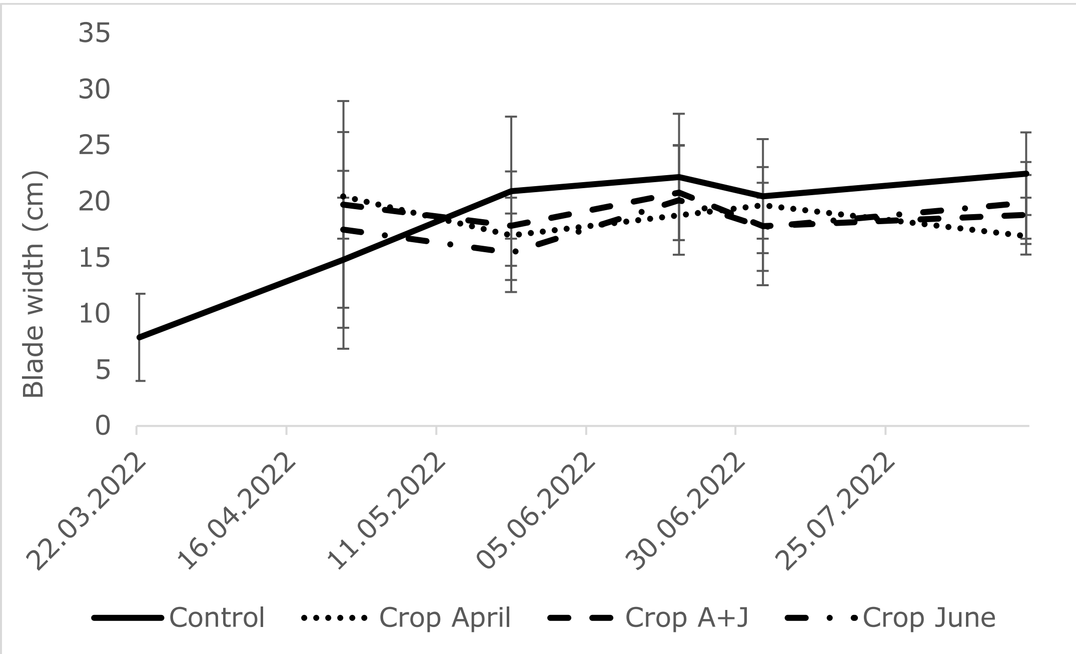

Figure 11. Seasonal growth in blade width (averages ± SD) of S. latissima *from the January deployment. All groups were monitored once a month from April to August, but Control was also measured once in March. For each monitoring trip, ten pants from each replicate were measured, except for in June when this was reduced to five plants due to time limitations. Crop April was unavailable in June, due to challenging weather conditions and time limitations.*

Length/Width relationship can be found for Control and Crop Aril from the October deployment in Appendix 1.

3.4 Case study: total biomass harvested from one growth season season

The highest biomass (kg m^{-1}) was found in Crop April from the January deployment with 18.49±2.49 kg m^{-1}, followed by Crop April from the October deployment (16.61±3.73 kg m^{-1}), Crop A+J from the January deployment (10.33±0.21 kg m^{-1}), and Crop A+J from the October deployment (9.62±1.12 kg m^{-1}). Control had biomass yields of 7.85±0.98 kg m^{-1} (October) and 6.69±0.52 kg m^{-1} (January). The lowest yields were found in Crop June with 5.8±1.4 kg m^{-1} (Table 2).

Figure 12. shows the biomass yield of *S. latissima* from both deployments, that could be harvested during one full season for the different treatments assuming total harvest were to include the cropped biomass and a harvest of the whole plants (full harvest) in July. For the October deployment Crop April had the highest biomass yield with a maximum of 2034 kg and a minimum of 1288kg, followed by Crop A+J with a maximum of 1074 kg and a minimum of 850 kg. For reference, Control had a maximum of 833 kg and a minimum of 687. In the January deployment Crop April had a maximum of 2098 kg and a minimum of 1600 kg, Crop A+J had a maximum of 1054 kg and a minimum of 1012 kg, and Crop June had a maximum of 720 kg and a minimum of 440 kg. For reference, Control had a maximum of 721 kg and a minimum of 617 kg.

Table 2. Average±SD of biomass yield (kg m^{-1}), as well as a total biomass yield for one season, including the cropped biomass and an assumed full harvest in July for each treatment in both deployments (kg for 100 m).

Average±SD biomass yield (kg m^{-1})								**Total biomass harvested (kg for 100m)**		
OCTOBER										
Treatment	**April Crop**	**Left after crop (April)**	**Kg/m one month post-crop (May)**	**June Crop**	**Left after crop (June)**	**Kg/m one month post-crop (July)**	**Additional growth post-crop (May-July)**	**Total biomass harvested (with full harvest in July)**	**Min**	**Max**
Control							n/a	**7.85 ±0.98**	**687**	**833**
Crop April	**2.1±0.47**	2.37±0.45	5.05±0.94				9.46±1.62	**16.61±3.73**	**1288**	**2034**
Crop A+J	**2±0.21**	2.22±0.29	4.73±0.56	**3.43±0.62**	3.82±0.72	4.19±0.83	n/a	**9.62±1.12**	**850**	**1074**
JANUARY										
Control							n/a	**6.69±0.52**	**617**	**721**
Crop April	**1.45±0.64**	1.6±0.83	3.92±1.56				13.12±1.33	**18.49±2.49**	**1600**	**2098**
Crop A+J	**2.1±0.16**	2.38±0.54	5.37±0.31	**3.74±0.03**	4.72±0.24	4.49±0.43	n/a	**10.33±0.21**	**1012**	**1054**
Crop June				**2.77±0.78**	2.8±0.91	3.03±0.89	n/a	**5.8±1.4**	**440**	**720**

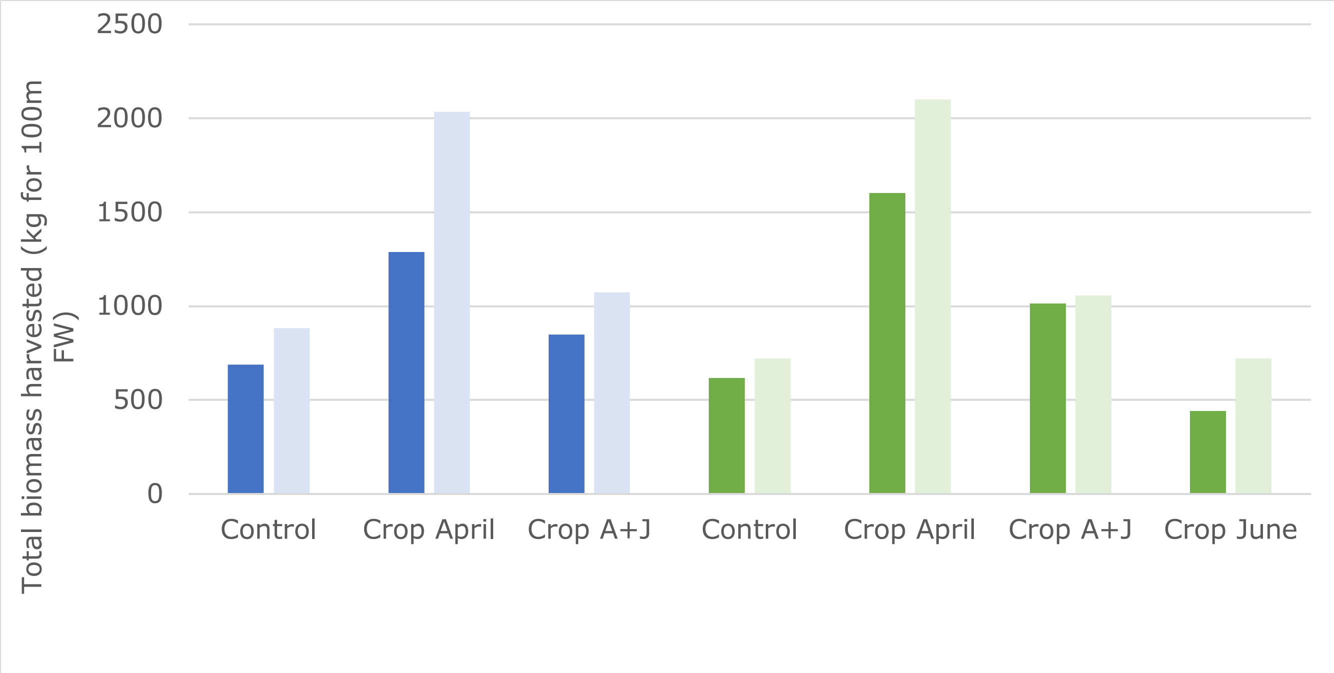

Figure 12. Biomass yield (FW kg/m) harvested including the cropped biomass and assuming a full harvest in July for all treatments and both deployments. Blue represents the October deployment, while green represents the January deployment. The lighter bars represent the minimum biomass harvested; the darker bars represent the maximum biomass harvested.

3.5 Biofouling

Three fouling species were identified on *S. latissima* during the experimental period and included in a qualitative analysis. There were two bryozoan species; *Electra pilosa* and *Membranipora membranacea*, and one mollusk, which was generalized as snail. The majority of fouling was by *M.membranacea*. The biofouling throughout the season is visualized in a qualitative analysis of three plants (R) from Control for each monitoring in Table 3. including the different organisms, and level of fouling. Images of representative plants from each monitoring can be found in Appendix B. The fouling level increased gradually from April, where there was little to no fouling, to August where plants were grazed and fouled upon to the point of breakage, and the tip of the blades were mostly gone. Snails were observed on the fresh tissue at the bottom of the lamina in August.

Table 3. Biofouling of M. Membranacea *and* E. Pilosa*, and snails in both deployments from April to August. Fouling levels are represented by numbers 1-5: 1- negligible fouling, 2- small colonies start to appear (dots), 3- small colonies visible and starting to grow (< 1cm), 4- mid-large colonies (> 1cm), 5- "take over" of significant parts of the blade. The presence of snails is indicated by A (absent) or P (present).*

OCTOBER DEPLOYMENT															
	April			May			June			July			August		
	R1	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**
M. membranacea	1	1	1	2	2	2	3	4	4	4	3	3	5	5	5
E. pilosa	1	1	1	2	2	2	2	3	4	4	3	3	5	5	5
Snails	A	A	A	A	A	A	A	A	A	A	A	P	P	P	P

JANUARY DEPLOYMENT															
	April			May			June			July			August		
	R1	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**
M. membranacea	1	2	2	2	2	2	3	3	3	4	3	2	4	4	4
E. pilosa	1	2	2	2	2	2	3	2	3	3	3	3	4	4	4
Snails	A	A	A	A	A	A	A	A	A	A	A	A	P	P	P

3.6 Dry matter and ash content

The dry weight (DW, average % of wet weight) of control plants increased during the experimental period, with no significant difference between the two deployments (p= .795) (figure 13A).

In the October deployment one-way ANOVA highlighted a significant increase in DW from March to August, F= 41.129, p < .001. For the January deployment a Kruskal-Wallis test highlighted a statistically significant increase in DW from March to August, H= 14.729, p= .012.

DW increased from April to June for all treatments and both deployments (figure 13B). For the October deployment there was no statistically significant difference in dry weight between Control and the crop treatments during the experimental period from monitoring in April. In June, Control had statistically significant higher dry weight than Crop A+J in the October deployment, highlighted by one-way ANOVA, F= 9.807, p= .035.

For the January deployment there was a statistically significant difference in dry weight between the treatments in April, F= 11.830, p= .008. Control and Crop A+J had significantly higher DW than Crop April (p= .029 and p= .011). There was also a statistically significant difference in DW between treatments in June, where Control had significantly higher DW than Crop June, F= 12.995, p= .007.

Ash content (% of dry weight) increased from March to August for Control in the October deployment (figure 13A), whilst for the January deployment it was more varied (figure 14A). A one-way ANOVA determined that there was no statistically significant difference in ash content between the two deployments, F= 1.085, p= .305. Outliers for the ash data were removed before statistical analyses and are not included in the graphs.

For the October deployment ash content increased during the experimental period, with a statistically significant difference in ash content between monitoring trips, highlighted by Kruskal-Wallis, H= 13.678, p= .018, where Ash content significantly increased from March to August (p < .001). For the January deployment ash content varied during the experimental period (figure 14A). A one-way ANOVA determined that there was a statistically significant difference in ash content during the experimental period, F= 14.247, p < .001, with a significant increase from March to April (p= .003) and a significant decrease from June to August (p= .028).

Figure 14B shows the ash content of *S. latissima* from Control and the cropped treatments for both deployments in the months with cropping (April and June). For the October deployment, a one-way ANOVA determined that there was a statistically significant difference in ash content between the treatments, F= 5.726, p= .041. Control had significantly higher ash content than Crop A+J in April. There was no statistically significant difference between the other treatments. For the January deployment, a one-way ANOVA determined that there was a statistically significant difference in ash content between Control, Crop A+J and Crop June, F= 11.042, p= .015. Control had significantly lower ash content than Crop A+J (p= .017) and Crop June (p= .061).

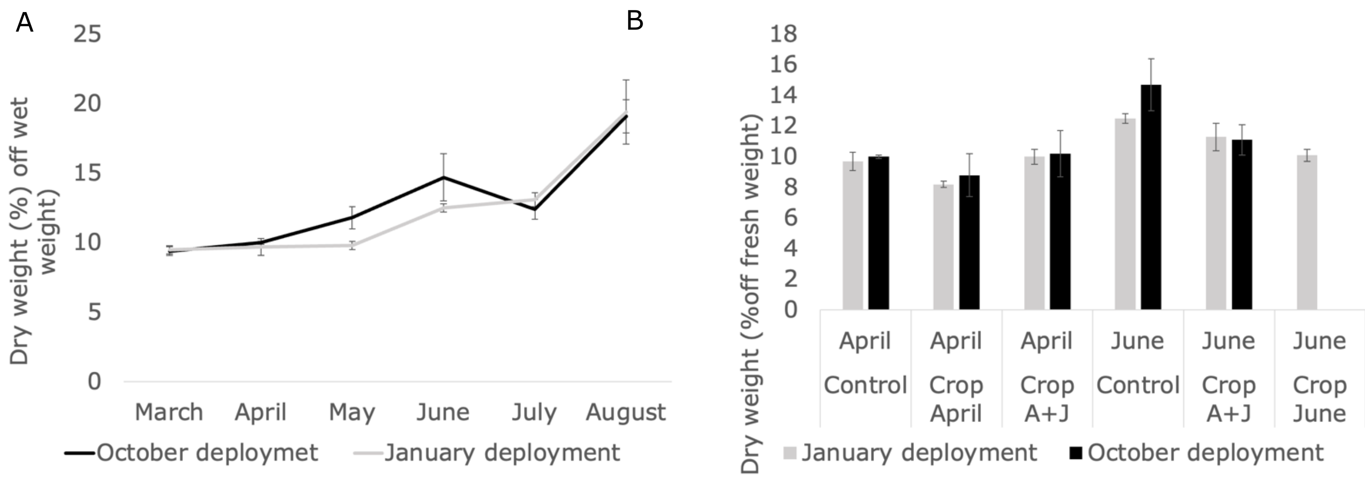

Figure 13. A) Averages ± SD of dry weight (% of wet weight) of S. latissima *control plants from both deployments during the experimental period. B) Averages ± SD of dry weight (% of wet weight) of* S. latissima *from control plants and the cropped plants in April and June, from both deployments.*

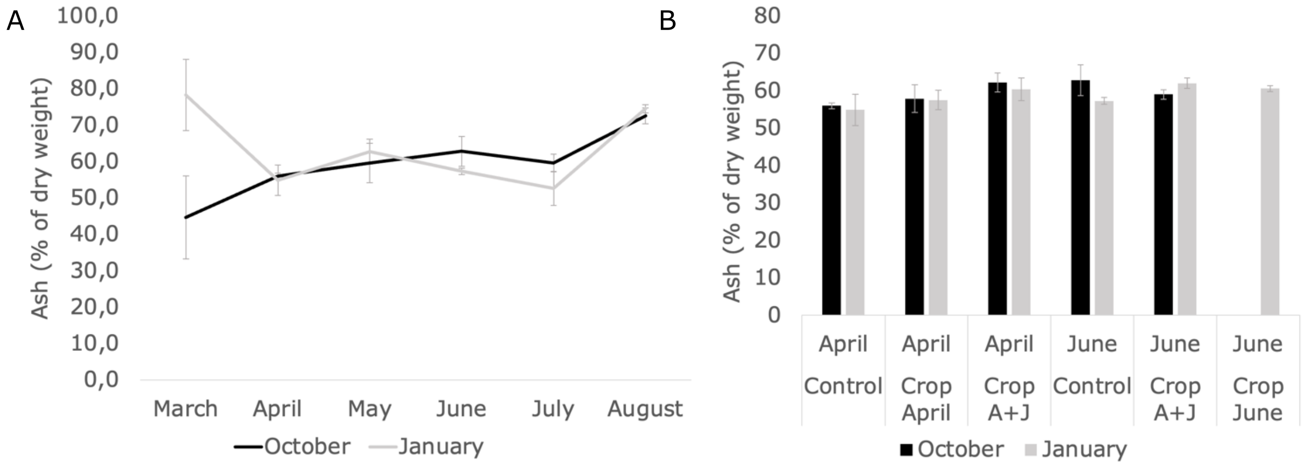

Figure 14. A) Ash content (% of dry weight) of S. latissima *from Control from both deployments during the experimental period. B) Ash content (% of dry weight) of* S. latissima *from Control, and cropped treatments in April and June from both deployments.*

4. Discussion

This study investigated whether cropping once or twice during one growth season could increase growth and biomass of *S. latissima*. The results show that cropping once early in the season, followed by potentially harvesting the regrowth in July can increase biomass yields, compared to conducting only one harvest. This study also looked at the seasonal biofouling, as this affects growth and quality of the kelp, and contributes to its potential for commercial applications. The results showed negligible levels of fouling for most of the growth season, up until July-August when fouling drastically increased. This study supports existing literature indicating that partial harvest through cropping has great potential for increasing seasonal biomass of *S. latissima*.

4.1 Growth and cropping

Lamina length and width for Control had seasonal patterns of increased growth at the start of the season. Length increased from March to June, followed by a significant decrease from July to August. *S. latissima* reached the longest length in June at approximately 80 cm which supports the pattern reported by Handå et al. (2013) who conducted a study on *S. latissima* from another sheltered site in Norway and also found that mean length peaked in June at approximately 80 cm. Lamina width increased significantly in the first month of the growth season in both deployments but stayed quite stable from there on. Other studies have also shown significant increases in blade width during the growth season from early spring to late summer (Handå et al., 2013; Rolin et al., 2017). Rolin et al. (2017) reported a range between 3 to 10cm and significant increase during the season, comparatively, blade width in the present study ranged from 8 to 32 cm. Plants from the present study are generally larger compared to Rolin et al. (2017), perhaps due to latitudinal differences, or differences in nutrient levels, however these were not investigated. Plants in the October deployment were generally longer and wider than the January deployment in the present study, likely due to longer time for growth, which has also been reported by several other studies, such as Handå et al. (2013) where length of plants from their August deployment peaked at 80 cm whilst plants from their February deployment peaked at 60 cm. The results of the present study also align with other studies stating that *S. latissima* has a growth pattern with highest growth in spring and early summer, followed by high decay rates exceeding the growth rate, leading to reduced length in late summer/autumn (Saunders and Metaxas, 2008; Andersen et al., 2011; Zhang et al., 2012).

The cropped groups had different patterns in length compared to Control, but width was not significantly affected by cropping. The cropped treatments in the January deployment were not measured in March, but considering they had the same growth environment as Control and was not treated differently this early in the season, it can be assumed that they had significant increases in length from March to April as well. Two months after the first cropping, *S. latissima* had grown back to a similar lamina length as before cropping for Crop April and Crop A+J in both deployments. Crop June (January deployment), however did not show the same regrowth, which was not surprising considering the seasonal growth pattern of *S. latissima* where growth slows down in summer months. These results also support the results from Rolin et al. (2017) who found that cropping in May resulted in regrowth back to similar blade length as Control. Cropping in June/July also resulted in regrowth, but at slower rates (Rolin et al., 2017). The present study, however, did not find regrowth in plants cropped in June, which is likely due to the level of biofouling found on *S. latissima*, compared to 0-5% fouling in the study by Rolin et al. (2017). Based on the results of the present study and existing literature, cropping of *S. latissima* in spring is more beneficial than cropping later in the season, and will lead to regrowth in length, but have little effect on width.

Biomass increased from March and peaked in June for Control in both deployments, followed by a significant decrease from June to August. The highest regrowth of biomass in this study was found when plants were cropped in April, which led to a regrowth of > 100% one month post-cropping. A study by Levitt et al. (2002) found that waiting four months between harvests compared to harvesting every month led to higher biomass yields, this is supported by the present study which demonstrated that biomass yields increased two-three months post-cropping, giving the kelp time to regrow. The meristem was left behind which allowed for this regrowth and showed to be successful for all treatments cropped in April, supporting multiple studies from South Africa, the Faroe Islands, and the Shetland Islands, investigating cropping/partial harvest of kelp (Levitt et al., 2002: Rolin et al., 2017; Bak et al., 2018). Rolin et al. (2017) found significant regrowth of *S. latissima* after the first cropping in May, and a slower regrowth when cropping in June. The present study supports these results by no or close to no regrowth after cropping in June, demonstrating that cropping earlier rather than later in the season results in higher regrowth of *S. latissima*. This can be linked to slower growth rates later in the season, coupled with higher biofouling, and a higher degree of plants being torn apart from wind- and wave action du to being larger in size and weight compared to earlier in the season (Saunders and Metaxas, 2008; Zhang et al., 2012; Kerrison et al., 2015).

4.2 Case study: total biomass harvested from one growth season

To evaluate whether cropping once or twice during the growth season would increase the total biomass this study compared biomass (kg from 100 m) between uncropped (Control) and cropped treatments (Crop April, Crop A+J, and Crop June), including a hypothetical full harvest in July. The results show that the highest biomass yields could be obtained with a crop in April and a full harvest in July with deployment in October (2034 kg) or deployment in January (2098 kg). Cropping once in April, followed by a second crop in June, and a full harvest in July also showed high biomass yields (1074 kg for October and 1054 kg for January), however only cropping once in June (720 kg) did not result in higher biomass than Control (721 kg). These results indicate that waiting until late in the season for first crop would not increase yields.

Multiple harvests at different times during the growth season can result in biomass applicable for different commercial products (Ferdouse et al., 2018). The biomass harvested in April and June of this study had no or very little biofouling and is therefore applicable as food grade (Ferdouse et al., 2018), while the biomass from July was heavily fouled upon and therefore more suited for other applications such as feed in aqua- and agriculture, fertilizers, and biofuels (Kerrison et al., 2015; Ferdouse et al., 2018). All these treatments showed higher biomass yields in one growth season than Control, which is strong evidence that cropping is an efficient way to increase seasonal biomass yields. The inclusion of control treatments in the present study, allowed for comparison between biomass yield from cropped and un-cropped treatments, which was not done in the study from the Faroe Islands (Bak et al., 2018). The results show that cropping once in April followed by a full harvest in July can more than double the biomass harvested in one season (kg for 100 m), furthermore, the biomass harvested at different times can be used for different applications, possibly widening the commercial market of *S. latissima*, and raising the commercial value.

Biomass had decreased significantly by August for all treatments in both deployments, likely due to generally lower growth in the late summer months, large lamina size, in addition to fouling and grazing by other marine organisms. Bak et al. (2018) were able to extend growth over two seasons without reseeding, this study was conducted in colder and more exposed waters in the Faroe Island, which resulted in less biofouling and enabled the plants to continue to grow for another season. These results support the suggestion from other studies that open sea cultivation has the potential to extend the growth season, due to stronger currents, less biofouling, and lower and more stable temperatures (Arrontes, 1990; Mols-Mortensen et al., 2017; Bruhn et al., 2016). The current study which was done at a more sheltered site indicated that *S. latissima* would not likely be able to grow another season without reseeding, due to the heavy biofouling and the loss of biomass at the end of the experimental period in August.

4.3 Biofouling

Biofouling increased during the experimental period and followed the same pattern for both deployments and was highest in July and August. Two bryozoan species; *M. membranacea*, *E. Pilosa* were identified on *S. latissima*, with *M. membranacea* as the dominating species. In addition, some snails were also observed on the last monitoring trip. Previous studies have linked biofouling of especially *M. membranacea* to increasing ST (Saunders and Metaxas, 2007), the present study supports the literature with higher fouling levels in summer when ST was at the highest in August at approximately 14°C, compared to 6-8°C in March-April. Most of the fouling was located on the oldest, distal end of the blades. Fresh tissue is created from the meristem at the proximal regions of the blade, and it has be suggested that cropping could potentially reduce biofouling by removing the fouled parts (Rolin et al., 2017). In the present study, the heaviest fouling was coupled with rapid decrease in blade length, and loss of biomass in August, this supports the results found by Rolin et al. (2017) where fouling by bryozoans severely damaged *S. latissima* in July/August. The severe fouling levels in the present study also aligns with another study from the same area (Frøya) stating that *S. latissima* had an average fouling coverage of 80% by August (Førde et al., 2015). The present study only analyzed plants from Control for biofouling, and therefore recommends future research to include biofouling analysis of cropped treatments as well to see whether cropping could reduce biofouling levels on *S. latissima.*

4.4. DW and ash

Moisture in kelp is linked to being higher in winter months compared to summer months, meaning that dry content would be at the lowest during winter. This pattern was seen in the present study with peak DW in August, and lowest DW in March. Average dry weight of *S. latissima* in the present study ranged between approximately 8% and 19%, which supports findings in previous studies such as Schiener et al. (2015) where dry weight ranged between 12.8% and 16% in *S. latissima* in Scottish waters. The levels increased from March to August in both deployments. Control had significantly higher DW compared to cropped treatments, one reason for this could be that after cropping, the thicker part of the plant with the meristem, is left behind, while the thinner parts of the blades, were taken back on land and analyzed.

As with DW, average ash content (%) also peaked in August for the present study, making up over 70% of the DW. The January deployment also had a peak in March, which aligns with previous studies stating that *S. latissima* has the highest ash content with approximately 40% (Schiener et al., 2015) in the winter months. Studies such as Marinho et al. (2015a) and Forbord et al. (2020) have reported ash content of *S. latissima* ranging between approximately 15 and 45%. The present study found higher levels compared to what is reported in the literature, ash content can be quite individual between plants, small sample sizes could therefore be a possible explanation for the high values. Ash has also been seen to increase with depth, and the present study deployed seedlings at 2-3 meters depth, compared to 1-2 meters depth in Forbord et al. (2020). It is unclear if this small difference in depth would impact the ash content, however, it is a possibility. Ash has also been seen to decrease from spring to summer until the onset of biofouling (Forbord et al., 2020), which is also evident for the January deployment in the present study where ash decreased from 62% in May to 52% in July, followed by an increase to 74,5% in August, supporting Forbord et al. (2020) who found decreases of around 10% from May to June/July as well.

4.5 Limitations and recommendations for future research

Conducting multiple harvests by cropping *S. latissima* can eliminate the need to reseed during one growth season, which creates an opportunity for reduced cultivation costs. Bak et al. (2018) were able to reduce costs per kg dry weight *S. latissima*, and cost of rig and growth lines by increasing yield from multiple harvests through cropping. The total cost per kg *S. latissima* in one growth season depends on the total number of harvests that can be done without reseeding, and the biomass yield per meter (Bak et al., 2018). The present study did not consider the economic aspect, and to determine whether the increased biomass yield gained through cropping is beneficial for the industry overall several factors need to be considered. The income of the extra biomass and the money saved from eliminating reseeding, need to be weighed up against the extra costs of the added labor for cropping, and the potential of the harvested kelp for commercial applications also needs to be considered, as kelp harvested later in the season is mainly suited for lower-quality products. Future studies would likely benefit from including the financial aspect to make even more robust suggestions for increasing biomass yield and lowering cultivation costs.

Suggestion for harvesting strategy to optimize yield and use of biomass from this study is deploying seeds in January, cropping once in April, followed by a full harvest in July. This method resulted in the highest biomass yield in this study, which include plants free of fouling from the crop in April, which could be used for human consumption. However, most of this biomass came from July, and the biomass at this point would likely be heavily fouled upon, as seen for Control. It could be suggested that a full harvest be done in June, although there were no data collected on biomass of Crop April in June it is reasonable to suggest that it would be similar to the biomass in June for Crop A+J and would therefore result in a high biomass yield with fresh tissue suitable for human consumption. Alternatively, the fouled biomass from the harvest in July could be used for lower quality products such as animal feed, fertilizers, or biofuels (Kerrison et al., 2015; Bak et al., 2019).

This study was limited by weather and time constraints, which resulted in no collection of growth measurements in June for Crop April, and less replicates for growth measurement for a couple of the monitoring trips, there was also one seeded rope missing during the experimental period. The study is also subject to human error, as growth measurements were done manually with folding rule and a handheld scale. Nevertheless, all measurements were done with the same method, and the same people. There are different ways in which growth of kelp can be measured, such as calculating mean length from all blades, choosing plants randomly, or choosing a specific group such as the 10 longest plants for example (Rolin et al., 2018). The present study picked the most representative blades from the different treatments. However, the results still showed similar patterns to the existing literature and adds to the evidence that partial harvest/cropping could be an alternative to increasing biomass yields from the same seeding.

5. Conclusion

The present study showed that cropping of *S. latissima* once or twice during one growth season results in regrowth in length, in addition to possibly doubling the maximum biomass that could be harvested during one growth season, compared to only harvesting once at the end of the growth season. This study therefore adds to the existing literature suggesting partial harvest as an efficient way of increasing kelp biomass yields.

S. latissima had a seasonal growth pattern with peak length and biomass in June for Control, while width increased in the beginning of the season and then stabilized. Plants deployed in October were generally larger than plants deployed in January, likely due to longer time for growth. Cropping in April resulted in >100% regrowth after one month, but cropping in June did not result in any regrowth, proving that cropping early in the growth season at this location is important for regrowth to happen. Biomass yields increased significantly compared to Control when cropping once in April, and cropping in April and June, but not when cropping only once in June, this was true for both deployments. Biofouling was also investigated for control treatments and showed a pattern with negligible biofouling from April to June, followed by severe biofouling in July and August. DW in *S. latissima* in the present study was within the ranges reported in the literature and increased during the growth season. Ash content was generally higher compared to previous studies, but still within reported ranges, and decreased from spring to summer until the onset of biofouling for the January deployment, supporting results from Forbord et al. (2020).

The results of this study support the existing literature suggesting that cropping once or twice in one growth season increases growth and biomass of kelp such as *S. latissima*. It also supports studies on the biofouling levels already seen on kelp at this latitude, with low levels in winter and spring, and high levels in summer, which is linked to decay and breakage of the plants, leading to loss of biomass. Research on the effect of cropping on biofouling, and the potential of cropping reducing cultivation costs is recommended for future studies.

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Appendices

Appendix A: Length/width relationship

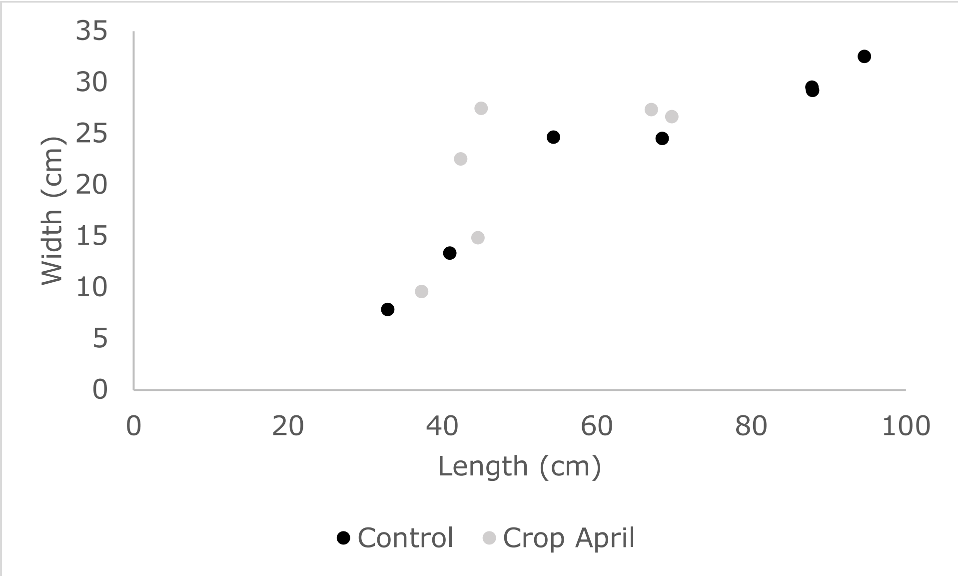

Figure A.1: Relationship between length and width of S. latissima *for Control and Crop April from the October deployment.*

Appendix B: Biofouling- representative plants

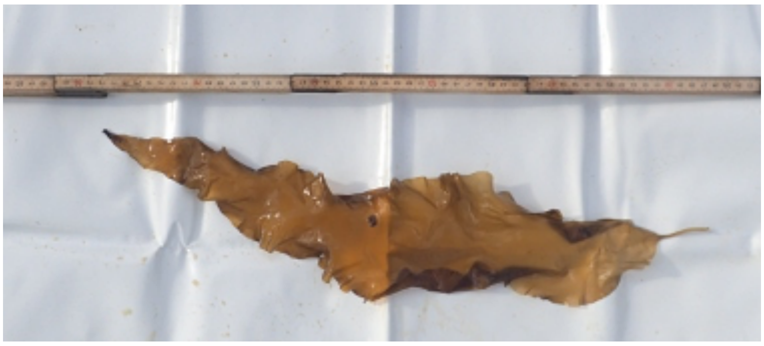

Figure B.1: Representative plant from April (October deployment.

Figure B.2: Representative plant from April (January deployment.

Figure B.3: Representative plant from May (October deployment).

Figure B.4: Representative plant from May (January deployment).

Figure B.5: Representative plant from June (October deployment).


Figure B.6: Representative plant from June (January deployment).


Figure B.7: Representative plant from July (October deployment).


Figure B.8: Representative plant from July (January deployment).


Figure B.9: Representative plant from August (October deployment).

Figure B.10: Representative plant from August (January deployment).

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