



ASTRAL

All Atlantic Ocean Sustainable, Profitable and Resilient Aquaculture

GA no **863034**

Research and Innovation Action (RIA)

Start date: 1st September 2020. End date: 30th September 2024

D2.5 New value chain at IMTA Lab Scotland



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863034

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Document administration

Deliverable number	D2.5
Deliverable name	New value chain at IMTA Lab Scotland
WP number	WP2
Deliverable due date	M46
Submission date	30.06.2024
Dissemination levels	Public
Lead beneficiary	SAMS
Responsible	Kati Michalek (SAMS)
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Internal reviewers	Pauline O'Donohoe (MI), Rozenn Le Vaillant (PMBA), Elisa Ravagnan (NORCE)

Document history and changes

Document history			
Version	Date	Modified by	Comments
1.0	19.04.2024	KM	Advanced Draft to Reviewers
	06.05.2024	Internal Reviewers	Reviewers return the document proofread and commented to the author(s)
1.1	17.06.2024	KM, AML, MSST	Final Draft to Reviewers
	21.06.2024	Internal Reviewers	Reviewers return the document proofread and commented to the author(s)
Final	27.06.2024	KM	Final revised document to coordinator for submission

Evidence of accomplishment

Report

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List of Abbreviations

AI	Artificial intelligence
ASTRAL	All Atlantic Ocean Sustainable, Profitable and Resilient Aquaculture
BMP	Biosecurity management plan
Chl-a	Chlorophyll-a ($\mu\text{g/L}$)
CI	Condition index (%)
CDN	Confirmed Designation Notice
DWS	Dry weight shell pair (g)
DWT	Dry weight soft-tissue (g)
FHI	Fish Health Inspectorate
FL	Frond length (cm)
IMTA	Integrated multi-trophic aquaculture
IoT	Internet of Things
HAB	Harmful algal bloom
HUCAP	Human capital development plan
LTA	Low-trophic aquaculture
MFW	Maximum frond width (cm)
MY	Meat yield (%)
N	North
NE	North-east
NE-SW	North-east to South-west
NORA	Native oyster restoration alliance
PaB	Port-a-Bhuiltin (i.e. IMTA Lab Scotland)
POC/N	Particulate organic carbon and -nitrogen
S	Salinity (psu)
SAMS	Scottish Association for Marine Science
SGR	Specific growth rate
SH	Shell height (mm, cm)
SL	Shell length (mm, cm)
SMEs	Small and medium-sized enterprises
SW	Shell width (mm, cm)
T	Temperature ($^{\circ}\text{C}$)
TWW	Total wet weight (g)
WP	Work package
WWS	Wet weight shell pair (g)
WWT	Wet weight soft-tissue (g)

1 Summary

This deliverable was created as part of work package (WP) 2 ‘New IMTA value chains and production methods’ of the EU H2020 All Atlantic Ocean Sustainable, Profitable and Resilient Aquaculture (ASTRAL) project and addresses the production value chain of IMTA Lab Scotland.

The overall objective was to develop and validate cost-effective low-trophic aquaculture (LTA) in an open water system. To achieve this, a total of nine species have been produced or introduced at IMTA Lab Scotland; including five seaweed (three brown i.e. kelp and one red species), three bivalve mollusc and one echinoderm species, and assessed for their overall prospective applicability for open water LTA.

This deliverable reports on all experimental trials undertaken during the lifespan of the project, consisting of ‘cultivation optimisation’ trials for well-established kelp species at site (*Alaria esculenta*, *Saccharina latissima*) and ‘proof-of concept’ trials for species that have been newly added to the system (seaweed: *Laminaria digitata*, *Saccorhiza polyschides* (kelp), *Palmaria palmata* (red); bivalve molluscs: *Ostrea edulis* (oyster), *Pecten maximus* and *Aequipecten opercularis* (scallop); echinoderm: *Echinus esculentus* (sea urchin)). Cultivation optimisation trials applied modifications to grow-out methodologies (cultivation depth, line orientation, stocking density) and identified optimal configurations for either species through improvements in cultivation performance as well as spatial and infrastructure efficiency. Irrespective of the type of trial, all species have been investigated for their cultivation performance (growth, survival, appearance and quality) in conjunction with long-term monitoring of key environmental parameters as well as modifications to operational practices.

For seaweed, results showed that brown species outperformed newly added red species in terms of deployment and grow-out success, with one species (*S. polyschides*) being a particularly promising new candidate for large-scale commercial cultivation. All trialled shellfish, or bivalve molluscs, performed well in suspended cultivation at IMTA Lab Scotland, with the European flat oyster (*O. edulis*) standing out for its significantly higher survival and growth when compared to traditional cultivation practices in the intertidal. The edible sea urchin (*E. esculentus*) did not perform well in open water cultivation with prevailing moderate current and wave regimes not suitable for this fragile species.

Information and data gathered on all trialled species will support the sustainable development of current and future aquaculture practices beyond a regional scale and beyond the concept of single species(group) cultivation. The co-location of species groups with differences in food but similarities



in cultivation infrastructure requirements, i.e. seaweed and shellfish, can increase the resource and spatial efficiency of the site and allow for the advancement of more circular production methods.

2 Introduction

IMTA Lab Scotland’s aquaculture production addresses processes involved in the ‘Growout’, i.e. from deployment to harvest, of low-trophic aquaculture species, seaweed and shellfish, complemented by ‘Seed Production’ processes for seaweed via SAMS commercial seaweed nursery (Figure 1; see highlighted areas).

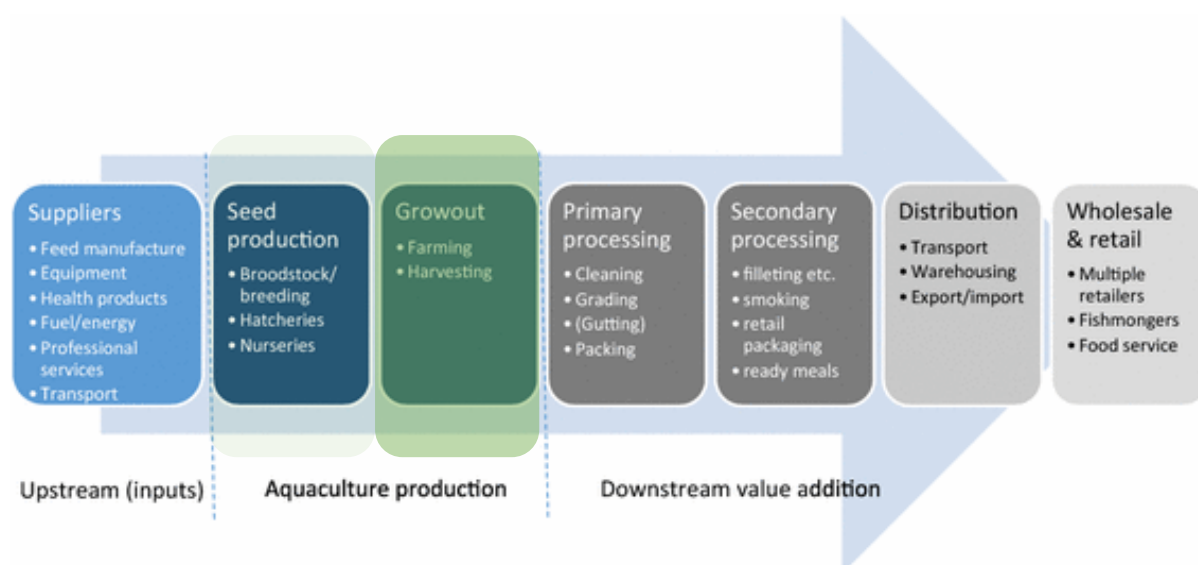


Figure 1. Highlighted (green) areas indicate IMTA Lab Scotland’s production value chain. Adapted from Bostock *et al.* (2016)¹.

Other aspects of the value chain are addressed in investigations and reports compiled by other WPs which can be found on the [ASTRAL website](#) or accessed via the EU open research repository at [ZENODO](#). Of relevance here are deliverable reports D4.1, D4.4, D6.3 and D7.7.

2.1 ASTRAL

The EU H2020 project ASTRAL has developed new, sustainable, profitable and resilient value chains for integrated multi-trophic aquaculture (IMTA) production within the framework of existing, emerging and potential Atlantic markets. This project gathered four IMTA Labs including open-water (Ireland, Scotland), land-based pump-ashore with partial (50 %) recirculation (South Africa) and recirculation 'biofloc' land-based (Brazil) systems and one prospective IMTA Lab (Argentina), focusing on a regional challenge-based perspective, including fish, mollusc, echinoderm, crustacean and algae

¹ Bostock, J., Lane, A., Hough, C., & Yamamoto, K. (2016). An assessment of the economic contribution of EU aquaculture production and the influence of policies for its sustainable development. *Aquaculture International*, 24(3), 699–733. <https://doi.org/10.1007/s10499-016-9992-1>

species. ASTRAL assessed how to increase circularity using IMTA methods of cultivation by 50 – 60 % compared to monoculture aquaculture and provided a circular business model, boosting revenue diversification for aquaculture producers increasing profitability by at least 30 %. New and improved innovative technology has been developed, including biosensors, sensors, Internet of Things (IoT) and an Artificial Intelligence (AI) data analytics platform has been validated at the IMTA Labs. Potential environmental and climatic risks for Northern and Southern Atlantic regions were addressed, delivering a monitoring programme and recommendations for Harmful Algal Blooms (HABs), pathogens and microplastics. ASTRAL has delivered an ambitious and gender-sensitive human capital development plan (HUCAP) which seeks to improve professional skills and create a highly trained workforce. This project gathered a collaborative ecosystem within the project framework bringing together and connecting industrial partners, SMEs, scientists, policy makers, social representatives and other relevant stakeholders promoting data exchange, knowledge sharing and business opportunities.

2.2 Integrated Multi-Trophic Aquaculture (IMTA)

IMTA is defined as the farming of aquaculture species from different trophic levels, and with complementary ecosystem functions in the same area or at the same site. This type of integrated culturing allows one species' unwanted feed, waste, and nutrients to be captured and converted into fertilizer and feed for other aquaculture species, taking advantage of synergistic interactions between species. In the 'classic' IMTA scenario, the combination of fed aquaculture species (e.g., finfish or shrimp) with extractive aquaculture species, which utilize dissolved inorganic nutrients (e.g. seaweeds) and particulate organic matter (e.g. suspension and deposit-feeders), allows growth in this type of system.

Due to the differences in nutritional requirements of extractive species, IMTA does not necessarily require the presence of fed species, yet for clarity is more often referred to as integrated low-trophic aquaculture (LTA). IMTA seeks to aid ecological balanced systems to improve environmental sustainability, enhance ecosystem services and boost economic stability by increasing biomass, lowering operational costs, providing product diversification, reducing risk, and creating jobs in rural communities while advancing societal acceptability².

² Chopin, T., (2013). Aquaculture, Integrated Multi-trophic (IMTA)., in: Christou, P., Savin, R., Costa-Pierce, B.A., Misztal, I., Whitelaw, C.B.A. (Eds.), Sustainable Food Production. Springer, New York, NY, pp. 184–205. https://doi.org/10.1007/978-1-4614-5797-8_173

2.3 ASTRAL IMTA Labs

The IMTA Labs form the heart of the ASTRAL project, providing the context for developing cost-effective, profitable and sustainable IMTA production. Here the term ‘IMTA Lab’ refers to the locations of the respective IMTA production site or ASTRAL pilot site, consisting of recirculation, flow-through, open-water and land-based production systems within the Atlantic area (Figure 2).



Figure 2. Location of the 4 (+1 prospective) ASTRAL IMTA production sites (= ASTRAL IMTA Labs).

Open Water IMTA

IMTA production can be carried out in differing aquaculture systems. Open water IMTA, as practiced by ASTRAL IMTA Labs Ireland and Scotland, refers to the farming of aquatic organisms such as fish, shellfish, and seaweed at sea with variable distance to the coast.

For non-seaweed species this involves the use of cages, nets, and other structures to contain and protect the farmed species while allowing natural water flow. Mooring systems consisting of anchors, ropes, and buoys are used to hold the farm installation in place and secured to the seabed, even in strong currents and rough weather conditions.



This type of system takes advantage of the ocean's natural environment, providing ample space and resources for growth, while aiming to minimize environmental impact. However, it is continuously exposed to prevailing environmental conditions, including wind and wave action. Unlike closed land-based systems, culture conditions are not controllable, and adaptations to grow-out strategies are restricted to species choice and modifications to existing and future cultivation infrastructure.

3 IMTA Lab Scotland - Coastal Open Water LTA

IMTA Lab Scotland developed and validated low-trophic aquaculture (LTA) by growing seaweed; predominantly brown i.e. kelp but also red species, alongside other commercially relevant species (bivalve molluscs, echinoderms) (Table 1).

Table 1. Overview of species trialled at IMTA Lab Scotland, including established and new species to the site.

Common Name	Latin Name	Role in IMTA	Established/New
Brown Seaweed			
Atlantic wakame	<i>Alaria esculenta</i>	Inorganic extractive species	Established
Sugar kelp	<i>Saccharina latissima</i>	Inorganic extractive species	Established
Oarweed	<i>Laminaria digitata</i>	Inorganic extractive species	New
Furbelows	<i>Saccorhiza polyschides</i>	Inorganic extractive species	New
Red Seaweed			
Dulse	<i>Palmaria palmata</i>	Inorganic extractive species	New
Bivalve Mollusc			
European flat oyster	<i>Ostrea edulis</i>	Organic extractive species	New
King scallop	<i>Pecten maximus</i>	Organic extractive species	New
Queen scallop	<i>Aequipecten opercularis</i>	Organic extractive species	New
Echinoderm			
Edible sea urchin	<i>Echinus esculentus</i>	Organic extractive species	New

Each species group plays an important role in maintaining ecological balance and enhancing sustainability within an IMTA system:

Seaweed absorbs (excess) nutrients from the surrounding water, improving water quality and reducing the risk of harmful algal blooms (HABs). Through photosynthesis, carbon dioxide dissolved in seawater is taken up and oxygen produced, helping to mitigate the effects of climate change and supporting respiration of other aquatic organisms in proximity, respectively. In addition, seaweed provides habitat and shelter for various marine organisms, including juvenile fish and invertebrates, contributing to biodiversity within the aquaculture system. By performing these roles, seaweed enhances the overall efficiency and sustainability of IMTA systems, promoting a more balanced and environmentally friendly approach to aquaculture while providing an additional revenue stream.

Filter-feeding shellfish such as **oysters and scallops** remove particulate matter, including plankton and organic debris, from the water thus improving overall water quality. By consuming organic particles, shellfish help recycle nutrients within the system, which can be utilized by other aquatic organisms for growth, including seaweed. They can reduce the accumulation of organic waste from other farmed

species, such as fish, by converting it into biomass with added economic value. As for seaweed, shellfish provide habitat and shelter for other marine organisms, contributing to the local biodiversity.

Sea urchins graze on algae, preventing excessive algal growth that could otherwise compete with or harm other farmed species by e.g. obstructing water flow and food supply in shellfish grow-out structures. By consuming and controlling algae populations, sea urchins contribute to nutrient cycling and the recycling of organic matter within the aquaculture system, promoting the health and growth of other species. As for seaweed and shellfish, sea urchins provide habitat and enhance biodiversity as well as providing an additional revenue stream for aquaculture operations.

3.1 Site Description

The IMTA Lab Scotland, site name Port-a-Bhuiltin (PaB), is a coastal open water aquaculture site located 200 m off the mainland shore in the Firth of Lorn-Loch Linnhe estuarine system, west coast of Scotland (56° 29.176 N, 5° 28.315 W) (Figure 3B).

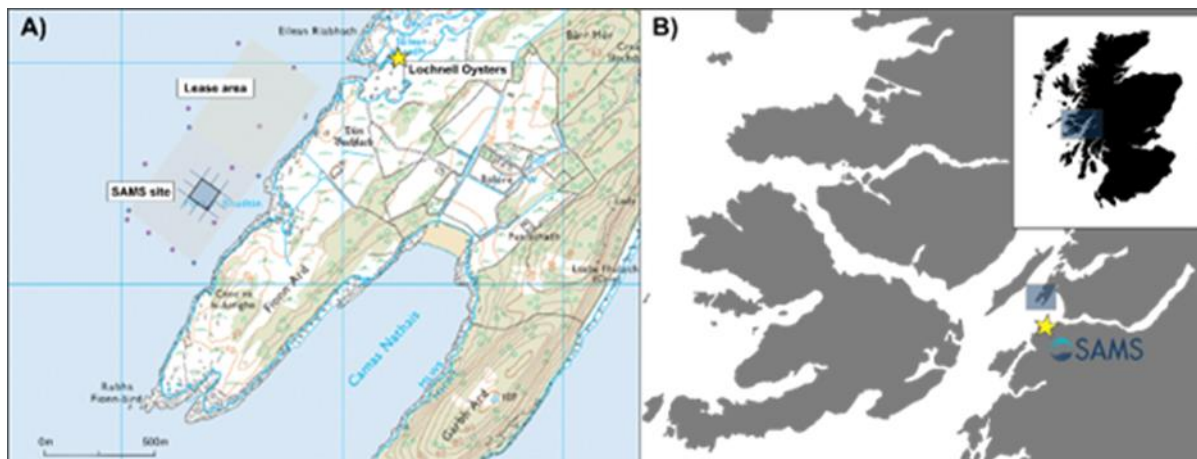


Figure 3. Lease area (A) and location (B) of IMTA Lab Scotland (Port-a-Bhuiltin, PaB), a low-trophic coastal aquaculture research site on the West coast of Scotland, ©SAMS).

PaB has been operated by the Scottish Association for Marine Science (SAMS) as an experimental seaweed cultivation site since 2014. Following a license amendment with Marine Scotland in 2020, the site is licenced for the cultivation of seaweed with selected invertebrate species for experimental non-commercial use. With this, PaB has transitioned from a seaweed monoculture site to a low-trophic aquaculture (LTA) site for the co-cultivation of extractive species groups.

The total lease area is 30 hectares and currently consists of one tensioned 100 x 100 m (= 1 hectare) rope grid submerged 3 m below the water surface (Figure 3A). The grid can support up to 48 seaweed growing lines of 50 m length, spaced 4 m apart, which are suspended horizontally and parallel to the main current flow at a depth of 1.5 m below the water surface. The system is modifiable and offers capacity for additional deployment infrastructure for seaweed and shellfish production as well as environmental monitoring equipment (Figure 4).

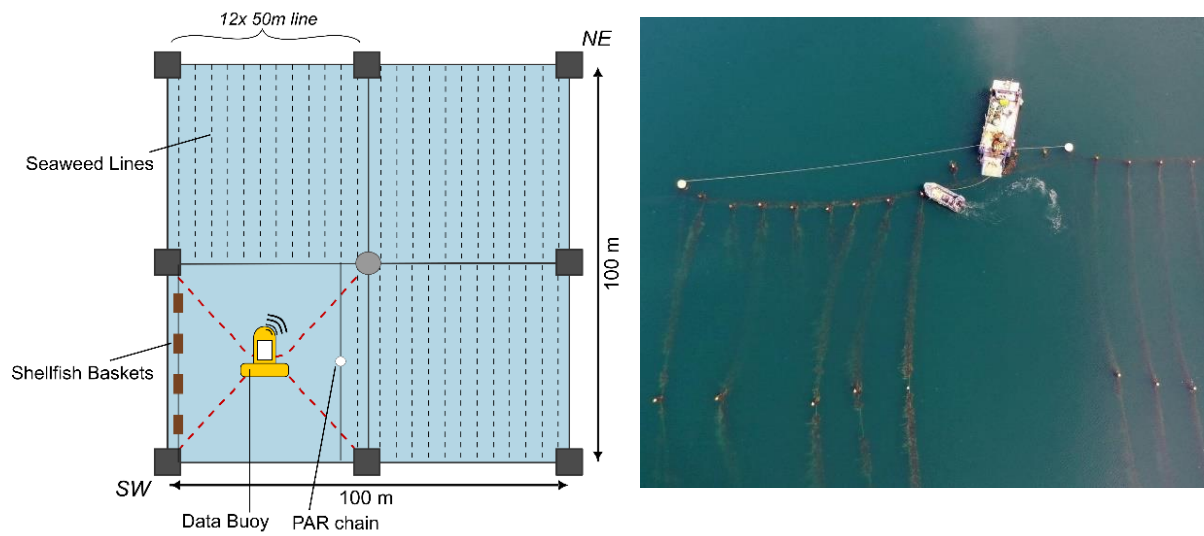


Figure 4. Left: Site layout with seaweed and shellfish cultivation infrastructure and temporary environmental monitoring equipment. Right: Aerial view of the seaweed harvest operation in June 2020 (©A. O'Dell, SAMS).

3.2 Cultivation Environment

Environmental parameters relevant for species growth and well-being are routinely monitored at site and have continued to be followed throughout the lifespan of the project.

Environmental monitoring has already provided multi-annual high-resolution datasets allowing for so called ‘data-driven decision support’; for example, aiding in deciding for the best time to deploy and harvest seaweed. The environmental parameters followed in ASTRAL are summarised in Table 2 and described in detail below, grouped into physical and nutritional parameters.

Table 2. Environmental monitoring during the ASTRAL project.

Parameter (Unit)	Measurement Frequency	Instrument
Physical Parameter		
<i>Temperature</i> (°C)	Continuous; at site visit	Onset HOBO MX2202; SonTek castaway CTD
<i>Salinity</i> (psu)	At site visit	SonTek castaway CTD
<i>Light</i> (lux)	Continuous	Onset HOBO MX2202
<i>PAR</i> (μmol/m ² /s)	Short-term deployments	PAR sensor chain (@SAMS)
Nutritional Parameter		
<i>Chl-a</i> (μg/L)	At site visit	Manual water sampling
<i>POC/N</i> (mg/L)	At site visit	Manual water sampling
<i>Nutrients</i> (μmol/L)	At site visit	Manual water sampling

Chl-a = chlorophyll-a; *POC/N* = particulate organic carbon and nitrogen; *Nutrients* = nitrate (NO₃⁻), nitrite (NO₂⁻), ammonium (NO₄⁺), orthophosphate (PO₄³⁻), silicate (SiO₄⁴⁻).

3.2.1 Physical Parameter

The site is moderately exposed to south-westerly winds with the main current flow in NE – SW direction. Water currents can vary considerably ranging from 0.1 to 500 cm/s with average surface currents speeds of 11 cm/s. The tide is semi-diurnal ranging from 0.15 to 4.51 m. The mean water depth at site is 30 m with muddy sand and mixed sediments.

The climate is temperate maritime, with maximum air temperatures of just below 6 °C in January and 21 °C in July, and night frost probable until mid-April. Rainfall patterns can vary greatly throughout and across years with frequent extended periods of heavy rain and often coinciding with storm events during late Autumn and early Winter (Figure 5).

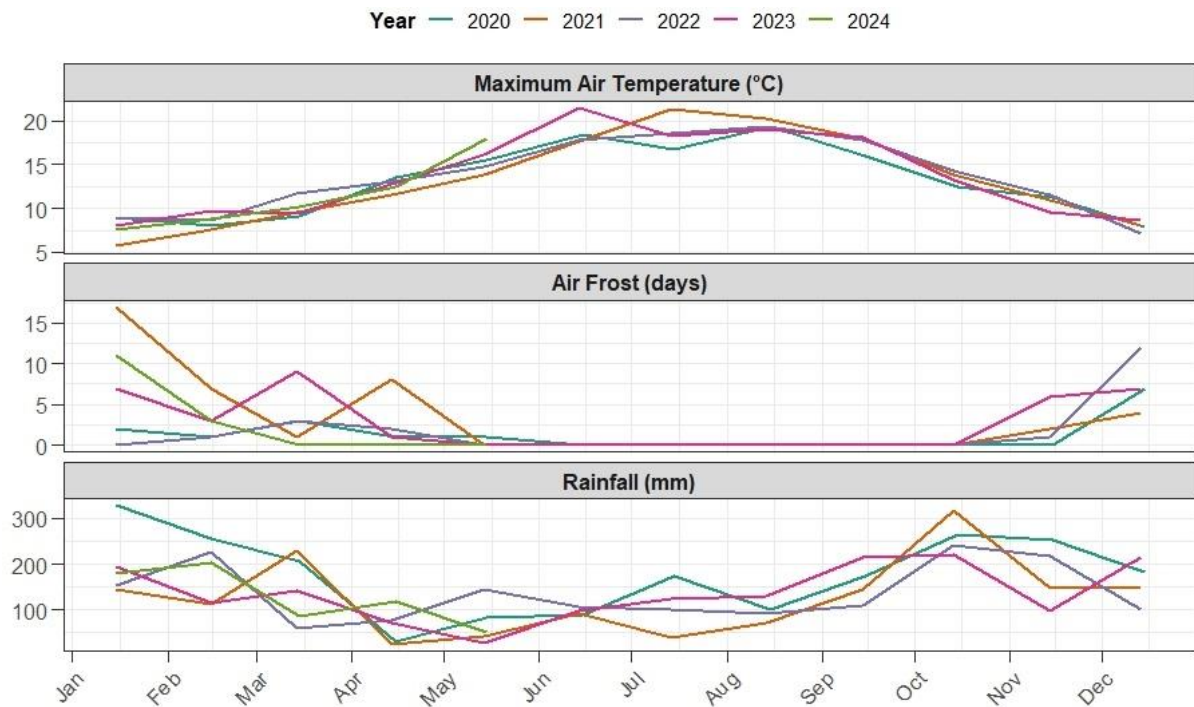


Figure 5. Weather data for MIDAS station Dunstaffnage [station nr: 918; MetOffice] over the course of 4.5 years (January 2020 – May 2024), ©SAMS.

Over the course of the project (Sep 2020 to date), average seawater temperature T at main seaweed cultivation depth (= 1.5 m depth) ranged from 6.6 °C in late Winter to 15.4 °C in mid-Summer, and salinity S from 21.5 to 33.3 psu, typically being > 32 psu (Figure 6).

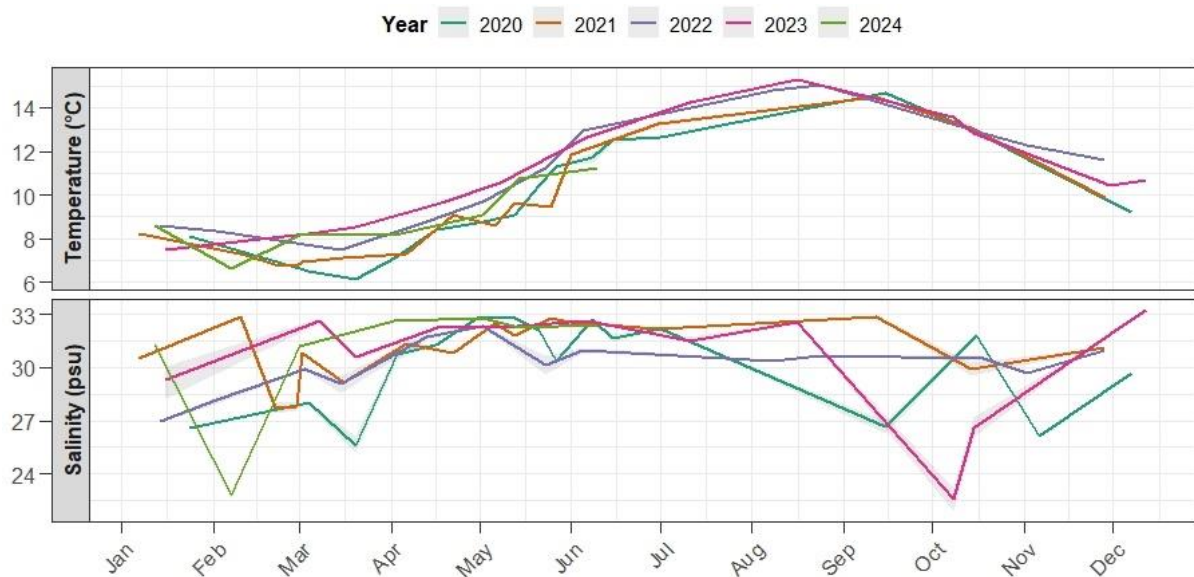


Figure 6. Seawater temperature and salinity at main seaweed cultivation depth of 1.5 m. Shown is CTD data averaged across 1 to 2 m water depth ($n = 4$) over the past 4.5 years (January 2020 – May 2024), ©SAMS.

Temporal variability in T and S was overall most pronounced in surface waters but could extend to ≥ 8 m depth depending on the season (Figure 7).

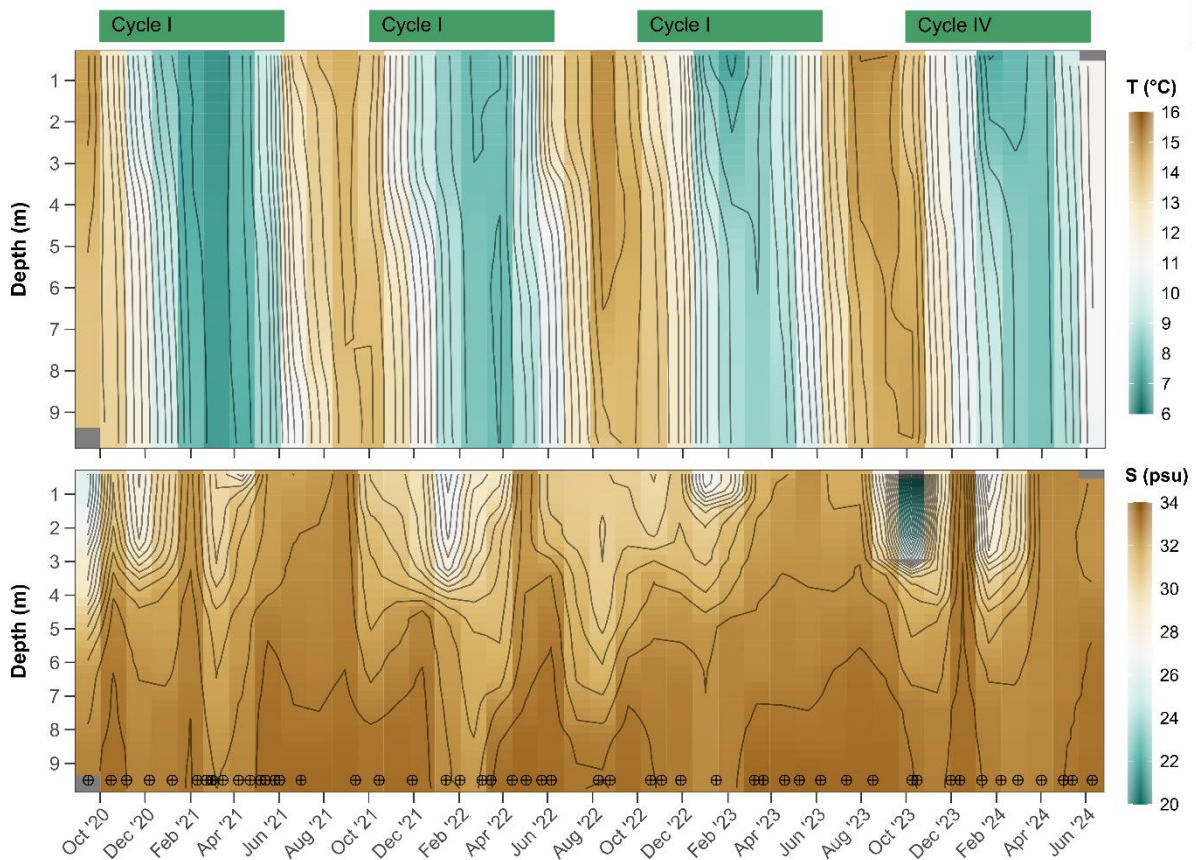


Figure 7. Depth profile (0 – 10 m; castaway CTD) of seawater temperature T and salinity S at IMTA Lab Scotland during the ASTRAL project. Top green bars indicate the annual seaweed cultivation cycle (Oct – Jun), ©SAMS.

Light availability also changes across season i.e. throughout a seaweed cultivation cycle. From late Autumn to mid-Winter, light intensities are very low and start to increase as the days are getting longer with the onset of Spring. Daily averaged light intensity ranged from as low as 4 to 4949 lux (average = 379 lux) between 23rd October 2020 and 2nd June 2021 (i.e. cycle I). Yet, light conditions can vary drastically over the course of a single day, influenced by e.g. cloud cover and time of year, as observed in early and late Spring at IMTA Lab Scotland (Figure 8B, bottom). For the availability and variability of light quality, i.e. photosynthetically active radiation (PAR), see section 0 (Figure 18).

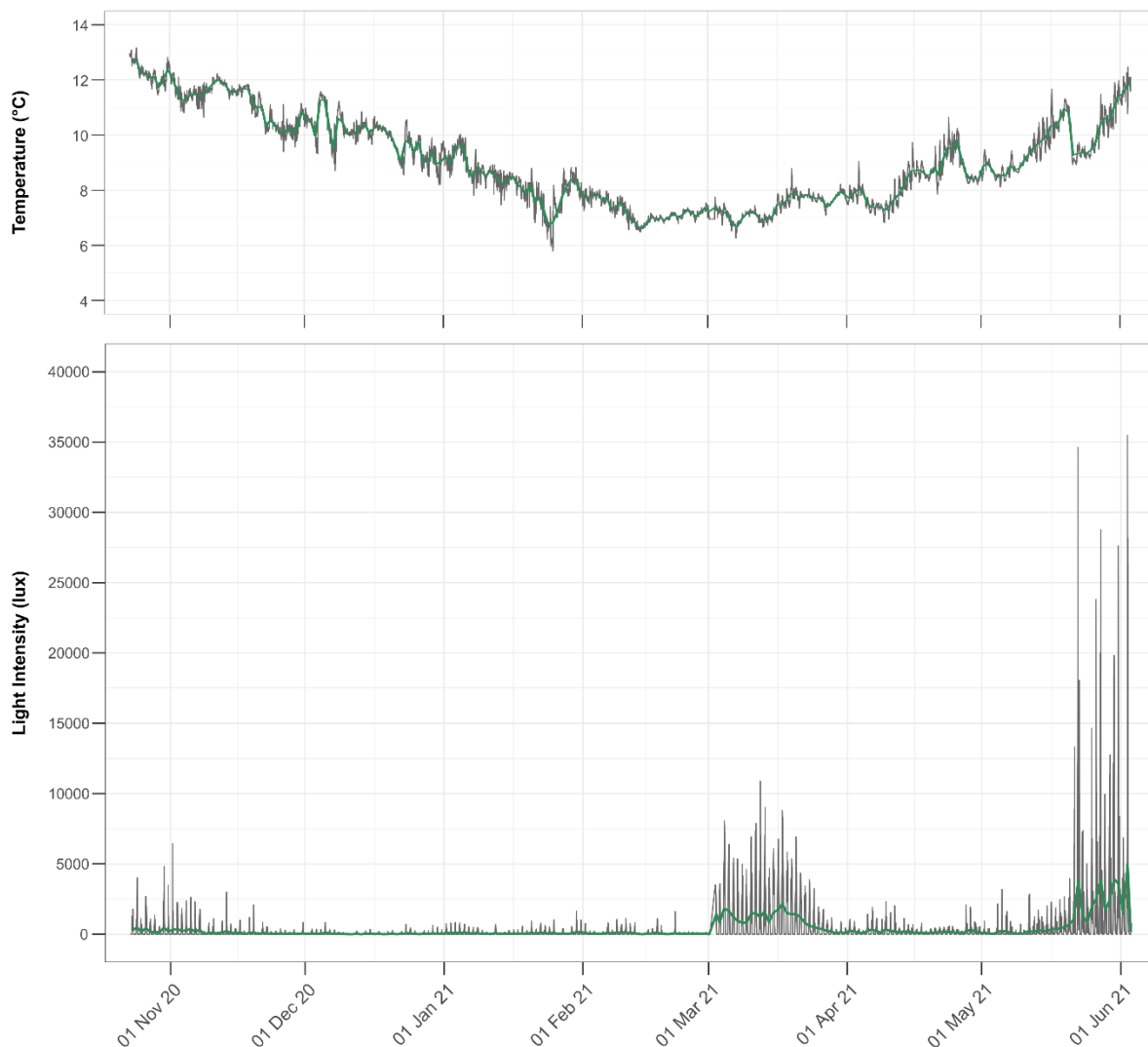


Figure 8. Temperature (top) and light intensity (bottom) at 1.5 m depth over a seaweed cultivation cycle (Oct 2020 –Jun 2021). HOBO logger recording every 30 min (grey line) with daily average (green line), ©SAMS.

3.2.2 Nutritional Parameter

Seawater samples have been collected routinely on a monthly average (more frequent in Spring, less in late Autumn to early Winter) from the centre of the site. Using a Niskin bottle ($V = 1\text{ L}$) three separate seawater samples were collected from 1.5 m depth, the common seaweed cultivation depth employed at site, and stored dark and cool during transport to SAMS laboratory. All samples were analysed for concentrations of chlorophyll-a (*Chl-a*), particulate organic carbon and nitrogen (*POC*, *PON*), and seawater nutrients (nitrate, nitrite, ammonium, phosphate, silicate) (see also Table 2). *Chl-a*, *POC* and *PON* provide good indication about the quantity and quality of food available for organic extractive species i.e. bivalve molluscs and sea urchin. Inorganic nutrients are naturally available in the seawater and additionally released by any marine organisms' metabolic activities, and are being readily absorbed by seaweed for growth.

Over the course of the ASTRAL project, a total of 50 water samplings have been performed, each accompanied by the recording of depth profiles for T and S (see Figure 7). During this time, concentrations of $Chl-a$ ranged from 0.01 – 7.20 $\mu\text{g/L}$, being indicative for and following the seasonality in phytoplankton abundance with highest and most variable $Chl-a$ levels corresponding to the phytoplankton spring bloom in April (Figure 9). Concentrations of POC varied less within and across years and ranged from 0.01 – 0.50 mg/L ; the highest values being attributed to a single sampling in November 2022. PON follows a similar seasonality to $Chl-a$, ranging from 0.01 – 1.15 mg/L with higher levels being observed in April – May and occasionally June – July. Here it is to note, however, that POC/N samples collected since mid-March 2023 are awaiting analysis and are not shown in Figure 9.

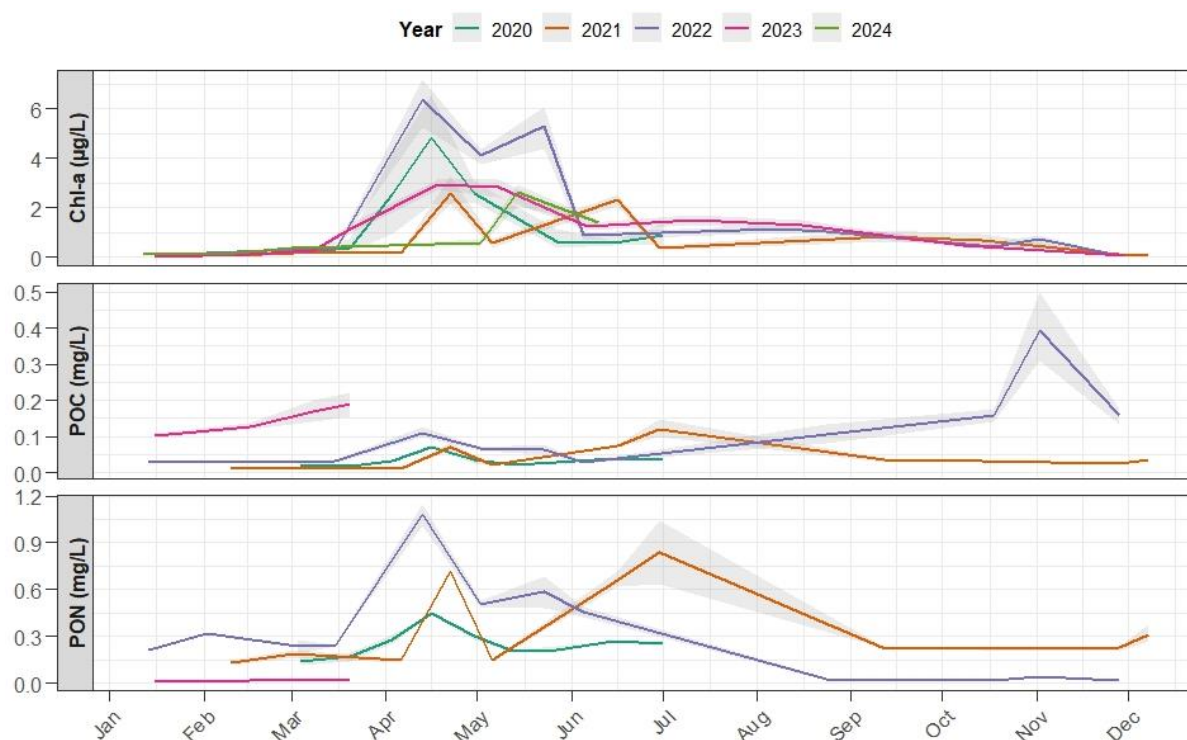


Figure 9. Concentrations of chlorophyll-a ($Chl-a$, $\mu\text{g/L}$) and particulate organic carbon (POC , mg/L) and nitrogen (PON , mg/L) over up to four consecutive years (Mar 2020 – Mar 2023 [POC/N] / Apr 2024 [$Chl-a$]), ©SAMS.

Seaweed relies on several key nutrients for optimal growth, primarily on sources of nitrogen being absorbed in the form of nitrate and ammonium, and phosphorus absorbed in the form of phosphate. Available nutrient concentrations varied throughout the year generally following a seasonal cycle (Figure 10). Nitrate levels were as low as 0 $\mu\text{mol/L}$ during Summer and increased over Autumn months to maximum levels of 9 $\mu\text{mol/L}$ in late Winter. Both phosphate and silicate concentrations exhibited similar seasonal patterns, ranging from 0 to 0.65 $\mu\text{mol/L}$ for phosphate and up to 9.64 $\mu\text{mol/L}$ for silicate. When considering each nutrient separately, the temporal variation remained consistent across years, with a few outlying values attributed to analytical variability within triplicate sample sets.

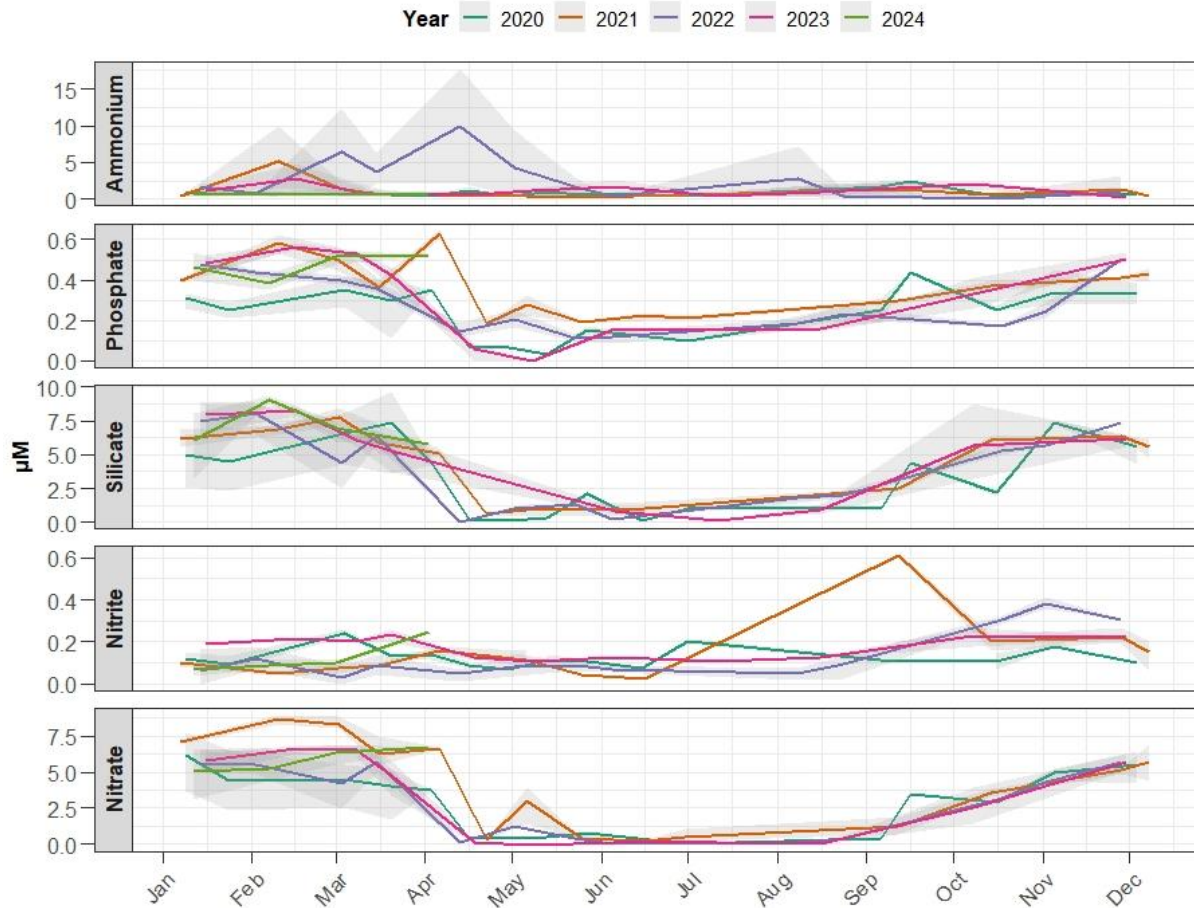


Figure 10. Annual variation in seawater inorganic nutrients (ammonium NH_4^+ , orthophosphate PO_4^{3-} , silicate SiO_4^{4-} , Nitrite NO_2^- , Nitrate NO_3^-) over the course of 4.5 years (Jan 2020 – Apr 2024), ©SAMS.

In summary, frequent storms and more severe weather during the Autumn and Winter months enhance vertical mixing of the water column, transporting deeper water nutrients closer to the surface. As Spring arrives with rising temperatures and increased light, macro- (seaweed) and microalgae (phytoplankton) compete for the same available nutrient pool, leading to its rapid depletion; note *Chl-a* increase i.e. phytoplankton bloom, and nutrient decrease in April – May (Figure 9 and Figure 10).

4.1 Kelp (*Saccharina latissima* & *Alaria esculenta*)

4.1.1 Introduction

Large brown macroalgae, collectively known as kelp (order: Laminariales), can be found along most Atlantic coastlines where they have been utilised by local communities for centuries. Along with wild harvest having a long and lasting tradition, kelp has proven very suitable for commercial cultivation being a highly productive, fast-growing and nutrient-rich crop with wide-ranging application potential for food and feed products to extraction of high-value compounds (e.g. fucoxanthin and kelp-derived biostimulants).

For seaweed farming to become a sustainable and economically viable industry, it's essential to overcome several barriers. These include lengthy licensing processes, limited access to processing facilities and markets, and operational inefficiencies. Key issues related to processing further include seasonal harvesting and the need for capital-intensive processing technology, which requires large biomass volumes to be cost-effective.

Operational inefficiencies can be addressed by reducing infrastructure and associated operational costs while maintaining or even increasing harvestable yield. One approach is to optimise mooring and material requirements relative to cultivation capacity, such as increasing stocking density. Another strategy involves developing cultivation systems that support efficient deployment and harvesting operations. Additionally, improving understanding of environmental-crop relationships and adjusting cultivation systems and harvest timing accordingly are critical to maximise productivity.

IMTA Lab Scotland's experimental trials have addressed many of these challenges by monitoring species-specific grow-out performance in relation to prevailing environmental conditions as well as exploring various deployment and grow-out configurations to assess the optimal cultivation conditions to produce high-yielding and high-quality kelp in an open water system. The following sections present the rationale, methodology, and key findings of each group of trials, many of which running over consecutive years i.e. cultivation cycles and involving more than one species (see Table 3 an overview).

4.1.2 Timeseries Monitoring

In temperate waters, a typical kelp cultivation cycle spans from deployment in early Autumn (end September/early October) to harvest in Spring (April to June). More detailed information on the methodologies involved in kelp culture can be found in ASTRAL deliverable D2.8 – Production Manual for Open Water IMTA. Harvest time is a critical operational decision and has predominantly been defined as the time of year when maximum crop yields can be achieved. However, research and industry focus is increasingly shifting to perform harvest when all requirements for the intended application of the product are met; particularly important when considering food safety requirements (e.g. trace metal concentrations) for food and feed products.³ Choosing the optimal harvest time one has to first understand environment-crop relationships as well as species-specific differences/similarities due to environmental cultivation conditions, and seasonal changes therein, directly affecting the growth and biochemical composition of the crop⁴; in other words the achievable quantity and quality at time of harvest.

In ASTRAL's first cultivation cycle (cycle I: 2020 – 2021), a timeseries monitoring study was performed involving two species commonly grown at our site (*A. esculenta*, *S. latissima*) and one additional Laminariales, the oarweed *Laminaria digitata*. Over the last 20 years, the focus has primarily been on upscaling the production of *A. esculenta* and *S. latissima*. Initially, the interest in *S. latissima* biomass was driven by its potential for generating seaweed-based biofuels. Currently, markets for both species are mainly focusing on food-based products, bioplastic production, and biostimulants. While being a much slower growing variety, *L. digitata* comprises of large quantities of laminarin, a polysaccharide associated with numerous health benefits (e.g., anti-obesity, anti-diabetic) and widely investigated for biomedical applications.⁵

The aim of this trial has been to gain a better understanding of each species growth and cultivation potential by following their specific growth rate (SGR), biomass yield, morphology and biochemical composition over the course of a cultivation cycle.

³ Steinhagen, S., Enge, S., Cervin, G., *et al.* (2022). Harvest time can affect the optimal yield and quality of sea lettuce (*Ulva fenestrata*) in a sustainable sea-based cultivation. *Frontiers in Marine Science*, 9(February). <https://doi.org/10.3389/fmars.2022.816890>

⁴ Broch, O. J., Alver, M. O., Bekkby, T., *et al.* (2019). The kelp cultivation potential in coastal and offshore regions of Norway. *Frontiers in Marine Science*, 5(JAN), 1–15. <https://doi.org/10.3389/fmars.2018.00529>

⁵ Karuppusamy, S., Rajauria, G., Fitzpatrick, S., *et al.* (2022). Biological properties and health-promoting functions of laminarin: a comprehensive review of preclinical and clinical studies. *Marine Drugs*, 20(12), 772. <https://doi.org/10.3390/md20120772>

4.1.2.1 Methodology

For each species, three 50 m long twine-seeded cultivation lines have been deployed 15th October 2020. From 7th January to 1st July 2021, lines have been visited every two weeks and samples collected for assessment of biomass yield and morphology at the time and subsamples stored for later biochemical composition analyses (see D2.8 section ‘stock monitoring’ for more detail on sample collection and processing).

In addition, five on-growing individuals of either species have been marked (coloured cable tie loosely fastened around the stipe) and a 6 mm diameter hole punched into the frond just below the meristem i.e. reproductive tissue (Figure 11) with the distance from the frond’s base to the hole being recorded (t_0). Individuals have been revisited over six consecutive sampling occasions during peak growth ($t_0 = 5^{\text{th}}$ of March to $t_6 = 17^{\text{th}}$ of June) and the distance from frond base to hole re-measured to determine *SGR* using the following equation:

$$SGR \text{ (cm day}^{-1}\text{)} = \frac{D(t_x) - D(t_{x-1})}{(t_x - t_{x-1})}$$

With D being the distance from frond base to hole at time t of measure.

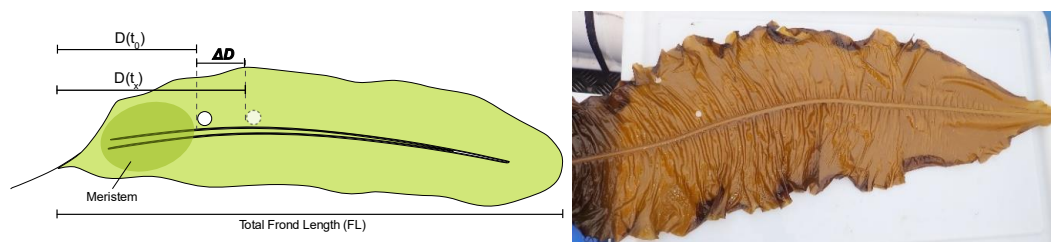


Figure 11. Assessment of specific growth rate (*SGR*; cm/day) in kelp fronds. Right: *A. esculenta* in early April with punched hole having moved visibly with frond growth, ©SAMS.

Seaweed sampling was accompanied by manual seawater sampling from growing depth (= 1.5 m) for concentrations of seawater nutrients, *Chl-a*, and *POC/N*, in addition to continuous recording of *T* and *Light* at depth using HOBO loggers (see section 0 for associated data).

4.1.2.2 Results & Discussion

All three kelp species have grown well during the 2020-21 cultivation cycle with established species *A. esculenta* and *S. latissima* reaching significantly higher biomass yields over time compared to the preceding cycle 2019-20 (Figure 12). At optimal harvest time i.e. mid to end of May, biomass yields of 7.67 ± 0.72 kg/m were achieved for *A. esculenta*, 11.3 ± 2.15 kg/m for *S. latissima*, and 6.22 ± 0.69 kg/m for *L. digitata*.

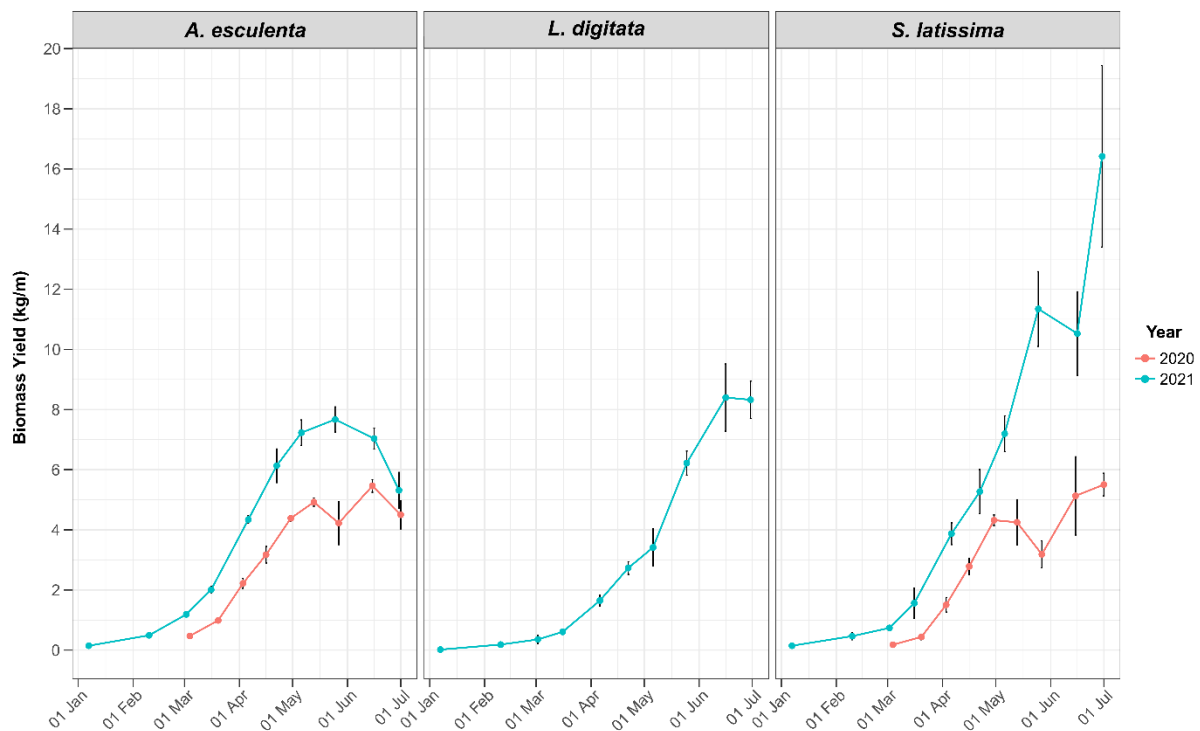


Figure 12. Progression in biomass yield (kg/m) in three cultivated kelp species (*Alaria esculenta*, *Laminaria digitata*, *Saccharina latissima*) between January and July 2021 and comparison to preceding year 2020, ©SAMS.

Growth was comparatively slow during the first three months of cultivation with average frond lengths *FL* of 62.5, 42.4 and 14.8 cm for *A. esculenta*, *S. latissima* and *L. digitata* respectively recorded at monitoring start (7th of January 2021). Latest by mid-March all species had entered their exponential growth phase (by early February for *A. esculenta*) which lasted until early to late May (*A. esculenta* and *S. latissima*, respectively) and mid-June for *L. digitata*. During this time, biomass yields doubled on average every 20, 16 and 15 days for *A. esculenta*, *S. latissima* and *L. digitata*, corresponding to maximum *SGR* of 2.15, 2.43 and 1.88 cm/day, respectively (Figure 13). From mid-Spring onward, increases in nutrient competition with proliferating microalgae, UV stress, and biofouling pressure result in the stagnation of kelp growth alongside natural erosion and the shedding of older frond material.

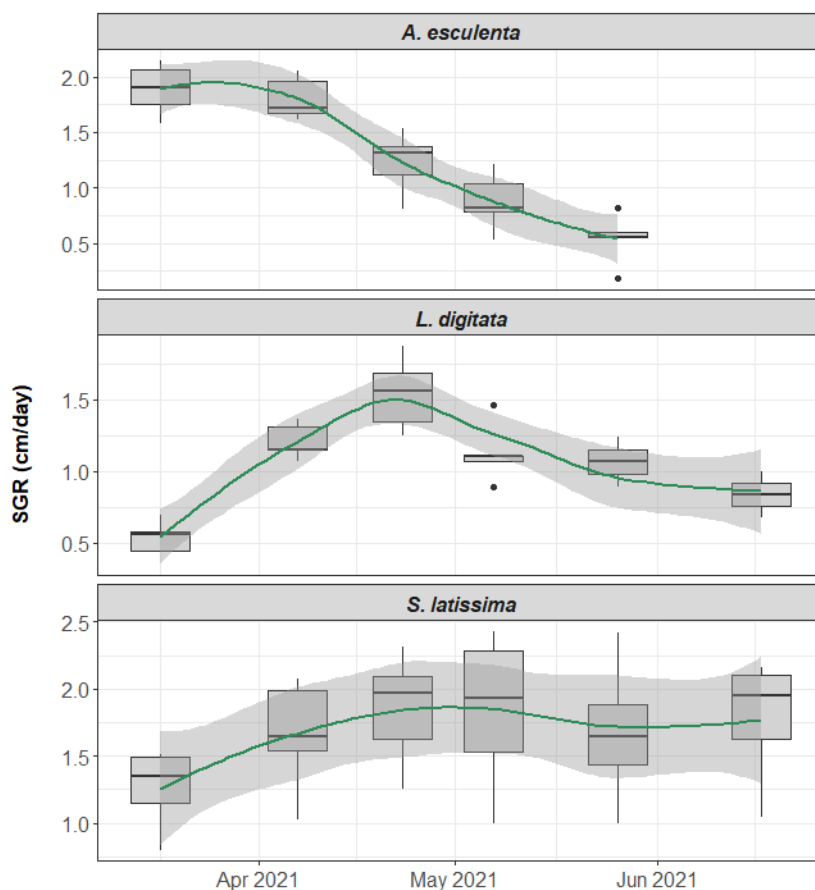


Figure 13. Temporal variation in specific growth rate (SGR, cm/day) in three cultivated kelp species (*Alaria esculenta*, *Laminaria digitata*, *Saccharina latissima*) between 5th March – 17th June 2021, ©SAMS.

The biochemical composition of seaweed fronds also changed over the course of the cultivation cycle and varied across species and parameter investigated (Figure 14). For *A. esculenta*, moisture content decreased significantly during growth from 88 % in January to 77 % in July, corresponding to a decrease in ash (from 34 to 21 %dwt) and increase in carbohydrate⁶ content (from 5.4 to 23.5 %dwt) over the same period. Temporal variations in crude protein and total lipid content were less pronounced with protein increasing from 3.9 to 6.3 %dwt and lipid decreasing from 5.4 to 3.9 %dwt. In comparison, biochemical profiles of both *S. latissima* and *L. digitata* varied less over the same study period as already indicated by relatively stable moisture contents (from 91 and 89 % to 88 and 85 %, respectively). Carbohydrate contents remained consistently low with average values not exceeding 5.5 %dwt. Only marginally more variation was observed for protein and lipid levels but without a temporal relationship; except for mid-March when maximum lipid concentrations of 6 %dwt coincided with minimum protein levels of 4 %dwt in *L. digitata*.

⁶ Total carbohydrate content refers here to 'glucose-equivalent' sugars, not including complex polysaccharides (mannitol, alginate, laminarin, etc.), using the DuBois method (phenolic acid hydrolysis) modified for macroalgal biomass. Dubois, M., Gilles, K. A., Hamilton, J. K., *et al.* (1956). Colorimetric method for the determination of sugars and related substances. *Analytical Chemistry*, 28(3), 350–356. <https://doi.org/10.1021/ac60111a017>

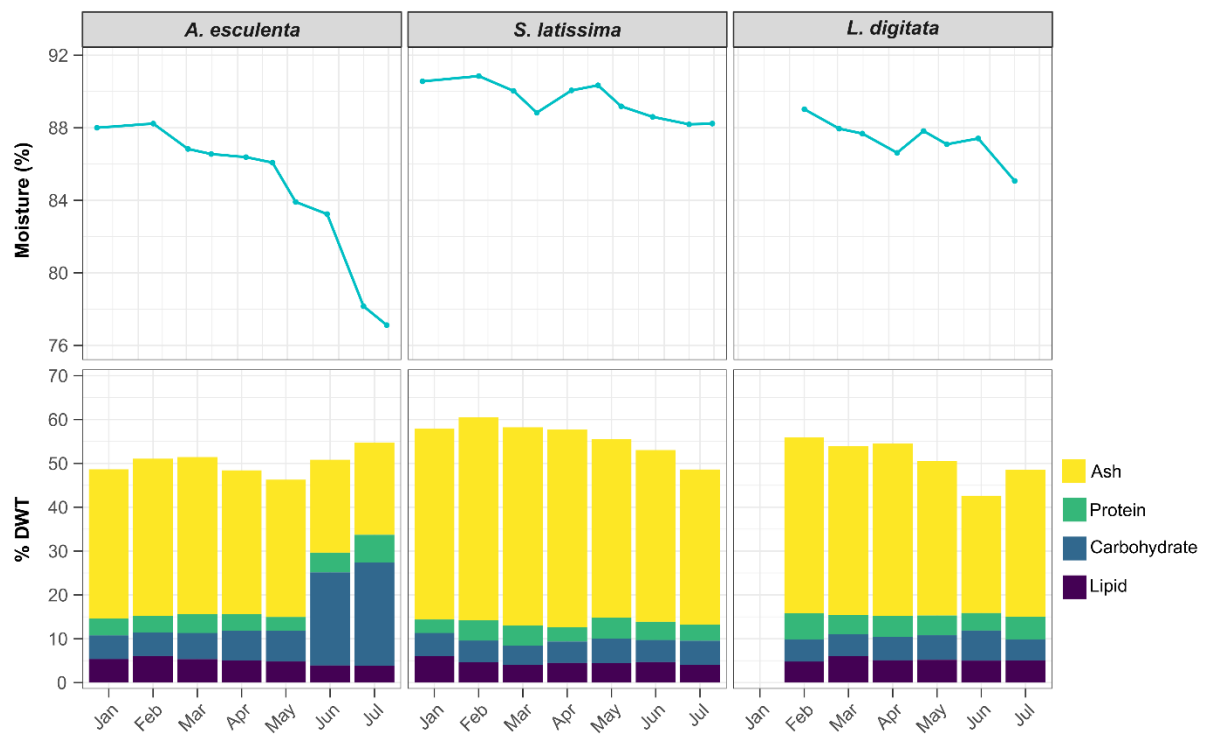


Figure 14. Variation in moisture content (%) and biochemical composition (%dwt ash, crude protein, carbohydrates, lipids) over a cultivation cycle (Jan – Jul 2021) for three kelp species, ©SAMS.

4.1.3 Optimal Cultivation Depth

The optimal depth for seaweed growth is generally determined by prevailing environmental conditions at depth, in particular by nutrients, light availability and quality (PAR), temperature, and water currents.⁷ With regard to seaweed farming additional considerations such as wave regime as well as practical constraints need to be considered, applying to both near-shore as well as increasingly developing offshore systems.

Considering seasonal environmental changes, developments in cultivation systems supporting multiple depth adjustments could allow for season-specific optimal cultivation depths to be selected while mitigating crop damage from UV, biofouling, and wave action. Practical options for large-scale adjustment of cultivation depth have been conceived but remain largely unverified to date.⁸

This section presents experimental trials performed to understand better if and how optimal cultivation depth varies across a cultivation cycle and whether depth optima vary across kelp species, *A. esculenta* and *S. latissima*. Here it was to determine whether depth adjustments may impact crop yield, appearance, and concentrations of valuable compounds (e.g. carbohydrates) at harvest. Findings can be used to evaluate existing cultivation strategies and to design improved cultivation systems to supply biomass for specific industry purposes.

Experimental trials have been performed over consecutive cultivation cycles, starting with a single-species pilot in cycle I to test the experimental approach (see section 4.1.3.1). Pilot observations and lessons learnt informed the improved and modified experimental methodologies employed over the coming cultivation cycles II to IV using both kelp species, *A. esculenta* and *S. latissima* (see Table 3 for timescales). There have been differences across trials in relation to experimental set-up and methodology, informed by preceding trial observations and research objectives addressed at the time. Here they are grouped into ‘Catenary Systems’ (4.1.3.2) and ‘Longline Systems’ (4.1.3.3), presenting their respective rationale, methodology, main findings and discussion.

All trials and treatments have been sampled for overall crop performance i.e. biomass yield, morphology, composition (as for ‘Timeseries Monitoring’, section 0) alongside routine environmental monitoring for main physical and nutritional seawater parameters (see section 3.2).

⁷ Wiencke, C. and Bischof, K. eds (2013): Seaweed biology - novel insights into ecophysiology, ecology and utilization. Springer-Verlag, 507 p. <https://doi.org/10.1007/978-3-642-28451-9>

⁸ Tullberg, R. M., Nguyen, H. P., & Wang, C. M. (2022). Review of the status and developments in seaweed farming infrastructure. Journal of Marine Science and Engineering, 10, 1447. <https://doi.org/10.3390/jmse10101447>

4.1.3.1 Pilot Trial (cycle I)

For the pilot trial, three 50 m cultivation lines twine-seeded with *S. latissima* have been deployed in October 2020 with the intend to ‘drop’ the centre of one line per season (Autumn, Winter, Spring) and sample for biomass yield across various depths in the following season (Figure 15). For example, line #1 (= Autumn line; dropped at deployment) to be sampled at the end of Autumn (Jan) alongside dropping line#2 (= Winter line) for sampling at the end of Winter, and so on. Several problems were encountered due course and included difficulties in maintaining consistent depth across each season, variations in the maximum depth per season, and the loss of the Autumn line mitigated by a later sampling by end of Winter. Despite these challenges, differences in crop performance were observed across depth and optimal depth i.e. the depth at which highest yields were achieved differed across seasons, with the Autumn/Winter optimum being shallower than the Spring optimum (0.5 and 1.5 m depth, respectively).

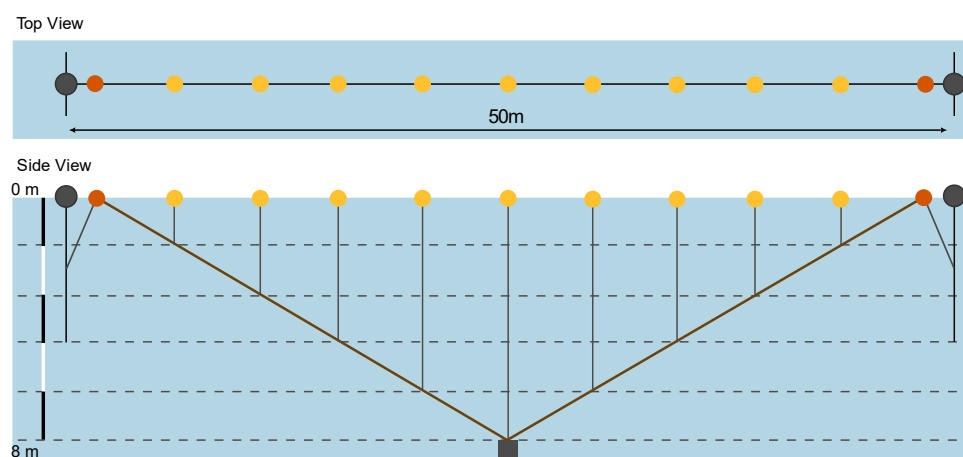


Figure 15. Pilot trial configuration to test for optimal seaweed cultivation depth, ©SAMS.

4.1.3.2 Optimum Depth – Catenary System (cycle II & III)

Several modifications and improvements were applied to the initial pilot configuration and employed in cultivation cycles II and III.

Here, catenary systems were used to provide more stability, operational control and better access at sampling. Two kelp species (*A. esculenta*, *S. latissima*) were trialled, using nine 4 m long twine-seeded treatment lines deployed at equal line spacing of 2 m in the catenary ladder at the centre of the system (Figure 16). One side of the catenary ladder was dropped to a depth of 4 m, allowing for sampling of treatment lines at depth intervals of 0.5 m (= 9 depths: 0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 m). A PAR sensor chain developed in-house (OptiCAL, ©SAMS) was deployed alongside with recording

depths being identical to treatment depths and measuring the amount of photosynthetically active radiation (PAR) available at recording intervals of every 10 min.

In cycle II, one catenary system per species was used with one set of treatment lines deployed 6th October 2021. Two additional sets of treatment lines were daisy-chained and maintained at 1.5 m depth allowing for staggered deployment and sampling across seasons using the same catenary. Set #1 (Autumn lines) was sampled 17th January 2022 and the catenary re-stocked with set #2 (=Winter lines) for sampling 13th April 2022 and deployment of set #3 (= Spring lines), sampled at main harvest 8th June 2022.

The trial was repeated in cycle III with some revisions. Two catenary systems were used per species and fully stocked at deployment (*A. esculenta*: 18th October 2022, *S. latissima*: 3rd November 2022), with one system to be sampled at the start of Winter and the other at main harvest in late Spring. One *A. esculenta* catenary was compromised by severe wear at line connection points and thus plans had to be revised to a single sampling performed in early Spring (21st March 2023).

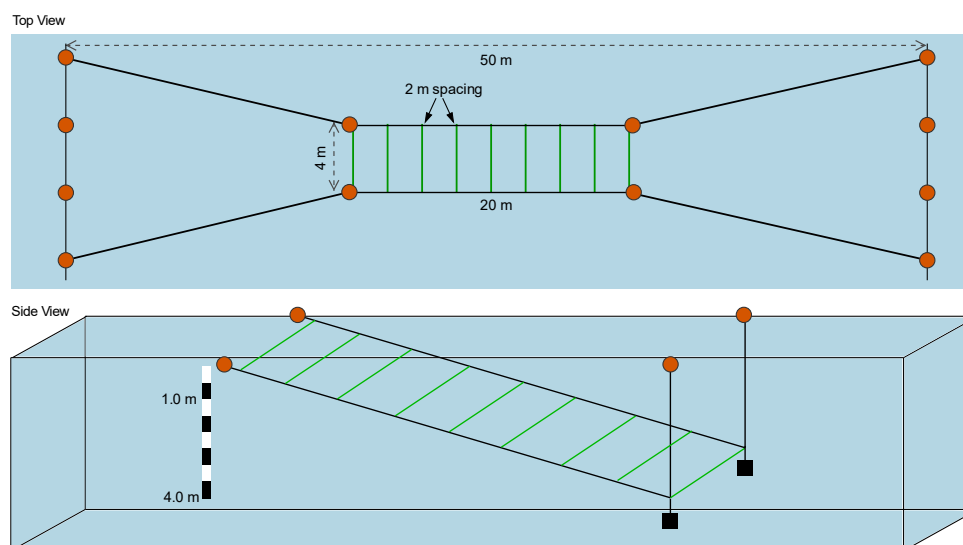


Figure 16. Improved configuration to test for optimal seaweed cultivation depth across seasons, ©SAMS.

For both species, biomass yields differed across cultivation depth but to varying extent depending on the season considered (Figure 17). In cycle II, largest differences were observed following Autumn (Oct 2021 – Jan 2022) with significantly higher yields achieved at shallow cultivation depth for either species. This finding was consistent with observations in cycle III following the Autumn-Winter period (Oct 2022 – Mar 2023), with an overall pre-Spring optimal cultivation depth of 0.1 – 1.0 m for *A. esculenta* and 0.5 – 1.5 m for *S. latissima*. Data collected following the Winter and Spring season was more variable, most likely due to variability in yield on the growing lines transplanted into the

catenary. Findings were consistent with those for frond length *FL* with significantly longer fronds in shallow cultivation following the Autumn-Winter season.

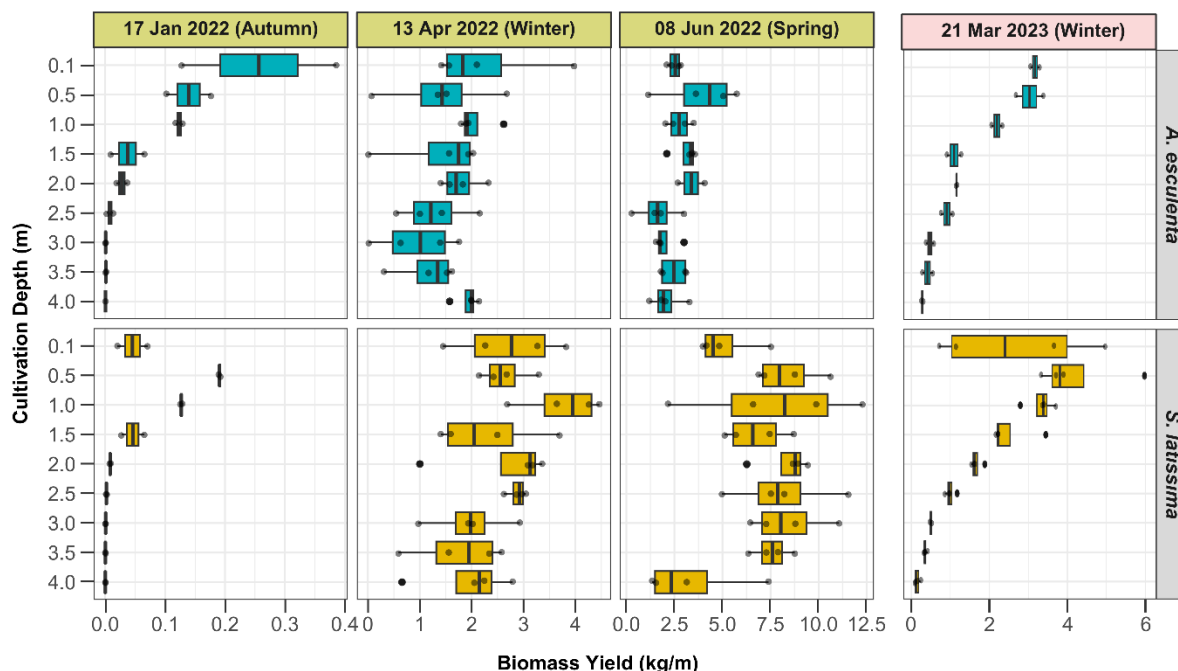


Figure 17. Variation in biomass yield (kg/m) across species (=rows) and seasons (=columns), over two seaweed cultivation cycles (sampling occasions in cycle II = green and cycle III = pink), ©SAMS.

Overall, our results show a significant departure in post-deployment optimum cultivation depth from the previously established 1.5 m optimum commonly used. Maintaining cultivation lines closer to the surface i.e. at shallow depth will have provided more light for the young sporophytes to photosynthesise and grow but will have also exposed them to increased freshwater inputs from heavy rainfall and wave action during darker Autumn-Winter months. However, our findings from two consecutive years clearly indicate that adjusting cultivation depth according to season can significantly affect crop performance. Additional trials were performed to determine whether these results would hold true when using standard cultivation lines (50 m instead of 4 m length) and whether depth-adjustment post-Winter would result in higher achievable yields and proportion of valuable compounds at main harvest (see next section 4.1.3.3 ‘Optimum Depth – Longline Systems’).

Analyses of corresponding PAR data is ongoing at the time of reporting. Data available to date cover a 3-month period which indicates just how variable light conditions are even in the very first meters of the water column, largely influenced by weather conditions e.g. overcast, tidal flow, and wave regime. Figure 18 shows PAR values averaged over midday from 1st April to 1st July 2022, with seaweed deployed at ≤ 1.5 m depth experiencing values of 10 to 300 $\mu\text{mol/s/m}^2$.

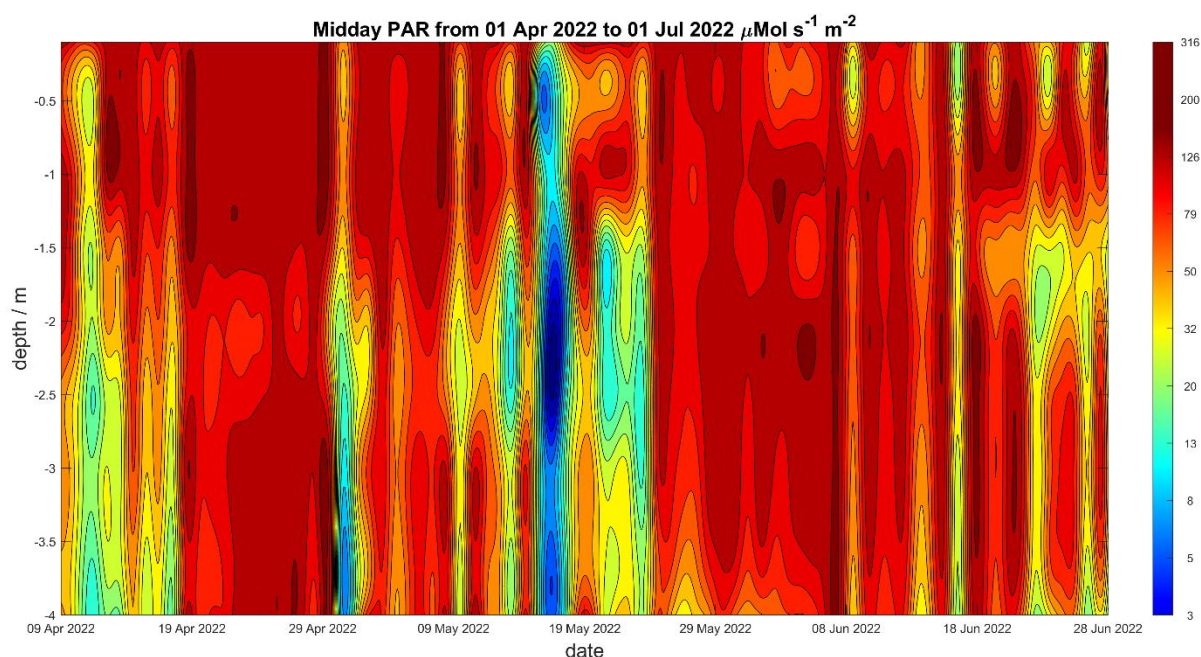


Figure 18. Variation in the amount of photosynthetically active radiation (PAR, $\mu\text{mol/s/m}^2$) across trialed deployment depth (0 – 4 m) over a 3-month period (April – June 2022), ©P. Anderson, SAMS.

4.1.3.3 Optimum Depth – Longline System (cycle III & IV)

Building on previous findings using catenary systems, additional longline systems were deployed in cycle III and IV to establish how utilising this new shallower post-deployment optimum might translate to higher yields at harvest. In brief, sets of longlines were deployed at shallow depth (0.5 m; hereafter referred to as ‘shallow’), regular cultivation depth (1.5 m; hereafter referred to as ‘deep’), or ‘shallow’ at first and moved to ‘deep’ at the start of Spring, to evaluate whether a single depth adjustment would improve biomass yield and quality at main harvest.

In cycle III, six 50 m longlines per species (*A. esculenta*, *S. latissima*) were deployed 18th October 2022 with the following configuration: 2x maintained in surface waters throughout entire cycle (Line ID: ‘shallow-shallow’, 2x maintained at regular depth (‘deep-deep’), and 2x deployed in surface waters and moved to regular depth (‘shallow-deep’). All lines were sampled twice, once at the time of depth adjustment (19th March 2023) and again at main harvest (2nd May 2023). Initial results indicated higher achievable yields at harvest for *A. esculenta* (up to 2 kg/m more for lines maintained in surface cultivation ‘shallow-shallow’) but not *S. latissima* (Figure 19). However, the experimental set-up was compromised by late season storms causing riser ropes to wrap around the cultivation lines and affecting line depth and damaging on-growing crops. Furthermore, the time interval between samplings was considered with depth adjustment preferably occurring earlier in March and harvest in mid-end May.

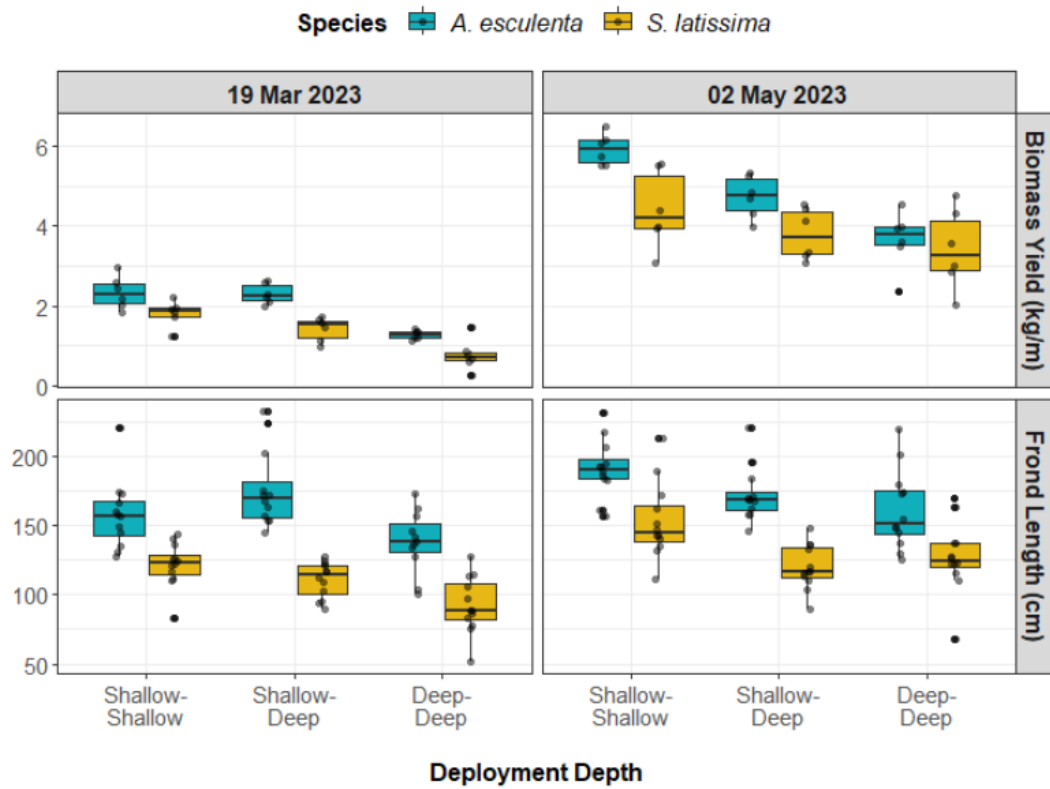


Figure 19. Optimum depth – Longline trial in cultivation cycle III, showing variation in biomass yield (kg/m) and frond length (FL, cm) across line deployment depths, with (shallow-deep) and without (shallow-shallow, deep-deep) depth adjustment post Autumn-Winter season, ©SAMS.

These issues were addressed during cycle IV by supporting riser ropes with stiffener pipes to avoid wrapping as well as extending the time period between depth adjustment and end-point sampling. The experimental set-up was identical to cycle III, with lines deployed 17th October 2023 and seasonal depth adjustment alongside sampling 1st March 2024 and final sampling at main harvest 13th May 2024.

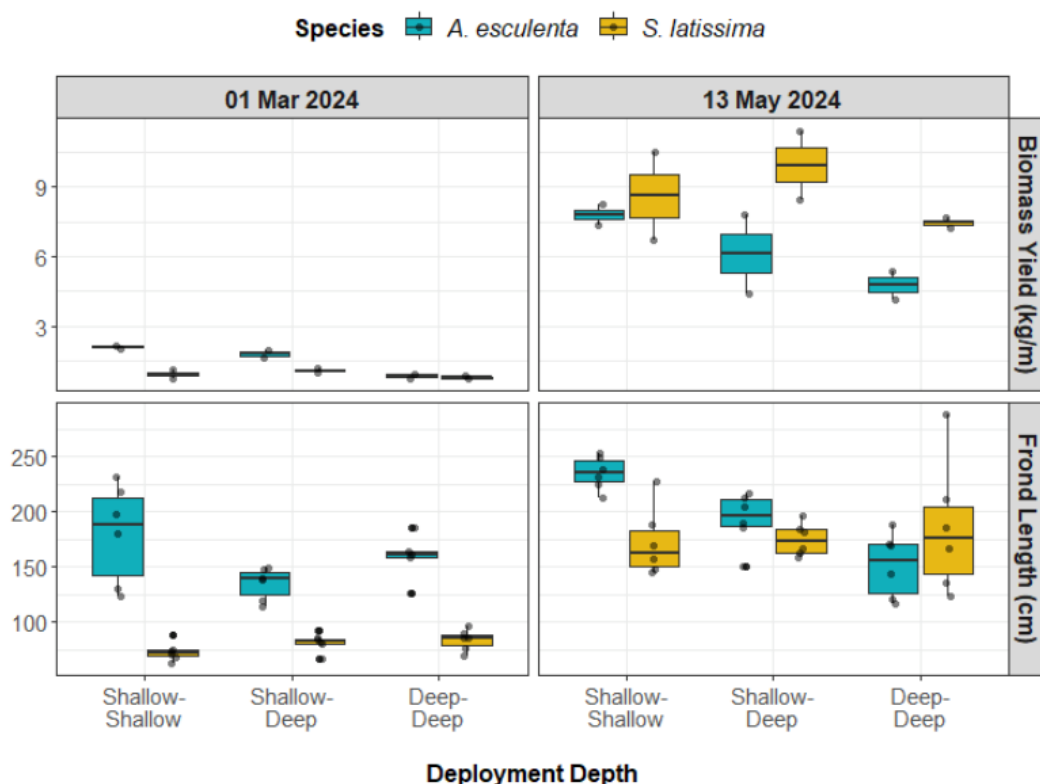


Figure 20. Optimum depth – Longline trial in cultivation cycle IV, showing variation in biomass yield (kg/m) and frond length (FL, cm) across line deployment depths, with (shallow-deep) and without (shallow-shallow, deep-deep) depth adjustment post Autumn-Winter season, ©SAMS.

Overall, the trial in cycle IV performed better than in cycle III, despite severe and extended storm events in Jan – Feb 2024 causing visible damage to *S. latissima* with fronds appearing whipped i.e. lateral sides removed. Recorded yields at harvest (13th May 2024) were notably higher than in the preceding cycle (1st May 2023) with consistent results across both cycles with greater yields being achieved in shallow cultivation (Figure 20). In contrast to cycle III however, *S. latissima* performed slightly better when lines were moved to greater depth post-Winter compared to lines that remained in either shallow or regular cultivation depth.

At the time of reporting, sample analyses for biochemical composition are ongoing with preliminary results shown in Figure 21. Carbohydrate contents were low following Autumn-Winter and increased throughout Spring, with levels increasing with deployment depth for *A. esculenta* (6.8 ± 0.9 %dwt at shallow-shallow to 8.4 ± 1.4 %dwt at deep-deep) and the inverse relationship for *S. latissima* (5.7 ± 0.04 % to 4.5 ± 0.1 %dwt, respectively). Changes in carbohydrate content were mirrored in moisture content i.e. moisture levels decreased with increasing production of organic compounds such as carbohydrates.

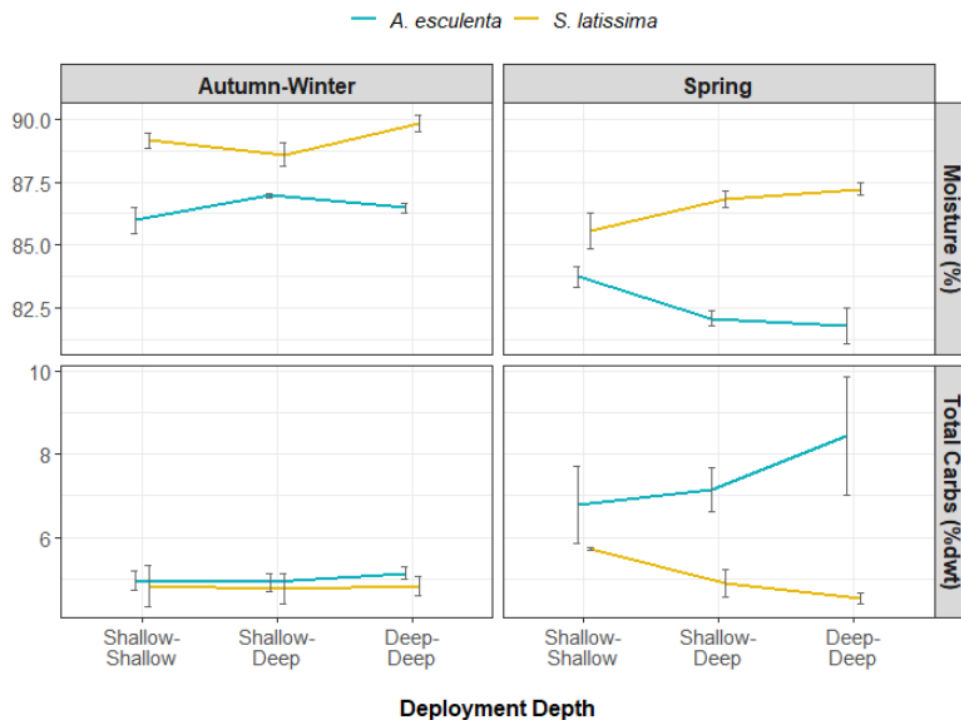


Figure 21. Variation in moisture (%) and carbohydrate content (%dwt) for kelp deployed at fixed cultivation depth throughout the cycle (0.5 m depth 'shallow-shallow', 1.5 m 'deep-deep') or line depth adjusted post-Winter (0.5→1.5 m 'shallow-deep'), ©SAMS.

To conclude, optimal cultivation depth trials performed including both catenary as well as longline systems and running over consecutive years, provided valuable information to improve operational efficiencies of seaweed cultivation sites. A one-time adjustment of cultivation depth post-Winter was shown to significantly improve overall crop performance, including achievable yields at harvest but in parts also crop appearance (e.g. frond damage, UV stress, fouling cover). With compositional analyses ongoing it has yet to be confirmed whether levels of high-value compounds i.e. polysaccharides such as mannitol and alginate, are affected by such depth adjustments which would provide additional control for product-specific culture.

4.1.4 Optimal Stocking Density

Stocking density, herein also referred to as line spacing, is another important practical consideration in farm design and operation. A principal strategy to improve cultivation efficiency and reduce capital expenditure is to increase the capacity of cultivation materials relative to structural material requirements (e.g. moorings and other supporting structures).

For seaweeds, maximising stocking density (meters of seeded rope per square meter area of cultivation space) can increase harvest yields while maintaining farm infrastructure costs at similar levels.⁹ Various approaches have been in development to maximise stocking density including catenary supporting structures, “splitter bars”, and “set lines”. These techniques aim for uniform line tension to prevent entanglement between adjacent longlines, which can significantly reduce operational efficiency. Untangling lines is time-consuming and can lead to crop damage, resulting in lower yields at harvest.

This section presents the work performed to investigate effects of stocking density on seaweed performance and gather information on potential optimal configurations for the current as well as future sites.

4.1.4.1 Methodology

The study commenced with testing the experimental design (cycle I; *A. esculenta* only) followed by extension to both kelp species (cycle II) and a confirmative combined experimental trial with ‘Optimal Line Orientation’ (cycle IV; see section 0 and Table 3) .

For each species trial, four stocking densities (line spacing = 0.5 m, 1 m, 1.5 m, 2.0 m) were generated using a catenary system deployed at 1.5 m depth with three replicate twine-seeded lines per treatment (4 m length) (Figure 22). Catenary systems were deployed in October and sampled the following May of each cycle, comparing biomass yield, morphology and biochemical composition across stocking densities for each species and cycle, respectively.

⁹ St-Gelais, A. T., Fredriksson, D. W., Dewhurst, T., *et al.* (2022). Engineering a low-cost kelp aquaculture system for community-scale seaweed farming at nearshore exposed sites via user-focused design process. *Frontiers in Sustainable Food Systems*, 6, 1–14. <https://doi.org/10.3389/fsufs.2022.848035>

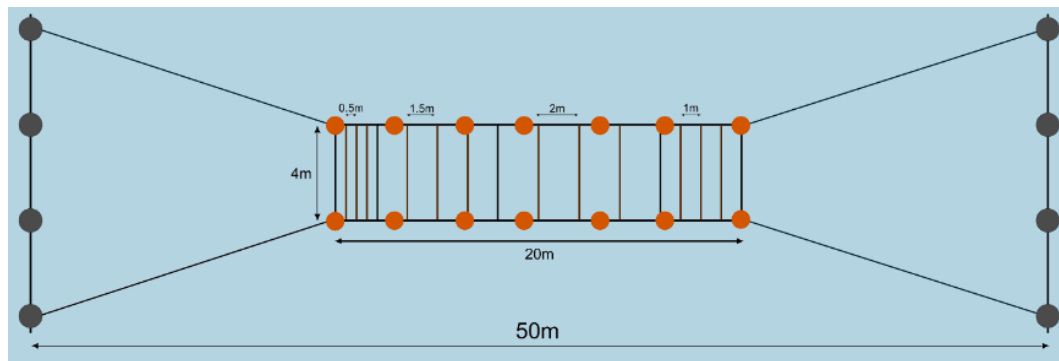


Figure 22. Catenary system used to investigate optimal stocking density in seaweed cultivation. Shown are treatment lines deployed at 0.5 to 2 m line distance in a 20 m long system tensioned by catenary lines, ©SAMS.

4.1.4.2 Results & Discussion

Stocking density affected species growth (frond length *FL*) and achievable yield at harvest. Differences in yield and *FL* were only marginal for *A. esculenta* but significant for *S. latissima* (Figure 23). Lines spaced 1 m apart produced almost double the yield compared to both lines spaced closer together (0.5 m) as well as further apart (1.5 and 2 m).

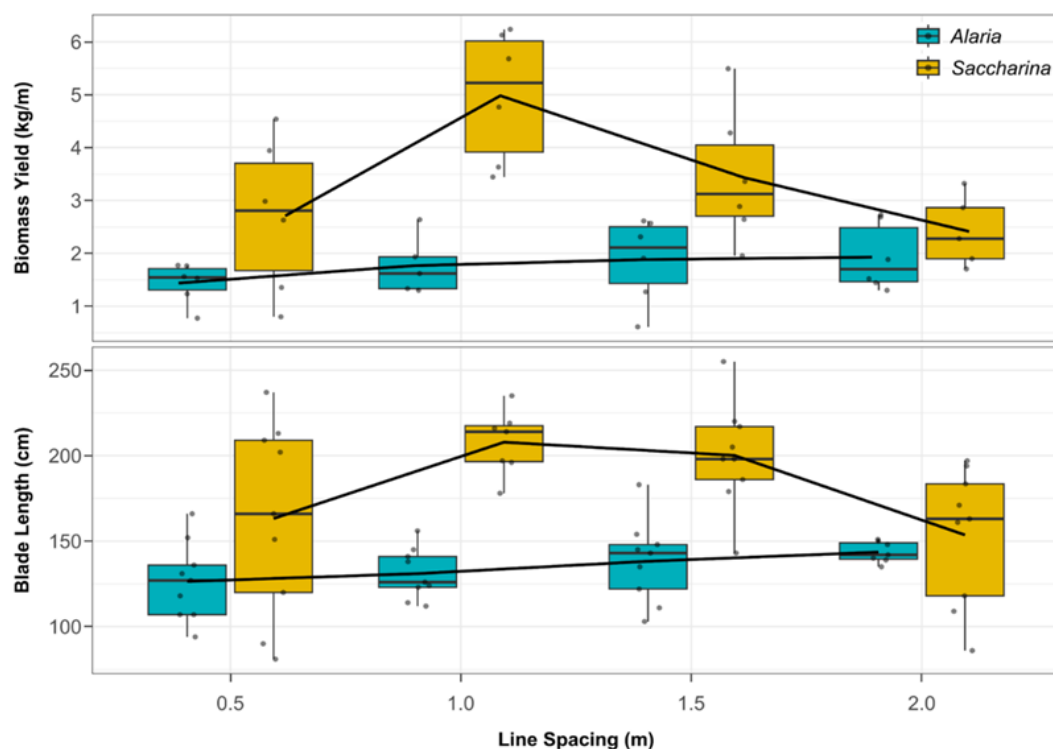


Figure 23. Species-specific variation in biomass yield (kg/m) and blade i.e. frond length (cm) at different stocking densities (= line spacings) at harvest 3rd May 2022, ©SAMS.

It is not yet understood why yields were lower at larger spacings. If at all one would have expected yields to increase with larger line spacing i.e. smaller stocking density due to more light availability

and less interference between individuals and adjacent lines. Whilst this was not the case for *S. latissima*, our findings indicate that high stocking densities are achievable for *A. esculenta* without significant reductions in harvestable yield.

Stocking density also affected the biochemical composition of the kelp at time of harvest. For *A. esculenta* moisture, ash and carbohydrate content were significantly different across line spacings with 10 % less moisture and more available carbohydrates at the lowest stocking density trialled (Figure 24, left panel). In other words, greater line distance seemingly allowed for more light penetration and thus photosynthetic potential for the fronds, increasing the capacity for carbohydrate production.

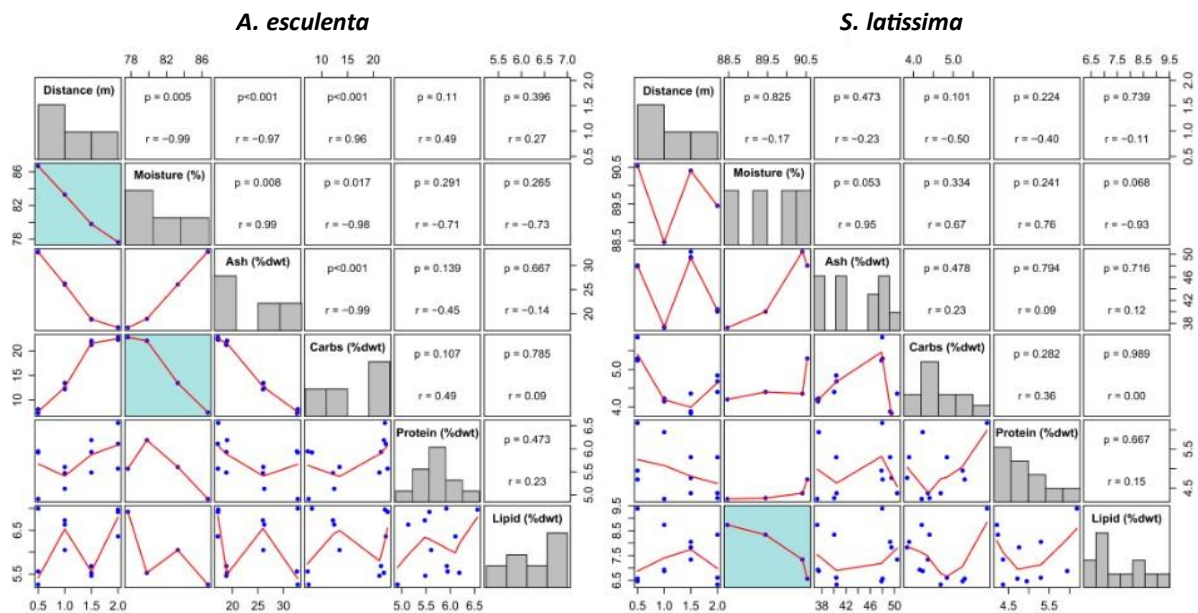


Figure 24. Correlation matrix showing variation in kelp biochemical composition (%wwt moisture and %dw ash/carbohydrates/proteins/lipids) cultivated at different stocking densities (line distance). Note highlighted relationships in light blue. ©SAMS.

For *S. latissima*, stocking density also affected individual compositional parameters although relationships were overall more variable and less pronounced than for *A. esculenta*. Carbohydrate and protein concentrations were slightly higher at higher stocking densities i.e. smaller line spacings. The effect of stocking density on lipid content was more variable, yet a negative correlation was observed between moisture and lipid content (Figure 24, right panel).

4.1.5 Optimal Line Orientation

An observation made during the pilot ‘Stocking Density’ trial led to further investigate whether the orientation of a cultivation line affects crop performance. When deployed parallel to, i.e. with the direction of the main current flow, the on-growing seaweed is likely to be exposed to different current dynamics and light exposure as well as interference with neighbouring individuals then when deployed perpendicular to i.e. against the main current direction. To our knowledge this concept has not yet been tested or validated elsewhere which led to the experimental trial presented here.

4.1.5.1 Methodology

This trial ran over two consecutive cultivation cycles (cycle III & IV; see Table 3) and employed both kelp species, *A. esculenta* and *S. latissima*. In cycle III, a pilot study was performed focusing on optimal line orientation only. In cycle IV, the trial was extended to combine line orientation and line spacing i.e. stocking density.

The general experimental set-up has been identical to the one used for optimal stocking density (see 4.1.4). For the pilot study, a single catenary system was deployed per species (*A. esculenta*: 18th October, *S. latissima*: 4th November 2022), each containing a series of 4 m long twine-seeded lines deployed 4 m apart either parallel or perpendicular to the main current direction within the same catenary. For the combined trial including also stocking density, this approach was modified by using two catenary systems per species, one deployed parallel to the main current direction i.e. the commonly employed configuration in seaweed farming (see also Figure 4), and the second set oriented perpendicular to the main current flow.

For either trial, single end-point sampling was performed at main harvest (2nd May 2023 and 14th May 2024) for comparison of crop performance (biomass yield, morphology, biochemical composition) across different stocking densities and line orientations. For the pilot study, it is to note that no samples have been collected for subsequent biochemical analyses i.e. trial results are limited to comparisons of biomass yield and frond morphology across line orientations.

4.1.5.2 Results & Discussion

Pilot study results showed that the orientation of the cultivation line relative to the prevailing current direction can affect achievable harvest yields. For *A. esculenta* significantly higher yields were recorded on lines deployed parallel to the main current while the opposite was observed for *S. latissima* where yields were significantly lower in this configuration (Figure 25). In perpendicular deployment, average yields have been 1.8 kg/m lower for *A. esculenta* and 2.9 kg/m larger for *S.*

latissima when compared to deployment parallel to i.e. with the main current flow. For *S. latissima* fronds have been significantly longer in perpendicular configuration with average *FL* of 153 cm compared to 110 cm.

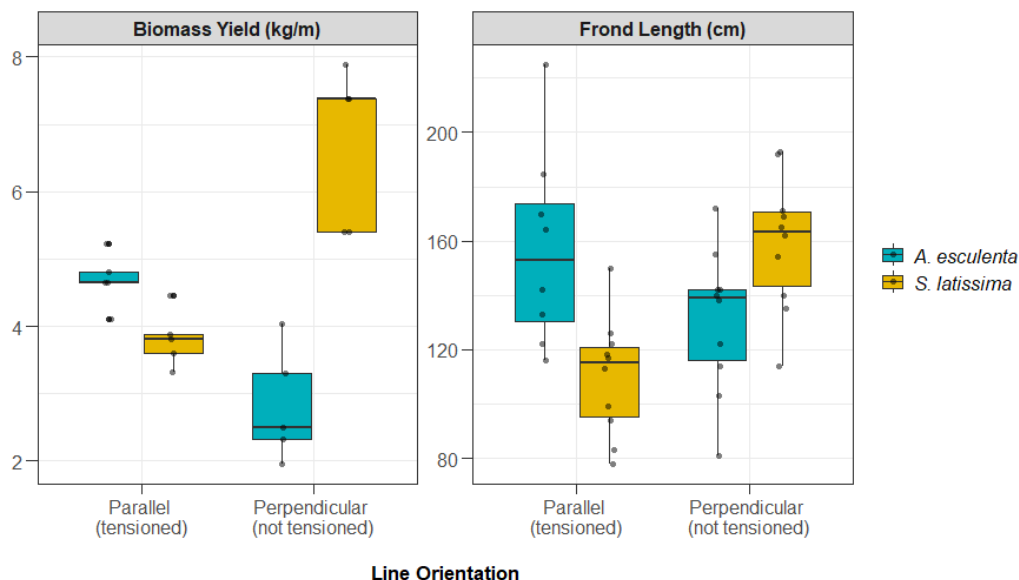


Figure 25. Effect of cultivation line orientation on harvestable biomass yield (kg/m) and frond length (*FL*, cm) of *A. esculenta* and *S. latissima* (pilot study, cycle III 2022 – 23), ©SAMS.

The observed differences can likely be attributed to the prevailing line tension present in either configuration. Considering the site layout as well as deployment strategy employed at IMTA Lab Scotland, ‘parallel’ lines are much more under tension than ‘perpendicular’ lines. Based on previous grow-out experience and ecological understanding of either species, *A. esculenta* thrives in high energy environments and thus is likely to benefit from the sudden and frequent pulling forces acting on high-tension parallel lines resulting in better growth performance and potentially higher yields as found here.

ASTRAL’s last cultivation cycle (cycle IV) was used to validate initial findings and to investigate whether observed effects of line orientation differ across line spacings i.e. stocking densities. Figure 26 shows the variation in harvestable yield across the four different stocking densities and the two line orientations. For *S. latissima*, yields increased significantly with line spacing and irrespective of the line’s orientation from 5.05 ± 1.12 kg/m at 0.5 m to 9.70 ± 1.70 kg/m at 2 m spacing (average values across orientations). This observation is different from the ‘Optimum Stocking Density’ trial in cycle II when highest yields were achieved at higher stocking densities of 1 m (see Figure 23) as well as from the ‘Optimum Line Orientation’ pilot when significantly larger yields were achieved in perpendicular deployment (see Figure 25); acknowledging that line spacing was kept consistent at 4 m.

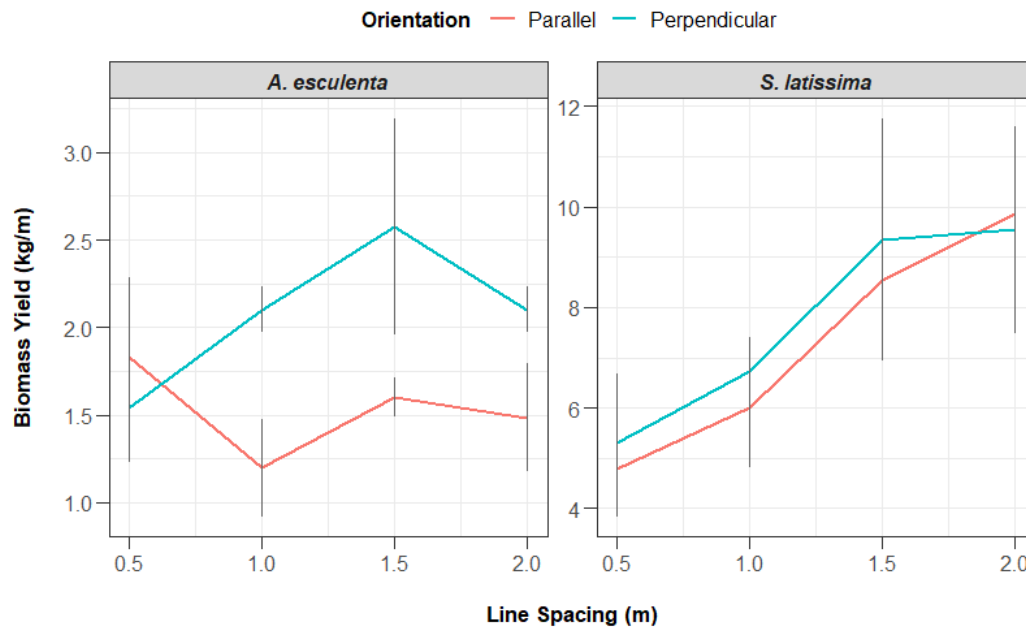


Figure 26. Effect of line spacing i.e. stocking density on kelp biomass yields when deployed parallel or perpendicular to the main current direction, ©SAMS.

In comparison for *A. esculenta* however, yields varied less across line spacings but were significantly affected by line orientation with generally higher yields achieved in perpendicular deployment. This observation is reversed to those made during the preceding pilot when parallel lines produced greater yields.

Compositional data generated to date showed that both moisture and carbohydrate content did not differ across stocking densities and line orientation for *S. latissima*. For *A. esculenta* deployed perpendicular to the main current however carbohydrate content increased with decreasing stocking density (Figure 27).

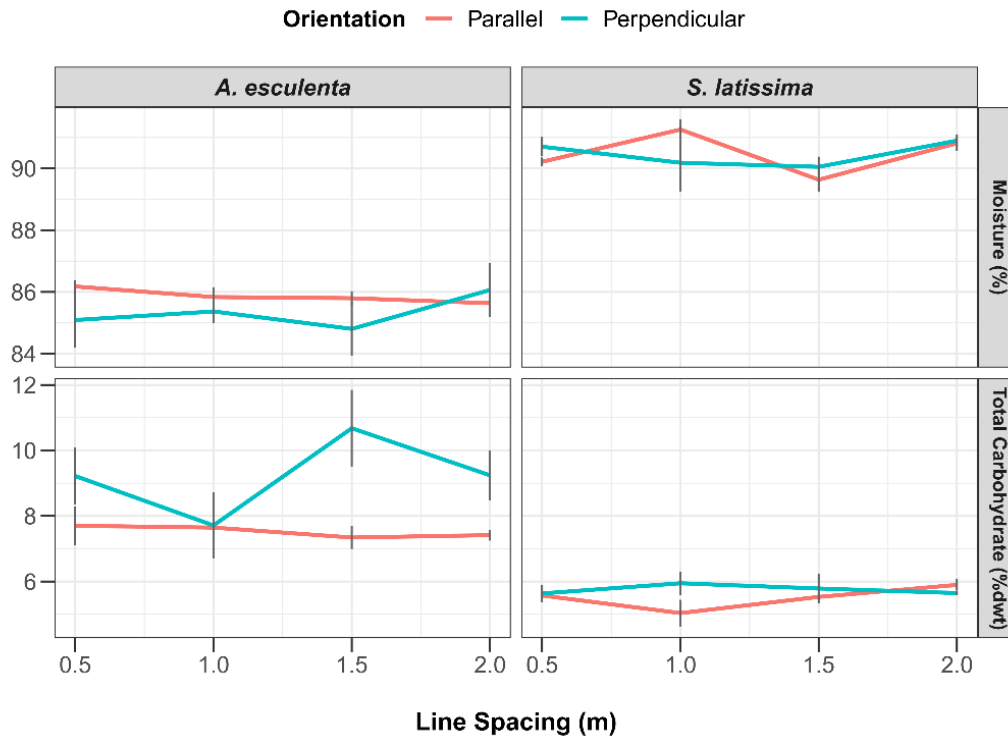


Figure 27. Variation in moisture and carbohydrate content across various line spacings i.e. stocking density (m) and line orientations for kelp species *A. esculenta* and *S. latissima*, ©SAMS.

Overall, harvestable yields in cycle IV have been noticeably smaller than for preceding cultivation cycles with on average 1.8 kg/m only for *A. esculenta* (approx. 7 kg/m in cycle I, Figure 12). This was also reflected in the crop's appearance characterised by heavy frond erosion and grazing marks; with slightly better appearance of crop deployed parallel and at lower stocking density (Figure 28, left).



Figure 28. Frond appearance at main harvest sampling (14th May 2024). Left: *A. esculenta* 0.5 m perpendicular (top) and 2.0 m parallel (bottom). Right: *S. latissima*: 1.5 m parallel line orientation, ©SAMS.

The differences in crop yield and appearance can largely be attributed to environmental differences across years. In winter 2023-24, the site has experienced heavy and frequent storm events over consecutive weeks between January and February, with heavy signs of whipping i.e. the loss of lateral fronds observed on *S. latissima* longlines deployed for the 'Optimum Cultivation Depth' trial (see section 4.1.3). With the exception for the *S. polyschides* timeseries monitoring, sample collection during cycle IV has been restricted to end-point sampling at harvest and thus the exact time and effect of storm damage on cultivation lines can only be suspected but not validated.

4.2 Brown seaweed (*Saccorhiza polyschides*, Furbelows)

4.2.1 Introduction

S. polyschides is a fast-growing annual species belonging to the class of brown algae (Phaeophyceae). This species is characterised by a broad flat stipe with frilled margins, a wide frond (thallus) divided into ribbon-like sections and most notably a large bulbous holdfast for attachment (Figure 29) and first described as a species by Greville (1830).¹⁰

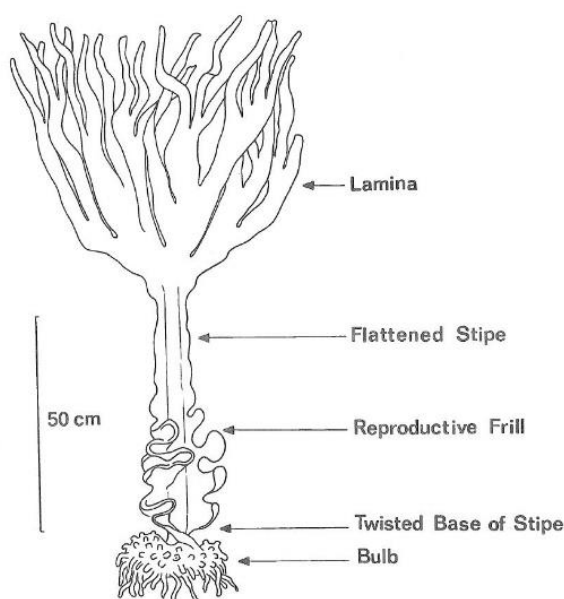


Figure 29. Left: drawing of adult *S. polyschides* sporophyte (Norton, 1970). Right: *S. polyschides* monitoring line deployed at SAMS IMTA Lab (2nd May 2024), ©SAMS.

Together with other large brown seaweeds, *S. polyschides* is an important species for the European kelp industry providing the raw material to produce gelling agents such as alginates.¹¹ Its potential for high biomass production (growth up to 4 m length in wild populations) and wide range of applications (food products, feedstock, nutraceuticals, biostimulants, etc.) make this species a promising candidate for commercial culture including IMTA.^{12,13}

¹⁰ Greville, R.K. (1980) *Algae Britannicae: Or, Descriptions of the marine and other inarticulated plants of the British Islands*, belonging to the order algae. Maclachlan & Stewart, 218p.

¹¹ Norton, T., (1970). *Synopsis of biological data on Saccorhiza polyschides*, FAO Fisheries Synopsis No. 83. Rome.

¹² Barbosa, M., Fernandes, F., Pereira, D. M. et al. (2020). Fatty acid patterns of the kelps *Saccharina latissima*, *Saccorhiza polyschides* and *Laminaria ochroleuca*: Influence of changing environmental conditions. *Arab J Chem*, 13(1), 45–58. <https://doi.org/https://doi.org/10.1016/j.arabjc.2017.01.015>

¹³ Cardoso, C., Almeida, J., Coelho, I. et al. (2023). Farming a wild seaweed and changes to its composition, bioactivity, and bioaccessibility: The *Saccorhiza polyschides* case study. *Aquac*, 566. <https://doi.org/10.1016/j.aquaculture.2022.739217>

Furthermore, it is a candidate species for large-scale offshore cultivation and considering its high production potential lends itself for high-biomass requiring applications such as biofuel production.¹⁴ European kelp cultivation is largely based on well-established species *A. esculenta*, *S. latissima* and *L. digitata* with *S. polyschides* having received far less attention. To our knowledge, this species is not grown commercially in the UK or elsewhere but provides high potential due to its growing characteristics and wide physicochemical tolerances.¹²

To gain better understanding of this species cultivation potential and performance, a monitoring study was performed at IMTA Lab Scotland over one cultivation season (cycle IV, 2023-24). *S. polyschides* growth and morphology were followed over time and further investigated for potential differences in biochemical composition and other commercially relevant compounds.

4.2.2 Methodology

Nursery-reared and twine-seeded from SAMS seaweed nursery, *S. polyschides* was deployed at SAMS IMTA Lab in October 2023. Starting from January 2024, the cultivation line (50 m length) was visited monthly to collect three biomass samples alongside routine environmental monitoring (CTD depth profile, seawater sampling; for details see section 0). Immediately after collection, samples were processed at SAMS for biomass yield (spun-down wet weight wwt per meter of cultivation line; kg/m) and frond morphology (frond length, maximum frond width, fouling cover). Subsamples have been collected and stored at -20 °C until further analyses for biochemical composition.

4.2.3 Results

The performance of *S. polyschides* in cultivation observed to date is exceptional, outperforming other kelp species deployed in terms of growth rate and biomass yield achieved over time (see section 0 ‘Timeseries Monitoring’).

S. polyschides entered peak growth in March 2024 and has since steadily increased in biomass yield with record values of 30.5 ± 4.6 kg/m recorded at the latest sampling (10th June 2024, Figure 31 left); equal to an increase of 2.3 kg/m per week since the start of April (Figure 30, left). At its peak, fronds have grown up to 1.9 cm/day reaching maximum length of $FL = 248$ cm in early May. Since then, frond length and growth have receded with average FL decreasing due to erosion of the distal frond and increasing fouling pressure. Maximum frond width MFW , measured at the proximal frond, continue

¹⁴ Kerrison, P.D., Stanley, M.S., Edwards, M.D., *et al.* (2015). The cultivation of European kelp for bioenergy: Site and species selection. *Biomass and Bioenergy* 80, 229–242. <https://doi.org/10.1016/j.biombioe.2015.04.035>

to increase (Figure 30, right). At the latest sampling in June, frond and stipe length have been recorded separately showing an average ratio $FL:SL$ of 1.7 i.e. a frond of 200 cm length would have a stipe of 120 cm length.

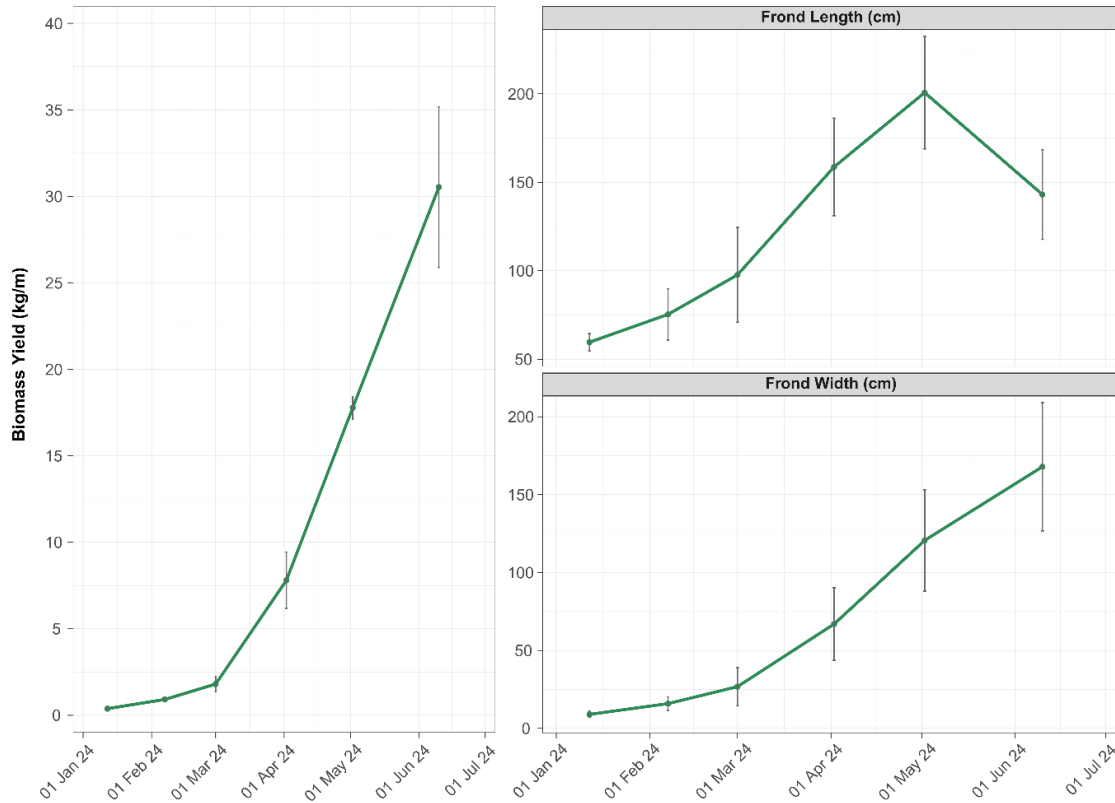


Figure 30. *S. polyschides* progression in biomass yield (kg/m; left) and frond length FL and maximum frond width MFW (cm; right) over the course of the cultivation season, ©SAMS.

Overall growth is expected to level off over the coming weeks as frond erosion and biofouling pressure increase (Figure 31). Current high yields have weighed down the cultivation line which was sitting at far greater depth when last visited in June (5 – 10 m as opposed to 1.5 m cultivation depth).

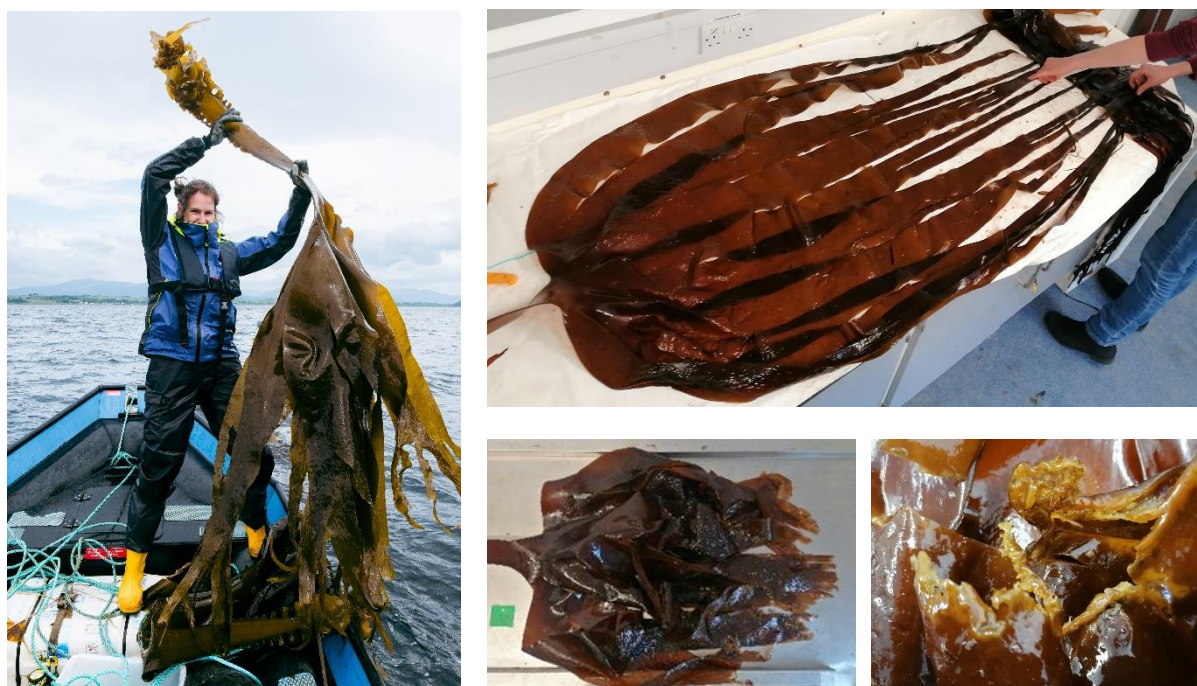


Figure 31. Left & bottom right: *S. polyschides* sampling #6 (10th June 2024) with distal frond erosion and grazing marks. Top right: sampling #4 (2nd April 2024) with intact fronds and no biofouling, ©SAMS.

Compositional analyses performed to date also show variation over the course of the cultivation period (Figure 32). Moisture content has decreased steadily from 93.4 ± 0.13 % in February to 91.6 ± 0.41 % in May followed by a slight increase observed in June. This corresponded to an increase in dry matter ash content, a measure of the total amount of inorganic non-combustible material it contains, increasing from 49.1 ± 0.66 % to 53.9 ± 3.37 % by April. Lipid content has remained comparatively stable over the study period with proportions of 4.9 to 5.9 %dwt. Carbohydrate levels on the other hand have changed noticeably over the peak growth season, steadily increasing from 3.3 ± 0.1 to 4.5 ± 0.3 %dwt in February and May 2024, respectively. Samples collected for compositional analysis in June and from future sampling visits will continue to be analysed for biochemical parameters as well as other compounds of interest such as polyphenol, trace metals, and complex polysaccharides.

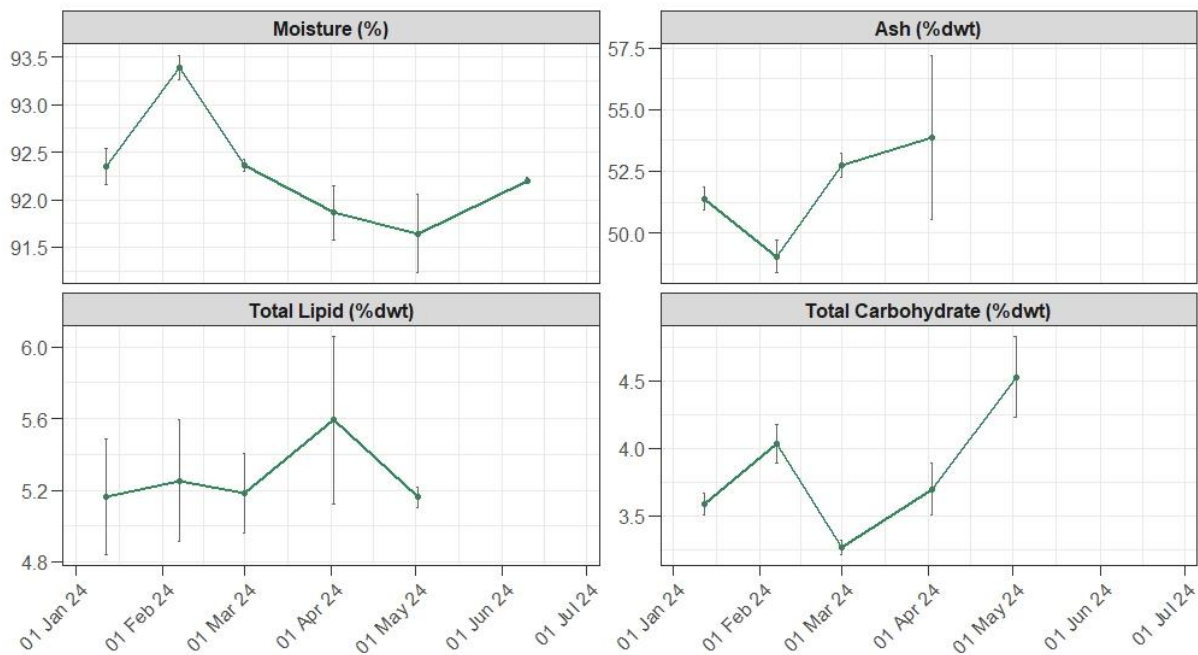


Figure 32. Biochemical composition of *S. polyschides* showing variation in content of moisture (%), ash, lipids and carbohydrates (%dwt) over the cultivation season, ©SAMS.

4.2.4 Discussion

S. polyschides has performed remarkably in cultivation at sea to date and its monitoring is continued beyond the planned end date at main kelp harvest in May 2024. Compared to other kelp, this species has produced more than three times the yield at harvest (see section 0) within the same cultivation duration. Another difference observed to date has been the much higher ash content of *S. polyschides* supporting available data collected in the 1940s from wild populations in Scotland and Portugal.¹⁵

Some practical considerations should be taken when growing this species at sea. With biomass rapidly increasing, cultivation lines should be checked frequently during peak growth to adjust line tension and adding additional floats to maintain the crop at the desired cultivation depth. In addition, the different morphology of the holdfast compared to other kelp species also provides less attachment surface to the growing line which can result in crop loss when handling the line.

As a fast-growing kelp, *S. polyschides* can efficiently absorb and utilise nutrients dissolved in seawater and reduce algal blooms, thus helping to alleviate eutrophication. Its fast growth and high nutrient uptake capabilities make it an excellent candidate for IMTA systems, with the potential to significantly enhance nutrient management, improve water quality, increase biomass production, support biodiversity, and contribute to economic sustainability.

¹⁵ Norton, T., (1970). Synopsis of biological data on *Saccorhiza polyschides*, FAO Fisheries Synopsis No. 83. Rome.

4.3 Red Seaweed – Dulse (*Palmaria palmata*)

4.3.1 Introduction

The red seaweed *Palmaria palmata*, commonly known as dulse, has a long-standing tradition for being used as food in some European countries such as Ireland and Iceland where it is collected from natural populations.¹⁶ More recently it has become a candidate species for commercial cultivation due to its widespread and common distribution on rocky shores of the Northern Hemisphere and high economic potential primarily owned to its high protein content of up to 35 %dwt and thus application as alternative protein source.^{17,18}

The cultivation of *P. palmata* has been studied for years as wild harvest cannot sustain the increasing demand for this species and derived products.^{14,19} Commercial cultivation options include land-based tank culture under controlled conditions or culture at sea following the deployment of seeded substrates. Cultivation at sea remains limited to small-scale trials performed in France and Norway with no commercial scale culture of *P. palmata* in Europe to date.

For open water cultivation, site selection is crucial as dulse is less well adapted to strong water currents and dynamic wave regimes compared to kelp species. Furthermore, *P. palmata* is sensitive to freshwater inputs as well as nutrient availability, in particular nitrogen N, experiencing stress by both too much and too little available N. Other focus areas include system design, maintenance and harvest to develop high-yielding and cost-effective cultivation operations.

A general bottleneck, irrespective of the production type, is the limited availability and high mortality of spores i.e. seeding material. Optimal seeding methodologies are one of the barriers to overcome when developing new value chains for alternative commercially important seaweed groups, including *P. palmata*.

This section describes the findings from a seeding trial for *P. palmata* performed at IMTA Lab Scotland in cycle III.

¹⁶ Grote, B., (2019). Recent developments in aquaculture of *Palmaria palmata* (Linnaeus) (Weber & Mohr 1805): cultivation and uses. Rev. Aquac. 11, 25–41. <https://doi.org/10.1111/raq.12224>

¹⁷ Naseri, A., Marinho, G.S., Holdt, S.L., et al. (2020). Enzyme-assisted extraction and characterization of protein from red seaweed *Palmaria palmata*. Algal Res. 47. <https://doi.org/10.1016/j.algal.2020.101849>

¹⁸ De Souza Celente, G., Sui, Y., Acharya, P., (2023). Seaweed as an alternative protein source: prospective protein extraction technologies. Innov. Food Sci. Emerg. Technol. 86. <https://doi.org/10.1016/j.ifset.2023.103374>

¹⁹ Stévant, P., Schmedes, P.S., Le Gall, L., et al. (2023). Concise review of the red macroalga dulse, *Palmaria palmata*(L.) Weber & Mohr. J. Appl. Phycol. 35, 523–550. <https://doi.org/10.1007/s10811-022-02899-5>

4.3.2 Methodology

Fertile individuals of *P. palmata* i.e. tetrasporic fronds, have been collected in late September 2022 from wild populations at Clachan Seil (56°19'02"N, 005°35'00"W), west coast of Scotland. Upon arrival at the SAMS seaweed nursery, fronds were disinfected and cleaned from biofouling using 70% ethanol, followed by several rinses with deionised water. Fronds were moved to tanks containing autoclaved aerated seawater and reels of twine (Kuralon twine; diameter: 2 mm, length: 6 m), with gentle water movement initiating spore release and settlement onto twine within 24 hours.

The seeded twine was deployed at IMTA Lab Scotland on the 2nd of December 2022. Two configurations were employed using 3 m long twine-seeded line each; one being deployed horizontally at main seaweed cultivation depth (as for all other seaweed species trialled) and the other vertically in the water column starting just below the water surface. Lines were re-visited in March 2023 and at peak harvest in June 2023 for assessment of growth performance, frond morphology and other relevant observations.

4.3.3 Results

Seeding was partially successful and some *P. palmaria* growth was observed on the line.

Upon the first visit early March 2023, sporophyte i.e. seeding density was low and inconsistent across the line, with estimated *FL* of up to 15 cm and anticipated reddish-brown colouration. Fouling and thus competition for space was already observed then with predominantly filamentous brown macroalgae naturally settling on the seeded lines. When re-visiting in June 2023, fronds were visibly discoloured to pale green (Figure 33). Also, sporophyte density and growth did not change notably from March while fouling pressure had increased with larger density and size of competing macroalgal species on the cultivation line.



Figure 33. Left: cultured dulse *P. palmata* (©J. C. Sanderson). Seeding and grow-out evaluation at IMTA Lab Scotland (12th June 2023), ©SAMS.

In summary, the main production parameters indicating cultivation success such as consistent seeding density along the line; sufficient biomass yield; expected crop morphology and appearance, were not achieved.

4.3.4 Discussion

The observed performance of *P. palmata* indicated that optimal conditions were not met at the site. Seeding density was low and patchy and obstructed further by high abundances of competing algae. Low density may be attributed to several factors, including but not limited to seed loss at time of deployment (poor handling and/or seed condition), insufficient density at time of twine-seeding, suboptimal conditions during spore release and rearing, substrate choice (material of twine and cultivation line), and deployment time. Results from this small-scale seeding trial are not sufficient to clearly identify one or more influencing factors for the seeding success in *P. palmata* cultivation at sea. Overall, more research is needed to optimise seeding performance focussing on the aforementioned factors.

Additional practical considerations and mitigation strategies could be employed such as frequent ‘weeding’ of lines i.e. manual removal of competing algal biomass, however, yields at harvest must provide sufficient revenue to warrant the resulting additional operational costs. Also, cultivation depth is of interest as pigment concentrations in *P. palmata* follow seasonal dynamics which are mostly correlated to the level of light illumination and temperature at growing depth.²⁰

Dobychina et al. (2020)¹⁹ reported significantly higher *Chl-a* concentrations in winter compared to summer in *P. palmata* and suggested that photosynthetic efficiency is provided by accumulating pigments for the darker winter months. In addition, prolonged exposure to high light intensities was linked to a reduction in photosynthetic pigments. This observation would explain the discoloration of *P. palmata* fronds encountered at IMTA Lab Scotland between April and June 2023 when both temperatures and light intensities were high over extended periods of time (see Figure 6 for *T* at 1.5 m depth). Understanding better the underlying relationships between environmental cultivation conditions and phytochemical composition of *P. palmata* can further support operational decisions such as when is the best time for deployment and harvest to maximise yield and quality.²¹

²⁰ Dobychina, E., Ryzhik, I., Klindukh, M., et al. (2020). Seasonal changes in the concentration of photosynthetic pigments *Palmaria palmata* (Linnaeus) F. Weber & D. Mohr, in: International Applied Research Conference. Biological Resource Development and Environmental Management (BRDEM-2019). KnE Life Sciences, pp. 781–790. <https://doi.org/https://doi.org/10.18502/kls.v5i1.6170>

²¹ Vasconcelos, M.M.M., Marson, G. V, Turgeon, S.L., et al. (2022). Environmental conditions influence on the physicochemical properties of wild and cultivated *Palmaria palmata* in the Canadian Atlantic shore. J. Appl. Phycol. 34, 2565–2578. <https://doi.org/10.1007/s10811-022-02783-2>

4.4 European Flat Oyster (*Ostrea edulis*)

4.4.1 Introduction

The European flat oyster or native oyster *Ostrea edulis* is a bivalve mollusc species found along the western European coast and the Mediterranean Basin, as well as North America, where it had been intentionally introduced. Since its peak in the 1960s, global production has declined dramatically impacted by overfishing and diseases (mainly Bonamiosis and Marteilirosis) and the consequential shift to the cultivation of more resilient Pacific cupped oysters (*Crassostrea gigas* or *Magallana gigas*²²). Production has remained low since with Spain, France, the United Kingdom and Ireland being the main producers. However, with decreasing availability wholesale prices have increased, allowing *O. edulis* to occupy an economic niche being considered a luxury seafood item in many regions.²³

Despite lower production figures when compared to e.g. Pacific oysters, *O. edulis* cultivation has commercial value and has received increasing attention; not last due to the continued uptake of LTA such as seaweed-oyster co-culture practices. At the same time, numerous rewilding campaigns are underway across Europe to replenish natural populations of this ecologically important species (visit NORA²⁴ for more information). The FAO describes the future of *O. edulis* production being directly linked to the research capacity addressing the main problem – disease resistance and management. Here modifications to current production techniques have scarcely been addressed. In northern Europe, oysters are commonly grown in the intertidal area and being frequently exposed to the air during low tide. Especially in warmer weather this may cause overheating and desiccation, making the oysters more susceptible to contracting diseases and affecting overall growth and survival. Oyster farmers already apply mitigative strategies by deploying grow-out structure lower shore i.e. subtidally where air exposure is reduced. Considering current LTA developments, and here seaweed-oyster co-culture, information on how oysters would perform when integrated with seaweed cultivation infrastructure remains limited.

This section presents the findings from a two-year monitoring study (November 2020 – October 2022) assessing and comparing the performance (growth, meat yield, survival) of *O. edulis* grown in intertidal and subtidal cultivation. Here it is worth noting that the monitoring has been continued at the IMTA Lab Scotland to date and was only aborted after two years due to stock failures at the intertidal site

²² Bayne, B.L., Ahrens, M., Allen, S.K. *et al.* (2017). The proposed dropping of the genus *Crassostrea* for all Pacific cupped oysters and its replacement by a new genus *Magallana*: a dissenting view. *J. Shellfish Res.* 36, 545–547. <https://doi.org/10.2983/035.036.0301>

²³ FAO (2009). *Ostrea edulis*. In Cultured aquatic species fact sheets. https://www.fao.org/fishery/docs/CDrom/aquaculture/I1129m/file/en/en_europeanflatoyster.htm

²⁴ Native Oyster Restoration Alliance. <https://nora-europe.eu/restoration-projects/projects-overview/>

(see section 4.4.3). This work is a proof-of-concept study also addressing practical considerations of subtidal i.e. suspended cultivation at sea and opportunities for future developments.

4.4.2 Methodology

Approx. 2000 juvenile oysters (average shell height $SH = 34.6 \pm 3.0$ mm) were sourced from a commercial hatchery (Morecambe Bay, UK). Upon receipt, all oysters were inspected for suspected presence of the introduced non-native Pacific cupped oyster which were removed and disposed of following SAMS biosecurity management plan (BMP). Three sets of 200 individuals were deployed in AP6 grow-out baskets at either site: IMTA Lab Scotland (subtidal system) and at a neighbouring *O. edulis* monoculture farm, Lochnell Oysters (intertidal system), approx. 500 m NE of SAMS site (Figure 34).

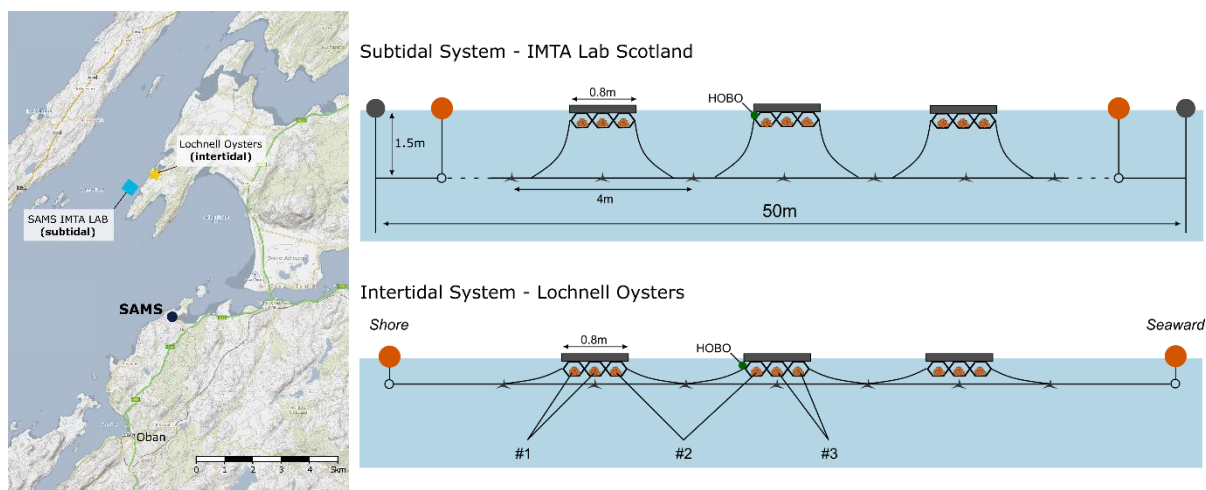


Figure 34. Site map [left] and deployment set-up for *O. edulis* grow-out in subtidal and intertidal cultivation [right], ©SAMS.

The deployment and grow-out systems as well as following bimonthly grading and sampling regime were kept identical across sites. At each visit, the baskets were inspected for structural integrity and obstructions to water flow, and thus food supply to the oysters, caused by excessive biofouling with baskets being cleaned and/or exchanged as required. The oysters were roughly graded by size into smaller and larger individuals and any mortalities recorded and removed. Three larger individuals were sampled per basket and site ($n = 18$ oysters) and transported to SAMS for subsequent processing for morphological traits: shell height (SH), total wet weight (TWW), shell pair and soft-tissue wet weights (WWS , WWT) and dry weights (DWS , DWT), respectively. The meat yield (MY) and condition index (CI), commonly employed wet and dry estimates of a bivalves' performance, have been calculated. Throughout the study, seawater samples have been collected as part of the site's routine

environmental monitoring for nutritional parameters (nutrients, chlorophyll-a *Chl-a*, particulate organic carbon and -nitrogen *POC/N*; see section 3.2.2) alongside HOBO® pendant loggers recording temperature and light intensity at either site (recording interval: every 30 min). Following on from the monitoring study, 20 subtidal oysters were harvested (19th January 2023) and held cool and dark at SAMS laboratory for a period of 25 days with twice daily checks for shell gaping behaviour to assess their longevity i.e. shelf-life post-harvest [Note: this information has been lacking so far for subtidally grown oysters].

4.4.3 Results

Oyster growth followed a seasonal cycle mainly being dictated by prevailing environmental conditions as well as the oysters' reproductive stage. Main growth occurred between April/May and September/October during which time the oysters exhibited a consistent isometric growth ($TWW = 0.00014SH^{2.95}$ ($r^2 = 91.1\%$) i.e. the weight of an oyster varied as a cube of its size), irrespective of site (Figure 35, right). Overall, oyster *SH* ranged from 3.3 to 8.4 cm (average 5.82 ± 1.32 cm) in subtidal culture and 3.4 to 7.1 cm (5.64 ± 1.07 cm) in intertidal culture. When expressed as shell growth rate, oysters grew between -0.9 and 7.7 mm/mth (average 1.55 ± 2.74) in subtidal and -2.0 to 6.2 mm/mth (average 1.09 ± 2.52) in intertidal culture (Figure 35, left & middle), with negative values being attributed to the destructive sampling regime as opposed to repeated measures of the same cohort of individuals.

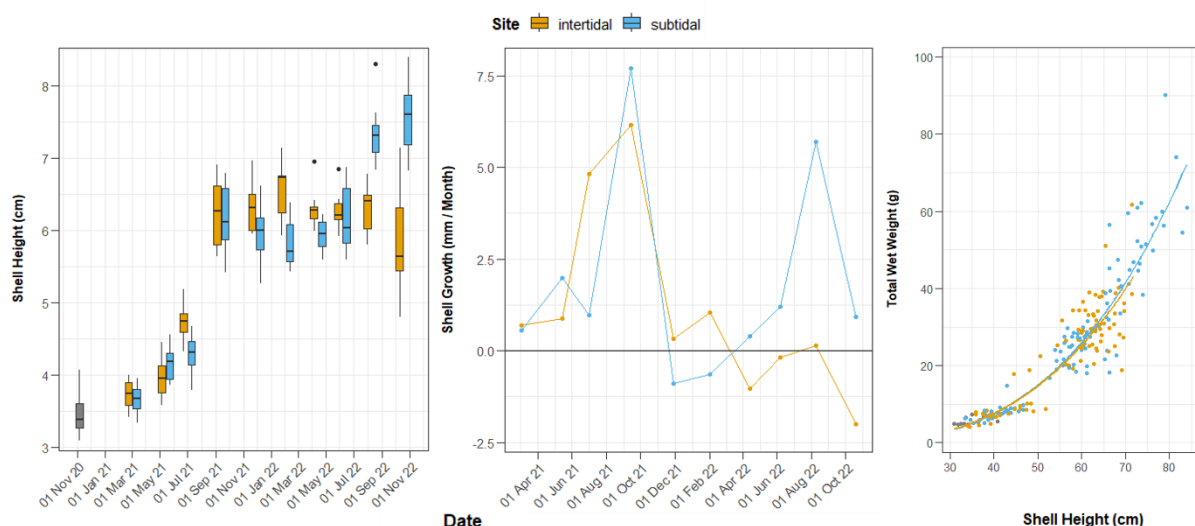


Figure 35. Temporal variation in shell height *SH* (cm; left) and shell growth rate (mm/month; middle) and size-weight relationship (right) of *O. edulis* grown in subtidal and intertidal cultivation, ©SAMS.

Figure 36 summarizes the development of oyster tissue and meat yield during the two-year monitoring study and beyond that for IMTA Lab Scotland. Oyster soft-tissue has grown exponentially between March and September, following the main spawning event in early Spring and prior to secondary spawning in late Summer. Oyster meat yield, indicative of the crops ‘fatness’, is derived from morphological traits and thus shows similar seasonality, with MY being lowest post-spawning and highest immediately before spawning events.

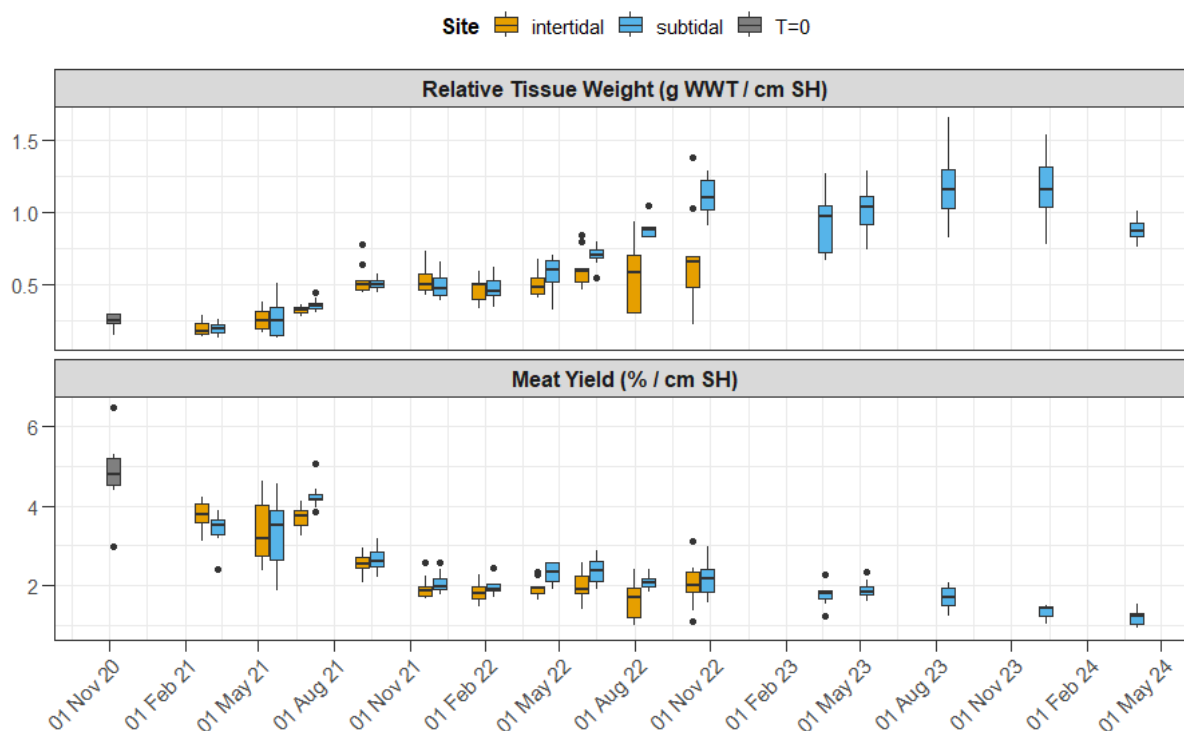


Figure 36. Variation in *O. edulis* size-corrected soft-tissue weight (g/cm) and meat yield ($MY = WWT / (WWT + WWS)$; here divided by shell height SH for size-correction) in subtidal and intertidal cultivation, ©SAMS.

During the two-year comparative study (i.e. excluding subtidal data post November 2022), linear regression analysis showed a significant effect of Date ($p < 0.0001$) and to a lesser extent also Site ($p < 0.05$) on relative oyster meat yields [$MY \sim \text{Date} + \text{Site}$; $F\text{-statistic} = 93.7_{(2,177)}$, $r^2 = 50.9\%$], with marginally greater MY being achieved in subtidal cultivation.

However, despite a comparable overall performance at either cultivation system, intertidal oyster growth has stagnated from Spring/Summer 2022, coinciding with extended hot weather periods and rapidly increasing oyster mortality at this site (Figure 37).

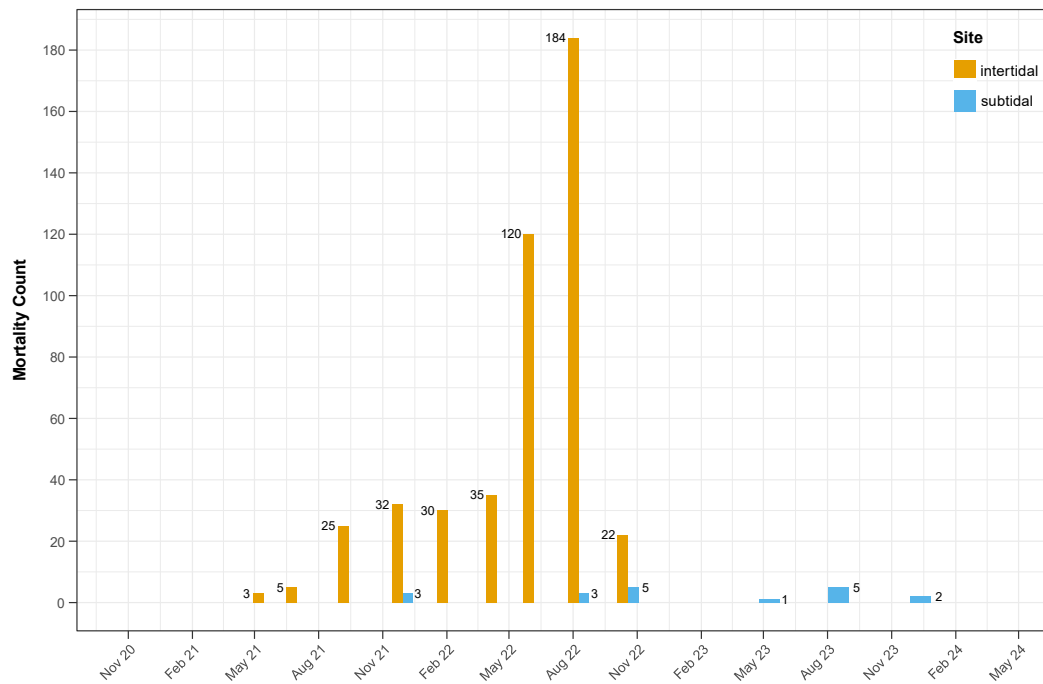


Figure 37. Number of recorded mortalities for *O. edulis* in subtidal and intertidal cultivation, ©SAMS.

When considering the entire study period, mortality rates were significantly higher in intertidal compared to subtidal culture with average values of 76.7 % and 1.8 % respectively. In fact, of the 600 individuals deployed at either site only two individuals remained in November 2022 and therefore terminating the comparative monitoring. These two survivors, together with two of equivalent size from subtidal culture, were screened for presence of the Bonamiosis disease-causing parasite *Bonamia ostreae* using a novel non-destructive qPCR test developed by the Roslin Institute, University of Edinburgh UK. Whilst results did not confirm any presence of *B. ostreae* at either site, the small sample size does not allow for it to be ruled out as a contributing factor in addition to the heat stress experienced by the intertidal oysters during air exposure.

For the subtidal oysters, shell gaping behaviour and therefore overall expected shelf life varied across individuals. Of the 20 oysters monitored, 8 (40 %) showed no shell gaping or other signs of perishing (e.g. foul odour, valve springing back upon applying pressure) and can be assumed still alive even after 25 days of cool storage. For the remaining population ($n = 12$ or 60 %) shell gaping commenced after 5 to 21 days (average 10 ± 5.4 days) and signs of perishing after 1 to 9 days (average 4.0 ± 2.5 days). Overall, and using the first sustained shell gaping as threshold, subtidal oysters had a minimum shelf life of 5 to 7 days in 9 °C storage but are likely to sustain periods of up to two weeks when stored cooler.

4.4.4 Discussion

This study identified differences in overall performance between oysters cultivated intertidally and subtidally. Most strikingly, survival was significantly lower in the intertidal with mass mortalities diminishing almost the entire population in a matter of weeks. Although testing did not confirm the presence of *B. ostreae* at either site, this should not be ruled out as the sample size available for testing was too small to be robust. The intertidal cultivation site has been tested positive for *B. ostreae* in the past and assigned a confirmed designation notice (CDN) by the local authorities involving a Bonamia management area for this location and the wider area (Figure 38).²⁵ As there is no treatment for *B. ostreae*, movement restrictions for disease control are the only avenue to contain and prevent further spread.

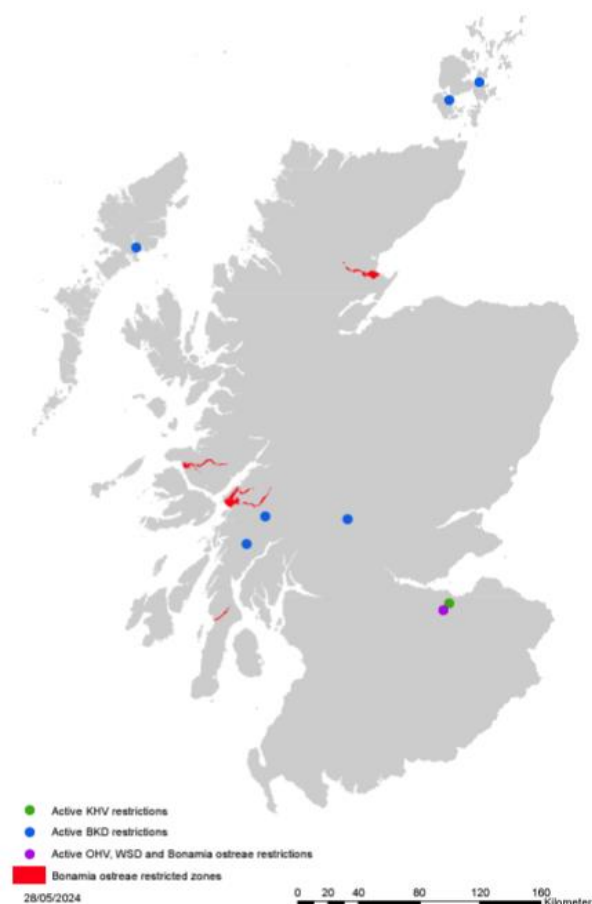


Figure 38. Map of active movement restrictions on fish and shellfish. Note confirmed designation notice (CDN) for *Bonamia ostreae* in study area (red). Scottish Government, Fish Health Inspectorate (FHI).

We further observed differences in growth and meat yield across oyster populations. These have been marginal during the first 1.5 years of the study but changed drastically from April 2022 coinciding with increasing mortalities at the intertidal site. As mentioned earlier, oyster growth is governed by

²⁵ <https://www.gov.scot/policies/fish-health-inspectorate/movement-restrictions-on-fish-and-shellfish/>

prevailing environmental condition, reproductive stage and general immune health of the oyster. With extended heat stress and likely disease infection experienced by intertidal oysters during Spring/Summer 2022, less energy would have been invested in shell and soft-tissue growth and rather directed towards immune response to ensure survival, thus explaining reductions in SGR and relative tissue weights. Oysters grown in suspended culture experienced far less environmental variability and given the overall low mortality rate were unlikely to have been affected by diseases. Most oysters reached market size (70 mm) after two years at sea while acknowledging that the deployment size of ~35 mm far exceeded the industry standard of 5 – 6 mm *SH*.¹² Yet with growth being most rapid during early development it is not unlikely for *O. edulis* to have reached market within three years of cultivation at sea. The role the adjacent seaweed cultivation played in growth could not be quantified. However, frond erosion providing added particulate feed as well as increased oxygenation of the water from seaweed respiration are only two aspects that may have impacted the performance of oysters deployed alongside seaweed lines. Another aspect to investigate further is the role seaweed may have played in the presence/absence of pathogenic organisms such as *B. ostreae*. This is because seaweed surfaces are known to host an abundant and diverse microbial community with some strains possessing antimicrobial and antiviral properties.

Overall, for successful oyster cultivation at sea, grow-out infrastructure and site set-up will have to be designed with environmental and practical considerations in mind. At IMTA Lab Scotland oysters were grown in polypropylene AP6 baskets, each consisting of three separate holding baskets connected with heavy duty cable ties and supported with dual floats for buoyancy. These systems have proven susceptible to breakage and would not be suitable for use in dynamic environments. Even for our moderately exposed site, severe and extended storm events such as in the Winter of 2023/24 resulted in repeated failures and substantial stock loss (Figure 39). With the view to expand LTA operations including installations further offshore, more robust grow-out structures will be required with frequent checks and maintenance for repair and biofouling control.



Figure 39. AP6 oyster basket. Wear and tear and storm damage in February 2024, ©SAMS.

4.5 Scallops (*Pecten maximus* & *Aequipecten opercularis*)

4.5.1 Introduction

The king scallop, *Pecten maximus* is a highly valued seafood delicacy and together with its close relative queen scallop *Aequipecten opercularis* dominates the scallop production in Europe including in the UK.²⁶ In the UK, *P. maximus* have mostly been fished from natural stocks, an industry that at its peak in the early 2000s was valued worth £30 million (approx. 35.4 million €) from just under 20,000 landed tonnes per annum. Production needs to include commercial culture to meet retail demands and although comparatively small in proportion many king scallops are produced in cultivation today. For the UK cultivation takes place mostly on the west coast of Scotland with 39,000 *P. maximus* at 120 g and £1.79 (2.11 €) per individual produced in 2022; an increase in production of 44 % compared to 2021 and contributing £0.07 million to the Scottish shellfish industry (total value = £10.4 million or 12.7 million €).²⁷ *A. opercularis* is also produced but in much lower quantity and first sale value with 600 individuals of 40 g and £0.13 (0.15 €) per piece sold in 2022.

Either species is native to IMTA Lab Scotland's location and can often be found washed up on local shorelines. *P. maximus* has been selected as new added value species at IMTA Lab Scotland because of its presence in the area, established cultivation procedures and high commercial value, as well as potential practical and ecological synergies for grow-out in conjunction with other low-trophic species in an IMTA system.

The main objectives were to determine the scallops' cultivation and growth potential for open water culture and to set out best practices for suspended culture as well as in relation to practicalities and synergies of grow-out in conjunction with other species present, European flat oysters and seaweed.

4.5.2 Methodology

Following permit for experimental use by FHI, adult *P. maximus* were hand-dived (scientific divers; Tritonia Ltd., UK) adjacent to IMTA Lab Scotland in August 2022. Eight undersized scallops (i.e. < 10 cm *SH*; required harvest size) were recovered and deployed at site for an acclimation period of five months. The monitoring programme commenced in January 2023 by deploying two sets of stacked baskets (nestier trays) from the oyster system lines holding 4 scallop individuals each (Figure 40). Trays were inspected every 3 – 4 months for repeated morphological measures of shell height *SH* and -

²⁶ Laing, I. (2002). Scallop Cultivation in the UK: a guide to site selection. Department for environment, food and rural affairs (DEFRA), Centre for environment, fisheries and aquaculture science (CEFAS).
https://www.cefass.co.uk/publications/files/scallop_cultivation.pdf

²⁷ Munro, L. and Murphy, J. (2023) Scottish Shellfish Farm Production Survey 2022. Marine Scotland, Scottish Government.
<https://www.gov.scot/publications/scottish-shellfish-farm-production-survey-2022/documents/>

length *SL* (Figure 41), accompanied by cleaning and/or exchanging trays and recording of any mortalities and other observations.

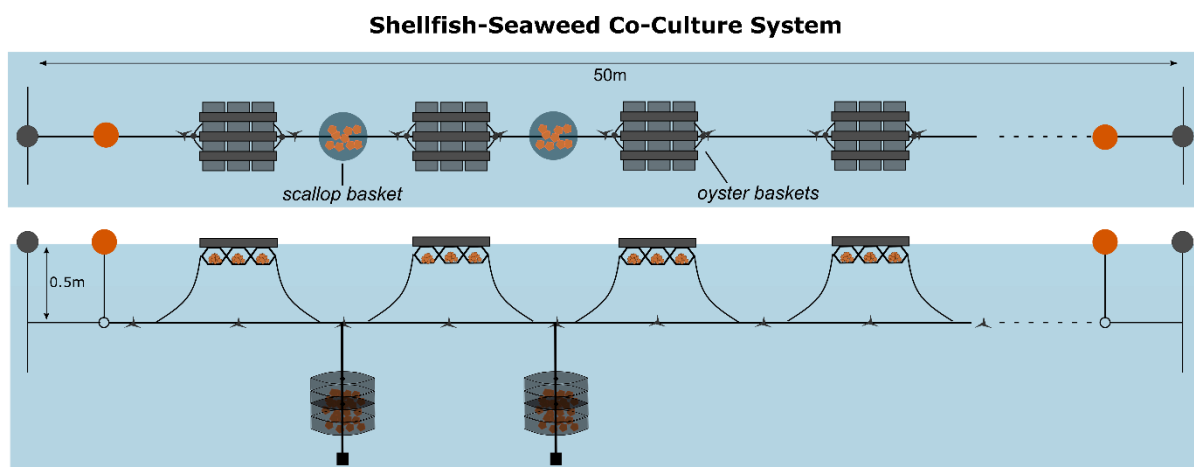


Figure 40. European flat oyster *O. edulis* and king scallop *P. maximus* co-culture system, adjacent to seaweed cultivation lines, ©SAMS.



Figure 41. Morphometric measures of shell height *SH* and -length *SL* (left), hand-dived *P. maximus* (middle; 25th August 2022) and set of four monitoring individuals in nestier tray (right; 13th December 2023), ©SAMS.

4.5.3 Results

During 15 months of cultivation (January 2023 – April 2024), *P. maximus* have consistently grown in shell height from 63.4 mm to 91.9 mm *SH* as well as shell length, starting with 70.4 mm and now averaging at 104 mm *SL* (Figure 42). Growth was significantly affected by time of year, being most rapid between May and August 2023 and continuing steadily before levelling off from December 2023 onward.

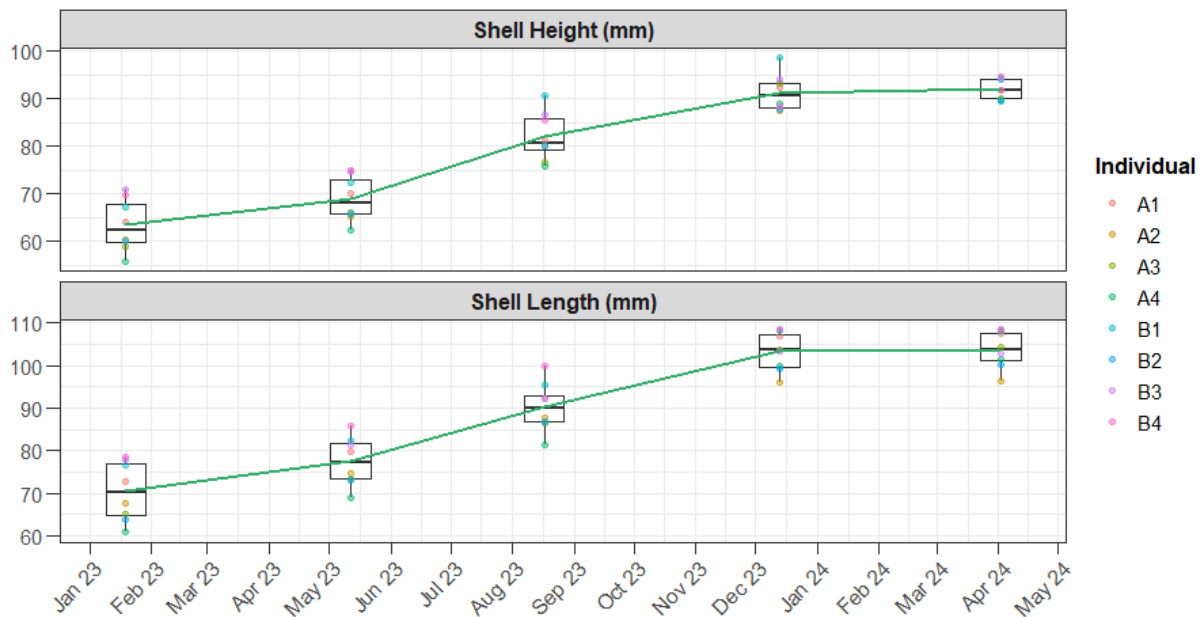


Figure 42. Growth in *P. maximus* shell height *SH* and shell length *SL* over time with running average (green line), ©SAMS.

Specific growth rates (*SGR*) for shell height ranged from 0.18 ± 0.71 mm/mth during slow growth to 4.11 ± 0.81 mm/mth during peak growth periods. For shell length these corresponded to 0.11 ± 0.18 to 4.03 ± 0.31 mm/mth, respectively.

Early in the *P. maximus* monitoring study, we observed scallop spat settling within the nestier trays which were later identified as queen scallop (*Aequipecten opercularis*) having been naturally recruited. Their and other species' presence on and alongside *P. maximus* (Figure 43, left) indicated the grow-out structures providing a nursery habitat for a variety of marine life. Two sets of 40 *A. opercularis* spat were translocated into separate trays joining the existing scallop stacks and commenced their monitoring for growth and thus potential as new added species for IMTA Lab Scotland in August 2023 (Figure 43, middle & right).



Figure 43. *P. maximus* with various shell epifauna (e.g. starfish, scallop and mussel spat, reef-building tube worms) (left). *A. opercularis* grow-out in nestier tray (middle) and scaled imaging for *SH* growth (right), ©SAMS.

Over the course of seven months, *A. opercularis* has grown from an average *SH* of 40 ± 3.6 mm to 59 ± 4.2 mm, corresponding to an average SGR of 3.37 mm/mth and 0.97 mm/mth during peak and slow growth periods, respectively (Figure 44).

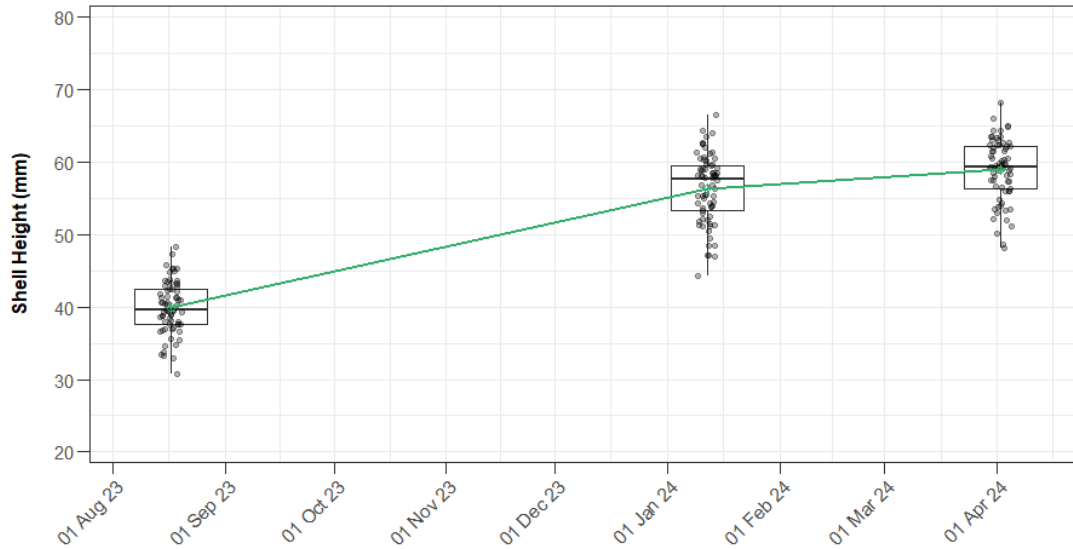


Figure 44. *A. opercularis* growth in *SH* (mm) over time, ©SAMS.

4.5.4 Discussion

Overall, both scallop species performed very well in suspended culture at IMTA Lab Scotland's open water site. Since the start of *P. maximus* monitoring in January 2023 there have been no mortalities and individuals have grown to a shell height *SH* of over 90 mm within 15 months of grow-out at sea. However, and similar to European flat oysters (section 4.4), the size at deployment exceeded industry standards with average *SH* of 63 mm compared to commonly used 20 – 33 mm.¹⁴

This trial was intended as proof-of-concept for growing scallops in suspended culture at a moderately exposed site as part of an IMTA system. Besides their good growth performance in culture to date, scallop grow-out infrastructure and their shells themselves have provided additional settling grounds for a wide range of marine species and potentially serving as nursery ground for some of them (see Figure 43). The fact that natural spat recruitment of queen scallops had occurred in the king scallop trays is peculiar and lends itself to further investigation.

4.6 Edible sea urchin (*Echinus esculentus*)

4.6.1 Introduction

The European edible sea urchins, *Echinus esculentus*, is a large globular sea urchin that can grow up to 16 cm in diameter at 7 – 8 years of age. This species is abundant in the NE Atlantic and commonly found on most rocky coastlines of the British Isles.²⁸ Yet since 1996, *E. esculentus* has been assigned 'near threatened' status on the Global IUCN red list²⁹ of threatened species.

Sea urchins are fished for their roe i.e. gonads as a highly-priced food product and sought after delicacy. Roe is rich in omega-3 fatty acids, protein, vitamin B₁₂, calcium and magnesium, and has been associated with improving bone strength, lower blood pressure and even improve mood. In Europe, a small fishing industry exists, mainly supplying domestic markets in south-western Europe. However, with gonad consumption not being established in European diets, investigation and development of commercial cultivation potentials have been scarce. A Scottish study surveying wild populations as well as monitoring gonad growth in tank culture showed *E. esculentus* appears robust in tank culture and that gonad yield and quality can be promoted with choice of (artificial) diet.³⁰

With investigations into the practicalities of a fully farmed approach lacking, *E. esculentus* has been selected as new added species for IMTA Lab Scotland. The main objectives were to assess their potential for cultivation at sea and to control biofouling build-up on cultivation infrastructure such as shellfish grow-out baskets.

4.6.2 Methodology

Edible sea urchins ($n = 20$; shell width $SW = 3 - 4$ cm) were transferred from the SAMS Aquarium facilities for deployment at IMTA Lab Scotland 10th of March 2023. Sea urchins were deployed in a separate AP6 basket as follows - left compartment: *O. edulis* only ($n = 35$), middle basket: *O. edulis* ($n = 35$) + *E. esculentus* ($n = 10$), right basket: *E. esculentus* only ($n = 10$) (Figure 45).

²⁸ Tyler-Walters, H., (2008). *Echinus esculentus* Edible sea urchin [WWW Document]. Mar. Life Inf. Netw. Biol. Sensit. Key Inf. Rev. URL: <https://www.marlin.ac.uk/species/detail/1311>

²⁹ International Union for Conservation of Nature's (IUCN) Red List of Threatened Species. <https://www.iucnredlist.org/species/7011/12821364#assessment-information>

³⁰ Kelly, M.S., Owen, P. V., Pantazis, P., (2001). The commercial potential of the common sea urchin *Echinus esculentus* from the west coast of Scotland. Hydrobiologia 465, 85–94. <https://doi.org/10.1023/A:1014553010711>



Figure 45. Deployment set-up for trialling *E. esculentus* potential to control biofouling build up, alone and in co-culture with *O. edulis*, ©SAMS.

O. edulis for this trial have been taken from the fourth AP6 basket (i.e. containing ≤ 400 non-monitoring individuals), selecting 70 of the larger individuals. Upon visits, compartments holding *E. esculentus* were provided with seaweed fronds (wild or cultivated) for sufficient food provision for this efficient grazer.

The experimental plan included the regular photographing of each compartment to monitor biofouling build-up and assess potential differences in fouling pressure attributable to the grazing of *E. esculentus*. In addition, the middle compartment was to be assessed for oyster health and survival as the co-inhabiting sea urchins may penetrate the oyster's hinge or interfere with valve gaping and thus filter feeding behaviour and efficiency.

4.6.3 Results

Unfortunately, the trial had to be terminated early and thus no results can be presented or discussed. During a routine check a few weeks into deployment, no sea urchins were to be found in any of the compartments whilst signs of any damage to or failure of the basket were absent.

4.6.4 Discussion

The cultivation of *E. esculentus* has not been successful at IMTA Lab Scotland and thus does not serve as a viable new added species for this LTA production system.

From the observations made, it can only be concluded that the prevailing wave and current regime at this exposed coastal location is too violent for such fragile species and that they got destroyed. Furthermore, it indicates that either a different environment, cultivation technique and/or grow-out structure, or probably a combination of all may be required to attempt successful cultivation of sea urchins in open water aquaculture.

5 ASTRAL IMTA Production Species / Value Chain

IMTA Lab Scotland focused on the development and validation of low-trophic production systems in open water aquaculture. During the lifespan of the ASTRAL project, nine low-trophic species were trialled and the formerly seaweed monoculture site transitioned to a seaweed-shellfish co-cultivation site practicing integrated low-trophic aquaculture in a dynamic coastal environment.

For seaweed this involved improving cultivation methodologies for well-established kelp species *Alaria esculenta* and *Saccharina latissima*, in addition to cultivation and seeding trials using less established brown (*Laminaria digitata* and *Saccorhiza polyschides*) and red (*Palmaria palmata*) seaweed species, respectively. Findings from cultivation optimisation trials showed that both the quantity and quality of harvestable crop can be significantly improved by applying relatively simple modifications to existing system configurations (see sections 0 to 4.1.5). Furthermore, production value chains could be established for newly added seaweed species; to highlight here is the promising cultivation potential of the fast-growing kelp *S. polyschides* which exceeded expectation in terms of achievable yields (see section 4.2.3). Biomass samples collected throughout its study will continue to be analysed for compounds of interest, e.g. trace metals of relevance for food/feed safety, as well as compounds of known value and application such as polyphenols and individual polysaccharides (mannitol, alginate, and laminarin). Successful at sea cultivation of *P. palmata* remains to be hindered by production hurdles both during the nursery as well as grow-out stage (see sections 4.3.3 – 4.3.4), some of which are being addressed in an ongoing PhD dissertation (Indicative title: ‘Material development for global seaweed cultivation’; SAMS-UHI 2021 – 2025). For IMTA Lab Scotland the four trialled kelp species showed overall the most potential for large-scale commercial cultivation with both similarities as well as differences observed across species.

In addition to seaweed, several shellfish species belonging to the group of bivalve molluscs have been trialled at IMTA Lab Scotland, including the European flat oyster *Ostrea edulis*, King scallop *Pecten maximus* and Queen scallop *Aequipecten opercularis*. *O. edulis* showed great potential for suspended culture at sea with significantly higher survival and better growth rates compared to traditional cultivation systems in the intertidal (see section 4.4.3). King and queen scallops have also performed well in suspended culture, showing good growth and 100 % survival to date (see section 4.5.3).

Shellfish and seaweed cultivation were found to complement each other due to their similarities in infrastructure requirements, e.g. cultivation lines can be shared, and shellfish baskets be used as buoyancy aid for seaweed lines, as well as differences in nutritional requirements for either species group i.e. absence of food competition. However, with shellfish species being contained in grow-out structures (baskets, trays, lantern nets, etc.) requiring frequent monitoring for damage and sufficient

water flow (obstructed by on-growing biofouling), this cultivation concept comes with additional time and staff requirements to consider and to be balanced with added economic value from the shellfish in culture. Considering its good performance in suspended culture and under acknowledgement of the continued decline of natural populations, IMTA Lab Scotland sees *O. edulis* as a viable candidate species for future LTA production at sea with the view to employ more robust grow-out structures in future to limit failures and stock loss (see section 4.4.4).

The trials conducted at IMTA Lab Scotland have provided valuable data on cultivation of low-trophic species in an IMTA system. Information on cultivation environmental parameters, species survival and growth were generated, and promotes the broader uptake of co-cultivation by local and international producers and enhance the sustainability of each species production value chain. These findings have contributed towards the development of new, sustainable, profitable and resilient value chains for IMTA production within ASTRAL and the framework of existing, emerging and potential Atlantic markets.

6 Acknowledgements

The authors would like to acknowledge contributions made to the delivery of IMTA Lab Scotland's work. To Dr P. Anderson (SAMS) for developing and maintaining the OptiCAL system and supporting data generation and interpretation. Also, Mr R. Marques (SAMS-UHI PhD student) for field support and valuable contributions to the *P. palmata* seeding trial presented herein. And finally, to the many helping hands from within and outside SAMS seaweed group during core seaweed events (deployment to harvest).