HORIZON
SEAWEED

REFLECTIONS ON OUR SEAWEED FARMING OPERATIONS 2016-2023

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New Wave Foods Ltd (t/a Horizon Seaweed)

March 2024

EXECUTIVE SUMMARY

This report summarises the seaweed cultivation trials on the west coast of Scotland by New Wave Foods Ltd (now trading as Horizon Seaweed, www.horizonseaweed.com). Our first farming cycle was in 2016, making us an early pioneer in the aquaculture of Scottish seaweed. In 2023, our strategic focus shifted towards expanding our wild harvesting and processing operation in Caithness. This pause in seaweed farming gives us an opportunity to reflect and share some of the knowledge gained over eight years. We are eager to see seaweed farming develop in the UK and Scotland is well positioned to lead this innovative marine industry. While there have been many academic papers, technical reports and feasibility studies published on seaweed cultivation that are relevant to production in the UK, many lack practical information to help farming and processing. This report is co-authored by Iskander Bond (leader of farming trials 2020-2023) and Peter Elbourne (company co-founder providing strategic direction to cultivation since 2016). We are confident that our direct experience will provide useful additional insight to existing materials. Of course, our working knowledge is from farming on the west coast of Scotland and we acknowledge that there are many seaweed cultivators across Europe who have reached far more advanced levels.

Atlantic wakame (Alaria esculenta) was the primary species for our research, but sugar kelp (Saccharina latissima) became increasingly important in later years. Our trials were always mindful of processing at our food-grade facility in Wick, where our experience in wild harvesting provided context for producing high quality seaweed. Our trials never aimed simply to maximise biomass. After using vacant shellfish lines in the Oban area for several years, in 2018 we installed our first seaweed farm within an 80 hectare site near the Isle of Kerrera. Over eight growing cycles, we deployed around 17km of lines at five different locations using various techniques and configurations. An average of 2 wet tonnes a year was processed through our Wick factory, although it is likely that we grew over 50 wet tonnes across all cycles.

8 GROWING CYCLES COMPLETED

5 DIFFERENT SITES USED

2018 INSTALLATION OF FIRST FARM

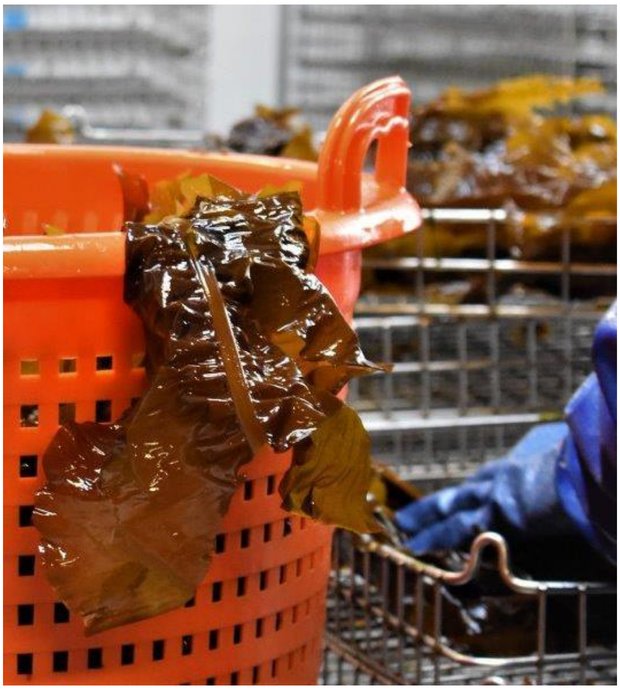
OVER **50** FRESH TONNES GROWN

OVER **16** FRESH TONNES PROCESSED

Our report is aimed at those with some working knowledge of seaweed and/or experience in aquaculture or related marine activities. To a degree, the report is framed around the vision our trials were geared towards: overcoming bottlenecks to ultimately unlock farming at scale in Scotland. We consider different scales for seaweed farming and alignment with processing, with the latter essential for a successful operation. The

majority of content relates to farming at sea, starting with factors around site location and integration with other forms of aquaculture. We review infrastructure, seeding methods, monitoring, maintenance and harvesting. We propose a production calendar based on our experiences in Argyll. The report includes information on biofouling, which is critical for determining the season end and applications for the crop. Once cut from the lines, seaweed must be moved efficiently and safely in a manner that preserves the integrity of the product. Therefore, we cover the shipping and handling of farmed seaweed.

The report provides some information on various methods of stabilising fresh seaweed, although there is more consideration around drying given it has been the backbone of our operations since 2016. We provide views on the merits of organic certification, which we hold for wild harvesting but never progressed for farming. There are brief considerations around markets for farmed seaweed. We reflect on the potential for seaweed aquaculture as a tool for the climate emergency and review other environmental effects. Lastly, we consider the jobs and roles needed for a seaweed farming operation.



We do not consider this document to be a definitive record of all our research, a manual for seaweed farming or a feasibility study. There is no economic modelling, although some costs are shared to guide the reader through certain aspects. Instead, it offers general considerations and insight into seaweed cultivation accumulated through a strategic approach to practical farming. The production of this report was part-funded by European Maritime and Fisheries Fund, repurposing a portion of an infrastructure development award. The majority of our seaweed cultivation trials were conducted with support from Highlands and Islands Enterprise.

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BACKGROUND

CONTEXT

The objective of this report is to provide a review of the seaweed aquaculture trials carried out between 2016 and 2023 by New Wave Foods Ltd (currently trading as Horizon Seaweed). Rather than a conventional record of activity, it offers reflections on the company's accumulated farming experiences. The original vision was to scale aquaculture to meet expected future demand for food-grade seaweed, supplementing an operation based around wild harvesting. We had a particular focus on growing Atlantic wakame (Alaria esculenta), which has myriad culinary applications but can only be wild harvested in modest volumes. While farm tonnage remained low, the early R&D was geared around considerations for phased increases in volume. Where possible, emphasis was placed on unlocking bottlenecks likely to be seen when deploying, harvesting and handling large quantities of seaweed.

We decided to pause our aquaculture trials in 2023 to focus on our wild harvesting and processing in Caithness. Seaweed farming must be carried out at a larger scale than the level we reached to achieve viabiliity. We aim to return to farming in the future and will remain actively engaged with seaweed aquaculture in Scotland and beyond because we will require farmed biomass to satisfy demand for certain species. This production will be more efficiently delivered by a company focused on aquaculture. We have an opportunity to share some of our practical experience to help the nascent UK industry develop. We have been active members of the Scottish Seaweed Industry Association since 2018 and we are eager to see the organisation continue to proactively support seaweed production in Scotland.

This document does not attempt to provide an economic analysis of different scenarios and should not be considered a feasibility study. Nor does it provide a definitive handbook for seaweed cultivation. It lays out general thoughts around key topics, venturing opinions on some elements and referring to the literature for others. Much of the knowledge gained is around production of Atlantic wakame and sugar kelp (Saccharina latissima), which show noticeable differences despite both being large kelps. Undoubtedly, our insight will not completely align with the experience of other active seaweed farmers, especially those operating outside Scotland and the UK. The seaweed farming landscape in Europe has shifted considerably since we commenced our trials: many seaweed farmers have gained deeper knowledge than ourselves. Nevertheless, there will undoubtedly be transferrable concepts that could help others make improvements to their seaweed farming operations.

FUNDING

The collation of this report was supported by European Maritime and Fisheries Fund, repurposing part of an aquaculture infrastructure development award to New Wave Foods (SCO2734). In addition, Highlands and Islands Enterprise provided grant funding for cultivation R&D between 2017 and 2022. Our farming trials would have been substantially curtailed without this support.

COMPANY BACKGROUND

New Wave Foods Ltd was established in 2015 following several years of research into the potential for seaweed. The founders saw the importance of starting with wild harvesting, given the quality of the resource available in Scotland, whilst also pioneering aquaculture at sea for future growth. Our efforts centred on food uses and in 2018 we launched the first retail products using our seaweed as the star ingredient. This was under the SHORE brand, which we soon used as the identity for our entire operations: all the way through from sourcing (wild harvesting and farming) to processing at our Wick factory and marketing both the retail products and wholesale seaweed.

In July 2023, the SHORE brand was acquired by Aquascot Ltd – our employee-owned sister company and lead investor, with decades of experience in the Scottish food and drink industry. This gives New Wave Foods the opportunity to focus on producing high quality seaweed for a range of markets. We created the Horizon Seaweed brand to reflect our position as a leading supplier, carefully hand-harvesting and processing a variety of species from wild coastline. Our earliest investigation into seaweed highlighted the multitude of applications. Narrowing down into food uses provided a clear vision around which we could design our operations; all reputable food manufacturers require technical expertise, commitment to innovation and continuous supply of quality ingredients. This has proven the case, but other markets are equally aligned to the way we produce seaweed. Operating as Horizon Seaweed helps us unlock opportunities beyond food.

Wild harvesting in Caithness

The core of our operations is based in Caithness, a remote region in the far north of Scotland with a strong community spirit and longstanding maritime heritage. Horizon Seaweed is licenced to harvest seaweed at over a dozen different stretches of rugged coastline. Each site has its own characteristics, varying between rocky outcrops, weathered boulders and pristine sandy beaches. With few sheltered bays, the wild shoreline is continually exposed to swells and storms. This high water exchange means that a wide range of seaweed species thrive in clean conditions. In total, 17 different

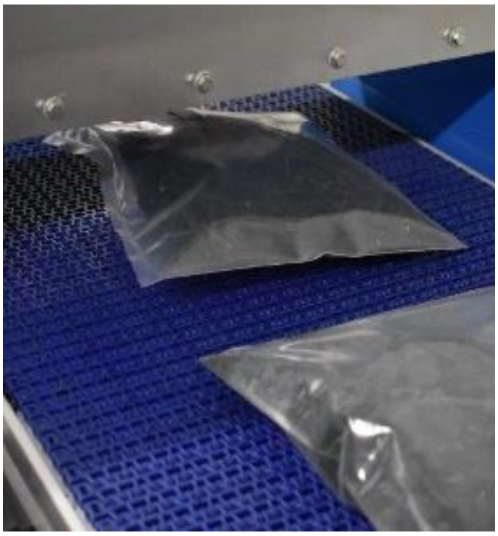
species are within our harvest quotas (20% of the total biomass each year, as determined through baseline marine ecology surveys). In practice, around half of the species are not abundant enough to schedule into regular production. Nevertheless, there is enough range in species to permit harvesting year-round, with some available for 2-3 months and others for 9-10 months. Volumes in winter months may be impacted by adverse weather, although there are rarely days where seaweed cannot be harvested on at least one site. There are more than six species in season during spring, which is typically the busiest period of the year.

Our harvest team carefully plan each day according to the weather and tide, building up knowledge of species, sites and seasons. All wild seaweed is harvested by hand, which means each plant can be cut to allow reproduction and regrowth. This is also an important first step in quality control. Ecological monitoring started in 2015 to validate our sustainable methods have minimal impact on the rocky shore habitats. Our harvesting operations have been certified organic by Soil Association since 2016.

Species within Horizon Seaweed wild harvest quotas in Caithness

Scientific name	Common name(s)
Ascophyllum nodosum	Knotted wrack, egg wrack
Fucus serratus	Toothed wrack, serrated wrack
Fucus spiralis	Spiral wrack, flat wrack
Fucus vesiculosus	Bladder wrack
Himanthalia elongata	Sea spaghetti, thongweed
Pelvetia canaliculata	Channelled wrack
Alaria esculenta	Atlantic wakame, dabberlocks, winged kelp
Laminaria digitata	Kelp, oarweed
Laminaria hyperborea	Kelp, tangle, cuvie
Saccharina latissima	Sugar kelp, sweet kelp, sea belt
Chondrus crispus	Irish moss, carrageen, sea moss
Mastocarpus stellatus	False Irish moss
Palmaria palmata	Dulse
Porphyra species	Nori, purple laver, sloke
Osmundea pinnatifida	Pepper dulse
Ulva intestinalis	Gutweed
Ulva lactuca	Sea lettuce, green laver

Processing at Wick



We process seaweed at our food-grade factory in Wick, a short distance from our harvest sites around Caithness. Seaweed is washed in fresh water and carefully batch-dried at low temperature to preserve nutrients and bioactives. Once dry, seaweed is milled to a range of sizes and packed to customer specification, including metal detection. Product goes through quality control throughout the process. A detailed HACCP system and food safety management programme is in place. Our factory has been certified since 2016 for both organic production by Soil Association and food processing by SALSA.

While we supply fresh seaweed to some customers, production is oriented around drying to allow continuous year-round supply. Dried seaweed is more easily taken through size reduction, creating a denser product for transport and storage. Our systems permit complete traceability back to the exact location where the seaweed was harvested. Seaweed is sold by the kilogram and despatched in parcel or pallet quantities.

Most of our staff take part in both harvesting and processing, given that harvest trips are limited to around half a day given dependence on ties. Wet and dry processing is prioritised on busy weeks to maximise throughput. Any quieter periods for harvesting can be filled with milling and packing dried seaweed from stock.

The Processing section includes further information specific to handling farmed seaweed at our Wick facility.

Seaweed farming

We recognised at the outset that farming seaweed at sea was going to be important in the future: not only to scale up overall production, but also to target key species with limited volumes available from wild harvest. Our seaweed aquaculture journey started in 2016 with a trial of Atlantic wakame with The Scottish Association for Marine Science (SAMS) on their site near

Dunstaffanage, by Oban. With existing aquaculture, research expertise, marine operators and infrastructure, the Oban area was undoubtedly the best location in Scotland to carry out applied research into seaweed farming. We later decided to take more control over our trials, working with local contractors and mussel farmers to add seaweed to existing shellfish licences and deploying on vacant sites.

After a couple of growing cycles, we acknowledged that installing our own sea farm would catalyse our trials by offering more flexibility and continuity. We installed our first seaweed farm in late 2018. Other aquaculture companies and research centres had deployed seaweed at sea in various scales over the previous decade, but we were the first dedicated seaweed company in Scotland to achieve this milestone. Located beneath a headland south of the Island of Kerrera, the 80 hectare site looks out to Mull and beyond to the Atlantic Ocean. We also advanced the licencing for a sea area for a second farm installation. This process completed in 2023 but the site was not developed.

Species farmed by Horizon Seaweed in Argyll

Scientific name	Common name(s)	Production
Alaria esculenta	Atlantic wakame, dabberlocks, winged kelp	Primary focus of cultivation trials, majority of seeding and harvesting in every cycle
Saccharina latissima	Sugar kelp, sweet kelp, sea belt	Secondary focus of cultivation trials, seeded and harvested in majority of cycles
Sacchorhiza polyschides	Furbellows	Never seeded, but wild settlement on lines harvested multiple times
Laminaria digitata	Kelp, oarweed	Never seeded, but wild settlement on lines harvested once
Palmaria palmata	Dulse	One seeding trial, without any yield to harvest

Our R&D has given us extensive practical experience of seaweed farming in Scotland. We have trialled multiple seeding technologies and countless configurations of ropes and layouts at different locations. Atlantic wakame remained the primary species for our research, but sugar kelp became of secondary importance over time. We have also tested dulse seeding (without yield) and harvested modest volumes of naturally settled furbellows (Sacchorhiza polyschides) and kelp (Laminaria digitata). Key to all our trials was the connectivity into the processing of the harvested seaweed at our factory in Wick. Our experience with wild harvesting ensured we focused on producing and handling quality seaweed suitable for processing in a food-grade facility, rather than maximising biomass.

Summary of growing cycles

Harvest year	Line deployed	Total harvest [a]	Location(s)
2016	0.3km	0.3 wet tonne	Port a' Bhuiltin (SAMS)
2017	3.0km	1.0 wet tonne	Balvicar, Loch Spelve
2018	3.0km	1.7 wet tonnes	Balvicar, Cutter Rock
2019	5.5km	1.6 wet tonnes	Aird na Cuile, Balvicar, Cutter Rock
2020	1.5km	2.7 wet tonnes	Aird na Cuile
2021	1.4km	3.4 wet tonnes	Aird na Cuile
2022	1.4km	1.5 wet tonnes	Aird na Cuile
2023	1.2km	3.9 wet tonnes	Aird na Cuile

[a] As weight is taken at factory intake prior to processing, this is not total weight grown or harvested.

After completing our eighth consecutive growing cycle in spring 2023, we elected to pause our aquaculture trials to focus on our wild harvesting and processing in Caithness in the near term. The decision was driven by the recognition that commercially viable seaweed farming requires a significantly larger scale than we had operated at to date. This necessitates the installation of infrastructure both at sea and on land, which erodes investment for increasing capacities and efficiencies in Caithness. In total, approximately 17km of line sourced from three different hatcheries (originated by local broodstock) was deployed over five separate sites close to Oban. While 16 wet tonnes over eight years was processed at Wick, the actual weight of seaweed harvested was likely over 25 wet tonnes (accounting for discards and moisture loss). Earlier seasons saw several failures in growth for certain trials and often only a minority of the seaweed grown on the lines was harvested for processing (e.g. poor condition). Therefore, it is likely that 50-75 wet tonnes of seaweed were grown over the years.

AUTHORS

Iskander Bond, Research & Technical Specialist

Iskander completed a BSc in Applied Marine Biology at Bangor University that included a year working within the seaweed cultivation team at the Scottish Association of Marine Science. Iskander then went on to work in aquaculture at the Scottish Salmon Company.

Iskander took control over our farming trials in 2020, independently leading the last two growing cycles. He also has oversight of the majority of our technical systems relating to food safety, quality management and employee welfare. Iskander is the lead author for the majority of the report.

Peter Elbourne, Managing Director

Prior to co-founding New Wave Foods, Peter trained as a marine biologist and completed a BSc at Bangor University (dissertation on plants and animals that grow on seaweed) and a PhD at Newcastle University (dissertation on larval ecology). He worked in various sustainability projects after moving to the Highlands, on topics covering green travel, energy efficiency and local food production. Work as a sustainability consultant for Aquascot – a leading processor of Scottish salmon – evolved into business development in 2011. Research into seaweed commenced in 2012 and New Wave Foods was established in 2015.

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ACKNOWLEDGEMENTS

We worked closely with Stevie Jarron (Argyll Aquaculture) between 2016 and 2019, continuing to liaise on various projects in the following years. Our farming trials were undoubtedly catalysed by his unrivalled expertise on licencing, working at sea and pragmatic mindset on everything related to seaweed. Marine operations were contracted to Struan and Cameron Smith of Coastal Connection for the most recent growing cycles. Their range of vessels were ideal for our needs and the crew unwaveringly accommodating and knowledgeable. The staff of both the Scottish Association for Marine Sciences and Hortimare have also been invaluable sources of advice, thanks to their years of groundwork research and dedication to reliable seed supply.

Desktop research into seaweed aquaculture commenced in 2013. Many people within Horizon Seaweed – and the wider Aquascot Group – actively contributed to our farming trials and the authors acknowledge their collective efforts and influence over the last decade.

Maria del Carmen Busto Lope	David Lewis	Chris Nall
Hugh Coulson	Ed Ley Wilson	Dennis Overton
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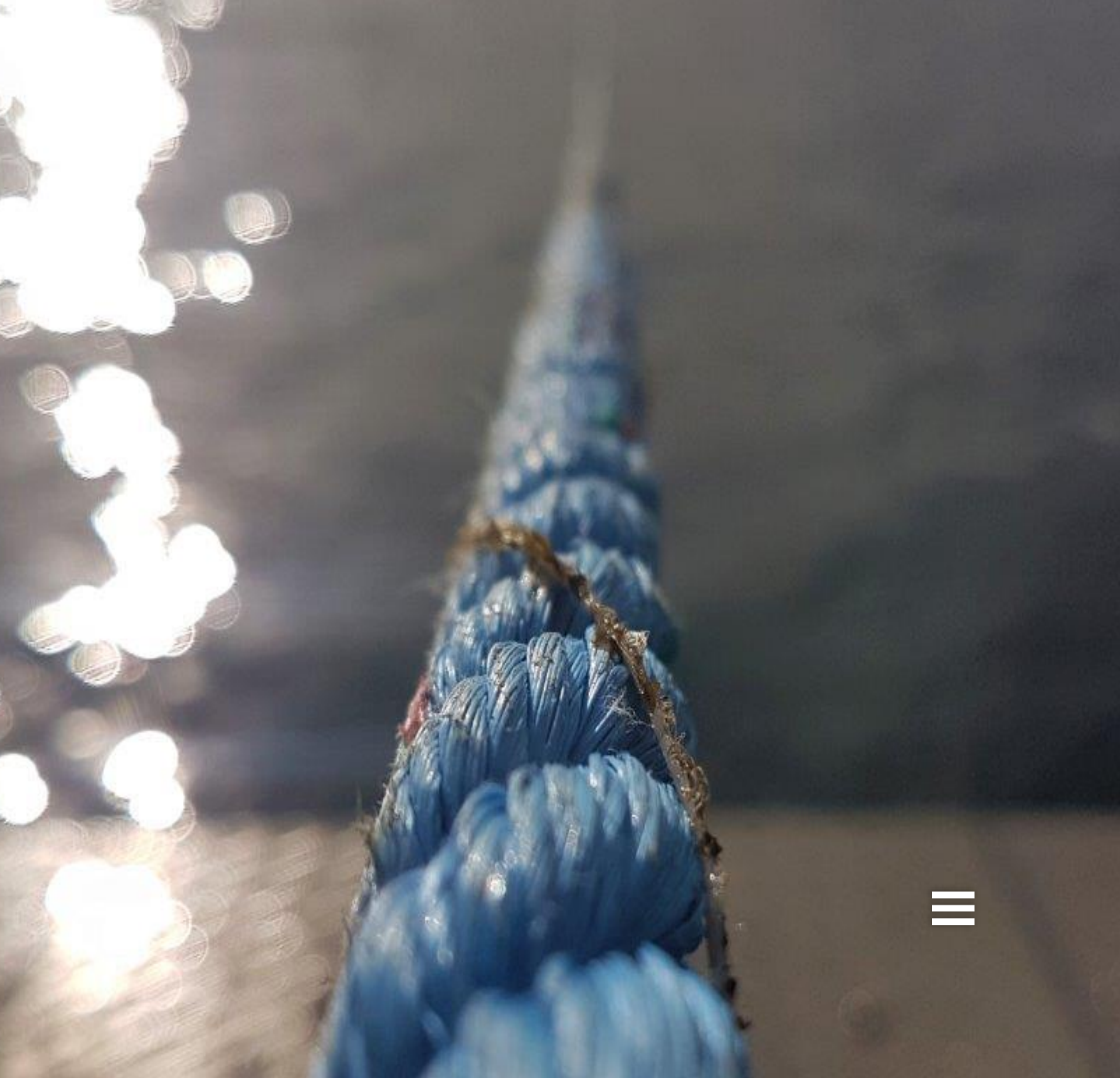
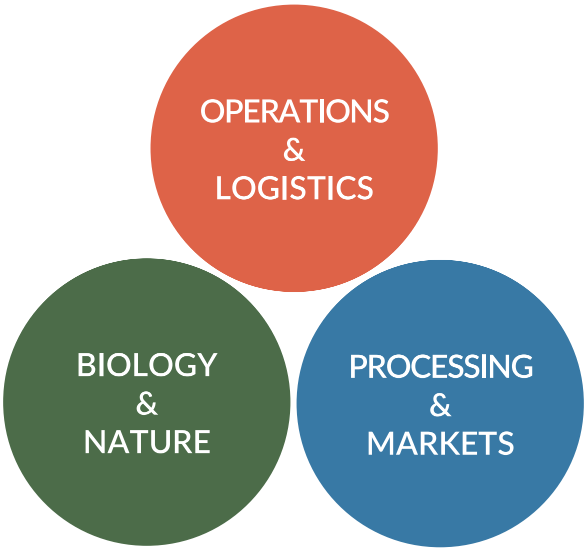
Stewart Harper	Craig Moffat	Lynsey Wilson
Fiona Harrington	Robert Murray	Simon Wrench

CONSIDERATIONS FOR COMMERCIAL FARMING



SOLUTIONS TO COMPLEX CONSTRAINTS



Our team dedicated years of concerted effort into seaweed farming and it is clear that there is no straightforward way to reach a successful commercial venture. There are various constraints that cannot be overcome in isolation. Some are natural limitations (e.g. biological challenges to control seaweed life cycles; working with seasons and local environmental conditions), some are specific to farming operations (e.g. efficient deployment and harvesting; handling fresh seaweed), some link to the downstream value chain (e.g. processing farmed seaweed into products required by markets).

We worked hard to identify simple solutions to these complex, interacting constraints. Ultimately, it is unlikely that there is any single solution that will enable scale and viability. Our approach was to trial methods and systems to reveal their shortcomings and potential for improvement.

DEFINITIONS OF SCALE

In discussing any aspect of seaweed farming, it is important to provide a context of the scale within which ideas are being applied. In reviewing the few definitions that have been presented elsewhere, the authors have not found a set that aligns with the perspective we present in this report. We will therefore define a set of scales based on specific quantitative and qualitative milestones we expect to be closely interlinked (presented in the table on the following page). The exact ratio between quantitative values have not been considered. An operation with two or more quantitative values in any one scale could be considered at that scale.

Scale	Total seabed area of all sites [a]	Total capacity for grow line	Annual harvest	Rough viable sales price [b]	Typical characteristics of farming operation
Micro	<10 ha	<1 km	<5 tonnes	>£5,000 per wet tonne	Small scale research and development. Limited commercialisation offering only supplementary income. Low degree of mechanisation if any. Practically all equipment is rented or shared.
Small	10 – 100 ha	1 – 20 km	5 – 100 tonnes	>£3,000 per wet tonne	More developed research and development. Limited commercialisation. Moderate degree of mechanisation. Equipment mostly rented or shared.
Medium	100 – 400 ha	20 – 150 km	100 – 1,000 tonnes	>£1,500 per wet tonne	Developmental. Semi-commercial. High degree of mechanisation. Owns most equipment, some rent or share agreements.
Large	>400 ha	>150 km	>1,000 tonnes	>£1,000 per wet tonne	Semi-developmental. Commercial. High degree of mechanisation. Owns most equipment, infrequent rent or share agreements.

[a] Total area of seabed licenced, allowing space for moorings and boat access, potentially over multiple sites;
[b] Indicative sales price for comparative purposes, not based on breakeven analysis.

Current regulatory definition

The Marine Directorate (then Marine Scotland) published the Seaweed Cultivation Policy Statement in 2017, which defines two scales of farm sites based on expected environmental impacts. Small – Medium sites containing 0 – 50 x 200m longlines are seen as unlikely to have significant impacts, whilst Large contain >50 x 200m longlines and are seen as more likely to have significant impacts. These have anecdotally been based on contemporary mussel farming knowledge, as seaweed farming had not yet been practically commercially explored at scale in the UK. There were also limited studies on the environmental effects of seaweed farming at scale using practices that are being developed in the UK (Wood 2017). As of writing this report (February 2024), only three farm sites within the UK have deployed more than 10km of seeded line (50 x 200m). All these sites will most likely have only done so for at most two production cycles. It is possible that up to five other currently licensed farm sites will also cross from Small – Medium into Large scale production within the next five years.

The crossover point between these two scales represents ~30 to 80 wet tonnes of seaweed production per annum (3 – 8 kg/m yields). Based on our best knowledge, this volume will not be sufficient to achieve profitability without grant funding. A company of this size must either scale beyond and/or access revenue streams besides the sale of wet seaweed (i.e. research grants).

An important factor is farms crossing from Small – Medium into Large scale production being required to provide environmental impact assessments (EIAs) whilst gaining their license, often years before they will reach the production scale that requires them. An EIA for a single farm site in the UK could cost £50k.

In the opinion of the writers, lines should be drawn for when an EIA must be implemented. Then further lines must be drawn to determine the scope of an EIA depending on the plans specific to the proposal. This gives prospective farmers a clear framework to build their plans around, helping to reduce the uncertainty already faced by early scalers. However, the current regulatory definition exacerbates the cost of production challenges already faced by the author's definition of Small and Medium scale farmers. Unlike other industries, the seaweed sector does not yet have a large body of research to draw from or template for answering specific questions that arise during an EIA. Instead, early farmers must at best invest in research that will be of most benefit to later farmers who can use their work as a framework for themselves. Or at worst be unable to create an EIA that could feasibly demonstrate what would occur at a larger scale. The most recent studies on the subject are focused on determining the tools that should be used to measure the environmental impacts. They are also based on Micro to Small scale sites for a limited number of cycles. Whilst strategic partnerships between farmers and regulatory bodies can help alleviate some of this challenge, there are still significant costs involved that will deter early investment. The guesswork that has been used to determine where these lines should be drawn should be reviewed in the context of more recent studies, what can feasibly be achieved by early scaling farmers, and how the effects of seaweed farming compare to the concessions that have been given to other industries.

INTEGRATION WITH PROCESSING

Fresh seaweed has a low stability once harvested and removed from the water. It will rapidly degrade if it is not processed into a more stable state (e.g. dry, ensiled, frozen, chilled). This degradation can make the seaweed unusable for food within 48 hours. Beyond this time frame it is likely to degrade to the point where it is challenging to handle and transform it into a sellable product for any application. Without processing, an operation's ability to supply material, both out of season and to a less localised customer base, would be limited. A solution for a farmer would be to sell their crop within the stable time frame and have the customer handle processing, which is a proven solution many have found worldwide. However, regardless of the farmers involvement, for operations beyond the micro scale to be reached, some form of processing will need to be developed to handle the necessary quantities. Of course, this then connects into creating seaweed products to specifications for target markets. Our factory in Wick was designed as a food-grade operation, which allows access to a range of markets. However, many applications will of course take seaweed processed through a lower grade facility.

At any scale, the initial stabilisation of the seaweed will only be able to occur during the ~3-month harvest season. This can result in processing equipment being dormant for the remaining ~9 months of the year whilst adding to the seasonal challenges surrounding staffing. Processors will likely need to have alternative uses for their resources out of season. Some examples of this can be processing for other industries, shared space with farmers and value add processes to

stabilised seaweed stock. A few farmers in the west that have reached larger scales are utilising established processors that have alternative uses for their equipment. At the same time, farmers who are unable to utilise established processors – whether that is due to distance, mismatch of scale, and / or unique requirements – have taken on some forms of processing themselves. The details of processing are further discussed later in this report.

FARMING AT SEA

SITE SELECTION

Suitability for seaweed growth

Much work has been done to identify the key conditions that make a site suitable for seaweed growth. This include factors such as sea temperature, salinity, exposure, suspended sediment levels, flow rate and water exchange. Typically, historic data for many of these factors will not exist for prospective sites. Therefore an extend period of monitoring, or some inference using data for nearby areas alongside assumptions based on the site features, must be made prior to investment into a site.

- Sea temperatures are core subject of marine research. There are many stations recording, and models estimating, sea temperature online. A farmer may infer temperatures for their prospective sites using these tools.
- Imprecise salinity and suspended sediment levels can be assumed based on site features (i.e. proximity and magnitude of fresh water inputs). A degree of fresh water and turbidity can be tolerated by seaweed, however further consideration should be given to potential contamination and the intended end use for the seaweed (see Operational considerations section).
- Exposure is a factor that can be difficult to compare between sites, especially without lengthy experience of each site. This is also the most difficult to define consistently without standardised long term monitoring. A combination of average wind speeds, direction, and the fetch along clear seaward angles of approach to the site can be used to estimate relative exposure. Various websites can be used for this assessment. Some amount of exposure is beneficial to seaweed growth via the prevention of stratification and reduction in fouling organisms (e.g. via reduced settlement and/or increased dislodgement). However, greater exposure increases risks of mechanical damage of both the crop and infrastructure.
- Flow rate and water exchange are similarly characterised and can be broadly assumed based on charts of the local area and site-specific features. The kelp species farmed by the writers require at least a moderate flow rate and water exchange. These seaweeds have demonstrated tolerance of high flow rates in wild populations, with some of the highest quality seaweed being present in places such as the Clachan Sound. Whether seaweed farms could, or should, be in such high flow rate environments is yet to be determined. This is due to the challenges around seeding and possible effects on the hydrodynamics of these areas that might be of detriment to the environment.

Beyond determining these factors, a prospective farmer should still expect to have to validate whether a site is suitable for seaweed growth. This will come in the form of surveying the surrounding areas for wild populations of the species to be grown and performing trial deployments. The act of surveying the surrounding areas for wild populations will also be necessary for determining whether and where seed stock for the site can be obtained from.

Landing site

A landing site is any point where a farmer can load and unload their vessel. Identifying landing sites should be one of the first steps of selecting a viable farm location as they are a vital junction to the rest of the supply chain. The farmer will already have an idea of where they plan to operate and the following criteria should be considered when identifying viable landing sites.

- Continuous accessibility from sea is preferrable. Due to the timeframe constraints discussed later in this report, it is vital that all possible complications to these time frames are minimised. Ideally, a landing site will always be accessible from the sea, regardless of the vessel, tide, wind and other users. Having a landing site that can only be accessed during certain conditions or by certain vessels will create strain on the farming operations that will only become more pronounced with scale. Accessibility from land is just as important for the same reasons.
- Distance from the farmer, further processing, and/or end customers to the landing site should be minimised. A landing site that is several hours drive for the farmer is not conducive to the rapid response and frequent low intensity checks and maintenance required for efficient farming. Higher distances to processors or end customers reduce the reliability of being able to stabilise material within 48 hours of harvest. The west coast of Scotland has myriad islands with characteristics suitable for seaweed growth. If the landing site is not on the mainland, then ferry connections could create an additional constraint for onward logistics (e.g. harvests must complete in time for a lorry to meet a 5pm departure)
- Distance to farm site from land is also important. Additionally, in the UK, a higher level of qualification and vessel coding is required when going beyond 3 miles of a nominated departure point. This adds staffing requirements that could otherwise be avoided. Time and fuel for travelling long distances at sea also create issues.
- Proximity to working and storage area is helpful. As discussed later, space will be required to store materials and equipment year-round, with a further area required to perform onshore assembly of and maintenance work. Having a landing site as close as possible to these areas reduces the effort required to transport materials and equipment.
- Suitability for intended vessels and vehicles. Our small scale to date has allowed flexibility, but larger vessels and lorries will need more robust infrastructure.

For a scaled operation, the ideal landing site is a slipway and pier that can be accessed by the largest vessel available to the farmer during all times of year and conditions. It should be able to support the weight and movements of mechanical lifting equipment (telehandler or equivalent) and further transporting vehicle. It should be possible to unload materials and equipment and immediately deposit them in the working and storage areas. Recognising that delays can occur, the location should ensure that the crop will reliably travel a maximum of 48 hours to the facility where the crop will be stabilised. How far under the 48 hours will depend on the risks involved at the specific locations and tolerances of the farmer and processor. Considering the costs of haulage and low value per volume of wet seaweed, it would be most ideal if the stabilisation occurred near the landing site.

At the largest scales of operations, purchased or purpose-built landing sites are likely to be a viable investment as they are the surest way to establish all the points listed above. With the area for working, storage and processing being the main factors that can be challenging to find at existing landing sites. The exact scale at which an operation might wish to invest in such is subject to specific conditions of the operation, and so it is beyond the scope of what we can estimate.

Co-location with other aquaculture

Integrated multitrophic aquaculture (IMTA) is a popular topic amongst policymakers, researchers, and prospective farmers. By cultivating multiple species from different trophic levels in the same system, the complementary interaction between the species improves the overall efficiency and environmental sustainability of said system. Seaweed's functional position within IMTA is to extract excess nutrients from fed components, whilst reducing the acidity of the waters in the vicinity of the system. The yield of the seaweed is thereby increased by the excess nutrients, whilst other species benefit from the pH regulation. Initial studies on this concept are positive, demonstrating at least part of the complementary interactions can be fulfilled.

One of the primary questions to answer with such systems is to what scale each component should be at relative to the others to impart a significant benefit. Ideally, no one part would exceed the carrying capacity of the natural environment. For example, a question arises of how much seaweed is needed to be grown to offset a significant amount of the excess inputs from fed parts? Answering these types of question can ratify whether an IMTA system is working as intended, what would be a feasible level of increased efficiency and provide a model for how an IMTA operation could look.

Fossberg et al. 2018 case study

A component of waste from salmon farming is nitrogen, an excess of which under the right conditions can lead to upsetting the equilibrium of an ecosystem, possibly resulting in eutrophication. The nitrogen content of water can be a limiting factor in the growth of seaweed. Therefore, it can be of benefit to farm seaweed within the proximity of salmon farms to both remove excess nitrogen whilst improving the growth of seaweed. It could be further theorised that the reduced chances of localised eutrophication in low water exchange areas would also benefit the salmon (however this theory is not further explored in the case study).

A study by Fossberg et al. (2018) examined this relationship. The researchers documented the feed used, nitrogen released and biomass of salmon grown at a ~10 hectare salmon farm in Norway for twelve months. Then, during the five month period over which sugar kelp grows (February to June), the researchers deployed grow lines at locations with increasing distance to the salmon to monitor the growth of the seaweed. They recorded that, during this five month period, up to 1,500 tonnes of salmon was produced whilst concluding that 13.5 tonnes of excess nitrogen was released into the surrounding waters. The researchers estimated that a 25 hectare growing area for sugar kelp in the immediate surroundings of the salmon pens would produce 1,125 fresh tonnes of seaweed whilst absorbing 12% of the nitrogen released by the salmon farm. This amount of seaweed production would put an operation in the Large scale previously defined and so would represent a significantly sized operation on its own. The researchers go further to state that based on the reduced growth of seaweed further from the salmon farm from the more diffuse nitrogen, a 220 hectare area would be needed to produce enough sugar kelp to wholly absorb the inorganic nitrogen released by the salmon in these five months. This would likely mean near 10,000 wet tonnes of sugar kelp production, which is significantly more than all the sugar kelp currently farmed in Europe.

The absorption of nitrogen would only be for the five months when sugar kelp grows. During the entire twelve-month period studied, ~3,400 tonnes of fish feed was used to grow up to 3,000 tonnes of salmon. Only ~800 tonnes of this fish feed was used during the five months period. As the excess nitrogen in the water is a function of the amount of feed being used, and assuming that the relationship is always linear, 4.25 times more excess nitrogen could have conceivably been released during the whole year than in just the five months period. To achieve a mass balance of nitrogen release and absorption across the twelve month period studied would require the farming of ~40,000 wet tonnes of sugar kelp. The total hectare area of such production cannot be calculated based on the results presented in the study due to the gradient of lower growth of seaweed further from the salmon farm and upper limit to the density at which seaweed can be grown. Additionally, as the majority of the feed in these twelve months was used immediately after the growth season of sugar kelp, it is likely that the nitrogen from peak months would be too dispersed to impact the growth of sugar kelp in the following season. Further, such a practice of upfront growth of seaweed to extract nitrogen ahead of its input would substantially change the natural cycle of nitrogen in the surrounding environment. Levels would be unnaturally low whilst the seaweed is grown, then unnaturally high as the amount of feed used to grow salmon peaks. Simultaneously, the same disruption to the natural cycle of a number of other resources required by seaweed to grow would also likely occur. This all would invariably lead to transformative effects on the surrounding environment and break a precursor requirement of idealised IMTA by having a component exceed the carrying capacity of the natural environment.

Ignoring the infeasibility of achieving a one for one trade of the nitrogen inputs and outputs, a national scale vision for a nitrogen credit trading scheme could be considered. The calculations done here can be generously approximated as 13 times more seaweed needs to be produced than salmon across 100 times the area to achieve a nitrogen mass balance. In 2021, salmon farms in Scotland produced 205,393 tonnes of salmon across 140 sites (Marine Directorate, 2022). Assuming the salmon farm studied in Fossberg et al. (2018) is indicative of the average excess nitrogen generated by Scottish farms, this translates to 2.7 million wet tonnes of seaweed production required to balance the nitrogen influx (I,e, more than the annual production of South Korea, FAO 2024). Making various broad assumptions on salmon farm areas and stocking densities, a total of ~70km^2 of seaweed farms would therefore be required to absorb as much nitrogen as was added to the waters around Scotland by salmon farming in 2021. This level of seaweed production in Scotland may be feasible in the future, it is apparent that this volume represents an undertaking greater than that of the current Scottish salmon industry.

To re-iterate, seaweed farming is not a viable plan for nitrogen removal as the timing of absorption is not aligned with the timing of influx. Additionally, the efficiency at which nitrogen directly input from the salmon farms is taken up by seaweed will not be 100%. Further, there is every chance that any one other component required for seaweed growth will act as a limiting factor for such a scale of production being concentrated specifically around salmon farms. The removal of these scarcer forms of nitrogen and/or other components could negatively affect the local environment.

IMTA for the seaweed farmer

Polyculture of seaweed with shellfish was considered during our early trials, as a way to generate revenue from the operation prior to achieving reasonable costs of production for the seaweed. There are broad similarities between mussel farming and seaweed cultivation because both are based around growing on rope. While we had discussions with salmon farmers on collaborative projects, there are considerable challenges around working with large companies carrying out intensive aquaculture of high value products. We worked with several mussel growers in early years, which helped us consider practical objectives for scaling. However, we decided to avoid growing shellfish alongside seaweed for several reasons:

i) Our priority was to develop seaweed production. While shellfish could have generated revenue in early years, it was certain to divert attention from seaweed to some extent.
ii) Growth cycles are considerably longer for shellfish than seaweed, which would have lengthened commitments for trials.
iii) Any animal production would likely create complications for operations and scaling (e.g. licensing).
iv) The optimum location for seaweed production and shellfish production may not entirely overlap.

In the experience of the authors, the final point was shown to be the most important. Seaweed growth was relatively poor over multiple seasons at sites where seaweed was added to mussel licenses. It may be viable to co-locate in a more mature market, but it was challenging to see significant benefits in a development phase.

Conclusion on IMTA

Overall, it is likely that any co-location of seaweed with aquaculture in Scotland will be more successful with a mussel farming operation. Salmon farm effluent will result in improved seaweed growth, but this can come with contamination risk. This may create a challenging scenario for the seaweed farmer if the salmon producer uses it for justification to expand or exaggerates benefits of bioremediation.

		Scale of impact	
	Impact to Seaweed farmer	Co-location with mussel farmer	Co-location with salmon farmer
POSITIVE	Improved growth from nutrients	✓	✓ ✓
	Access to resources (equipment, labour)	✓ ✓	✓
	Growing space on vacant sites (readily exchangeable infrastructure)	✓	✓
NEGATIVE	Exploitation of inherent low environmental impact for bioremediation	-	✗ ✗
	Seaweed contamination risk	-	✗ ✗
	Conflicting ideal growth conditions	✗	✗

Wildlife and environment

The coastline and waters of the UK contains a wide range of wildlife, all of which can be placed on a scale of sensitivity to being disturbed by seaweed farming operations. The exact extent to which individual species could be disturbed depends on the specifics of the farm operations in question. Operations at all scales must consider the local wildlife and embed within their plans methods of minimising the chances of any disturbance occurring. The only viable mitigation method for more sensitive wildlife will be to avoid their habitats entirely. This can be done by adjusting site boundaries and splitting areas across multiple sites. Setting paths for vessels travelling to and from sites can also ensure habitats on route are avoided. For less sensitive wildlife there are a set of infrastructure design and management practices that can help reduced the chances of disturbance. A non-exhaustive list of those we consider possible to implement – and less often seen mentioned elsewhere – are below. A farmer could choose to implement any one of these if there are local wildlife who would otherwise be at risk of being disturbed:

- Set work schedules to avoid dates and times wildlife are active.
- Minimum standoff distances from shore for infrastructure and / or vessels to avoid interaction with land-based wildlife.
- Low footprint anchors reduce the possible impact on benthic communities.
- A policy of limiting the amount of noise during operations to only what is necessary.
- Staff training on how to notice signs of disturbance and how to avoid wildlife in the area (as we do for our operations in Caithness).

A prospective farmer should also be aware of the research that has been conducted exploring the possible effects of seaweed farming on the environment. This is to ensure that the plan and reasonings for their operations are both grounded and realistic. A good place for any farmer to start is the work published by Campbell et al. 2019. We discuss our outlook on some these points in the Environment and social effects section of this report.

Other marine users and social license

At any scale, improper plans for farming operations have the potential to negatively impact other marine users and the wider public. The current licensing process for farm sites requires the prospective licensee to account for all stakeholders needs before they are granted a license. It is the responsibility of both the licensee and relevant regulatory body to ensure that the requirements of all stakeholders are upheld in the details of the license and implementation of the farm site. Farmers should always engage with the relevant stakeholders at the very earliest stages of development, as there is not always a viable way to pre-emptively determine each stakeholders' requirements. As has been seen with multiple developments, if stakeholders are not consulted early enough it can result in negative responses to plans because they have been formed without their input. A community hearing about a project in a format that appears to show a fixed site selection and infrastructure has already proven to be a source of contention. If such a project were to have included communities from the start, some negative responses could have been avoided. This engagement should ideally occur before wider public consultation events.

Whilst early stakeholder engagement is important in determining their requirements, a farmer must still present a clear plan for stakeholders to comment on. Part of this plan should set out how the operation will mitigate the more commonly cited points of contention. Following is a list of some of these points and our outlook on them:

- Site locations should not significantly disrupt marine traffic. Some historic traffic can be seen using AIS data. Farmers should aim to supplement this data with knowledge of vessels not carrying AIS transponders. Site area visits, desktop research of local recreational activities and communicating with local communities provides a broader scope of local marine traffic information. Adjustments to site boundaries and splitting sites across multiple areas can help reduce the impact to marine traffic. In calm conditions, some shallow draft low speed vessels such as small dinghies and kayaks can be safe to navigate within the boundaries of a seaweed farm that uses the infrastructure we have worked with.
- Visibility of the farm site and any associated landing site should be limited to either infrequently visited areas or those already substantially developed. Site visits and area surveys with photographic mock ups of how a site might look can help. However, it can be a challenge to accurately portray the small buoys, that make up the majority of surface visible sections of infrastructure, when viewed from hundreds of metres away on the limited resolution of display screens or printouts. Locating near to or utilising existing infrastructure can make a proposal more appealing in this regard. Utilising infrastructure

components that are coloured similarly to the backdrop has been a mitigation method used across industries.

- Blocking productive fishing grounds should be avoided. Consultation with local fishermen is the most viable option of determining such locations. We do not anticipate that trawling can occur within the same area as a seaweed farm. We have experienced creels being carefully placed within the boundaries of our seaweed farm site without impeding work. We therefore anticipate that creelers and seaweed farmers can operate in the same areas.
- As discussed previously, all possibilities of disturbance to wildlife should be removed or mitigated.
- Interactions with local communities should be considered. Typically, reducing any deviations from the norm are desirable. Beyond this, a strategy for integrating with any stated community goals should be created, alongside commitments to utilising local services and workforce.

Offshore and windfarm co-locations

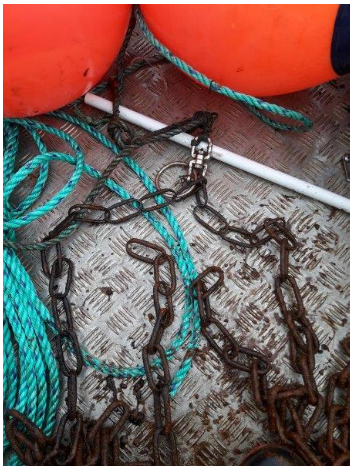
Seaweed farming operations at large scales will require more area of the sea than any other aquaculture industry currently being practiced in the west. Finfish and bivalve farming require less area than seaweed farming per unit of production. To avoid the difficulties surrounding other marine users and social licensing that using such areas could create, many see the future of seaweed farming as sites that are further offshore. The wind farm industry has reached similar conclusions for the same issues, leading to a natural expectation that seaweed farming could be co-located in these areas. However, there are a number of significant challenges and costs that will impact the viability of an operation intending to farm seaweed offshore.

As discussed earlier in this report, the accessibility of the farm site is of key importance to a viable farming operation. Ideally, distance from landing site to shore should be minimised to allow for frequent low intensity checks and maintenance of site infrastructure, whilst reducing the amount of time not either deploying seed or harvesting during the relatively short windows of opportunity for both. Wind farms that have been earmarked for co-location with seaweed farms in the Netherlands 18-77 km distance from shore (North Sea Farm 1). A vessel travelling at 15 knots (a high speed for vessels geared to work in the aquaculture industry) would take at least 40 minutes to travel to these sites, and over 2 hours to reach some of the furthest. This is without accounting for wind, tide, cargo, acceleration/deceleration of heavier vessels, speed/wake limits and operational best practices. Work arounds involving CCTV, drones, redundancies in the infrastructure, 24 hour staffing, higher efficiency deployment/harvesting systems and increased commitment of vessels could help reduce the burden of distance from shore. However, they all come with their own challenges and substantial costs that would otherwise not be required if the site were located closer to shore. Further, any one of these solutions could also be employed in making an operation with a site closer to shore more efficient.

Exposure generally increases with distance from shore, which will result in fewer days that can be worked at sea due to unfavourable conditions. Alongside the increased depth further offshore, a higher specification of infrastructure is required to withstand the harsher conditions. This both increases cost and reduces the lifespan of components, resulting in a greater waste of materials. There are no discernible yield trade-offs that can be made by placing sites further offshore. In fact, with greater exposure there is a higher chance of both unsuccessful seeding, and dislodgement / mechanical damage to the crop, likely resulting in lower average yields.

A farmer intending to place a site further offshore might also find it challenging to identify wild populations that are local to the site. There will be a lack of proximity to substrates that have been naturally settled by the seaweed species to be farmed. It could become best practice to place unseeded infrastructure in such locations to create the substrate for natural settlement of local populations to both validate the suitability for seaweed growth and create a 'genetically local' broodstock. It might also become important to demonstrate that the creation of a population in a previously uninhabited area does not disperse reproductive material in a significantly different manner to the population that was the genetic source. This level of uncertainty and increase in both the costs and timescale involved in developing a site could deter some prospective farmers.

Materials management, storage and onshore facilities



With any approach to seaweed farming, there will be large quantities of materials that must be stored and managed. Appropriate processes for both are a fundamental part of ensuring deployments and harvests occur efficiently and will ensure the materials can be used for their maximum lifespan. Small scale operations should expect to have to handle low tens of kilometres of rope, and hundreds of buoys, whilst large scale operations could be handling at least hundreds of kilometres of rope and several thousand buoys. Every component will require some form of manual assembly before and during deployments. Thousands of individual lengths of rope will need to be measured then cut precisely, with more knots / splices made in them to specific standards. A quality control system will be required to ensure this assembly is performed as intended. Incorporating this into the maintenance regime discussed later can then help spot and correct issues before they become more severe, whilst providing feedback on points where quality control should be improved. Condition checks and onshore maintenance are required to maintain the stock of usable materials between seasons. Buoys and other items will require cleaning of wild settlement. Grow lines will need cleaning of detritus, with twine removed if used.

An area will be required for assembly and maintenance work to be carried out. With space for lengths of grow lines to be laid out and measured for marking where buoys or spacer bars should be attached. Appropriate storage facilities can extend the lifespan of materials. Plastic items such as ropes and buoys will deteriorate if left in the sun and metal components will rust if left in high moisture conditions. Organic material left on components can rot in damp conditions, creating unpleasant odour. Undercover areas that remain dry year-round are ideal for storage.

Operational considerations

There are many operational considerations when selecting a farm site besides those previously mentioned, and do not fit a previous section of this report. With the variable coastline of the UK, these factors can be the main drivers of the final local considerations for farm site placement.

- Very low depths (<5 m) are unlikely to be suitable places for seaweed farms in the UK. This is due to the species currently farmed not requiring intertidal locations, the inaccessibility for some vessels depending on tides, and likely disturbance of the benthic environments at these depths. However, with greater depth comes higher mooring specification requirements (e.g. longer and large diameter mooring lines) and associated costs. Deeper waters are typically further offshore (see Offshore and windfarm co-locations). Moorings below 30m cannot be serviced by a SCUBA diver. Drones, infrastructure designs and management alternatives can reduce the reliance on SCUBA divers, however they remain the most versatile and available tool for underwater works.

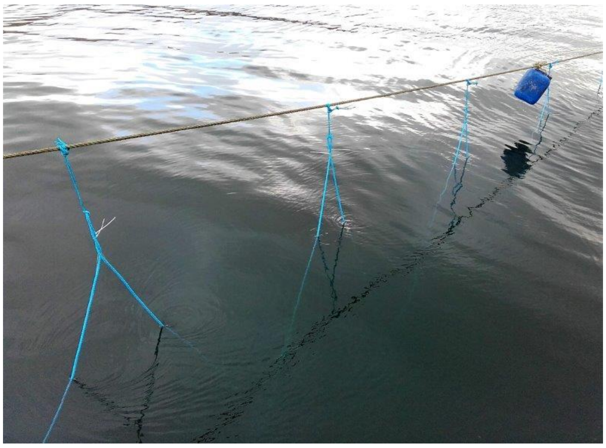
- The sediment type will determine what anchors can be used at the site and their effectiveness. Certain types of mud and sand will more firmly contain anchors than others. Screw anchors cannot be used with harder or looser sediments. Existing charts might not always appropriately depict these variations, making site surveys a prudent step before making assumptions about what anchors can be utilised.
- As discussed in the seeding and deployment section of this report, seed suppliers will hold stocks of seed from populations of seaweed species local to the areas of farms they have supplied. Establishing a farm within the scope of these existing seed stocks could avoid the need to obtain material for a new seed stock to be established.
- Having sites with different characteristics can be operationally beneficial. Overly sheltered conditions are unsuitable for quality seaweed growth, so some form of exposure is to be expected at any site. Having multiple sites can allow for some to be exposed to one direction, whilst others are sheltered to that direction and exposed to others. A cluster of such sites that can be serviced by the same landing point allows for work to carry on in a wider range of prevailing conditions. This helps to alleviate some of the uncertainty issues discussed later.
- Seaweed has a propensity to absorb contaminates (e.g. heavy metals, chemical pollutants) and harbour microorganisms. Farmers intending to sell their crop for uses that are sensitive to these factors (e.g. food, feed, cosmetics, nutraceuticals etc.) should consider the inputs of these that could impact their selected sites. Risk assessments for such should consider the land use in the vicinity of the farm, any water inputs, other marine industries, and local vessel traffic. Testing of local wild populations is a prudent step to take to help validate any assumptions, although this can be a challenge for intermittent sources.

FARM INFRASTRUCTURE

We have utilised several different infrastructure designs during our farming trials. Here we discuss each with regard to operations, rather than from the typical engineering perspective. This offers hindsight that is not always present at the initial design and engineering stage. It allows us to identify key operational constraints that can be overlooked or assumed insubstantial.

Retrofitted mussel rigs

Our earlier trials attached seeded lines to longline mussel farming rigs. Three methods were trialled, horizontal long lines, vertical droppers and continuous looped lengths, all at variations of depths and spacing. Entanglement issues were found when lines were not appropriately spaced in all three configurations, whilst most seaweed growth only occurred in a narrow depth range. As previously discussed, the areas where the farms were located had a water exchange and exposure that were less suitable for seaweed growth. These unfavourable conditions impacted the degree to which we could apply our findings to other sites.



Whilst these designs would be an appealing option for IMTA systems, early studies suggest that at least a 2:1 ratio of seaweed to mussel weight grown is needed for the seaweed to impart a benefit to the mussels (Walker, 2023). Our testing has concluded that these systems are not suitable for seaweed farming due to:

- The low length of grow line that can be attached to linear longline mussel rigs
- Poorer seaweed growth in a mussel farming location.

Sites where there is a higher level of exposure and water exchange would likely be more favourable for growing seaweed alongside mussels. To create an ideal IMTA system, there are several design choices that would need to be considered:

- Additional infrastructure installed to specifically grow seaweed on.
- Majority of infrastructure would need to be dedicated to seaweed growth.
- Entirely new designs that incorporate seaweed and mussel growing needs.

Grid

Ropes held at tension in a rectangle / square (grids) by an array of anchors at the corners are used by fin fish farmers to hold cages in place. Grids with sides beyond ~100m might use more anchors positioned midway along the sides to further secure them. Without the cages, grow lines can be attached to run in parallel along the length of these grids. Because of the established designs and installation processes of grids, this has been a popular option for seaweed farmers in the UK to date.

Appropriate spacing (the distance between each grow line) and tensioning of grow lines within the grid is key to utilising these designs successfully. Without appropriate spacing there will be entanglement between lines and a loss of both crop and efficiency in maintenance and harvesting. Without proper tensioning, there will be a similar risk of entanglement between lines. Furthermore, there will be potential for lines to sag to depths suboptimal for growth, necessitating more frequent placement of buoys along the line, which in turn increases costs and reduces deployment and harvesting efficiency. With higher tensioning, lower spacing can be used and, with wider spacing, lower tensioning is required. Higher tension is more challenging to work with as it requires more forces to achieve, in most cases necessitating mechanical aid. High tensions also impart a greater strain on components, which necessitates a higher specification (i.e. cost) to achieve the same service life. Achieving higher tension can also be further complicated by the interaction between grow lines. During deployment, the tensioning of subsequent lines can reduce the tension on lines already connected to the grid. The reverse is true for harvesting, where more tension will be put onto lines still in the water as lines are removed, making it harder to access subsequent lines.

A further operational challenge with these designs is the wild seeded communities that will grow on the components that are in the water year-round. Creating a rig that can hold a climax wild seeded community will invariably require higher specifications for the components. At the sites we have farmed, mussels and barnacles will establish themselves within two years on components that have remained in the water for the duration. The density of these species is far beyond that of seaweed and would have required a substantial increase in buoyancy to hold. Alternatively, spat settlement would need to be cleared at least once a year to avoid exceeding the specification of the design during harvest season.

The first rig deployed to our farm was a grid design, consisting of a 50 x 50m square and single screw anchors at each corner. The square itself was flanked on the north and south sides by a catenary system that is intended to distribute forces evenly across each line. Original plans were to utilise a 2m spacing between each 50m grow line, however it was found that even with mechanically aided tensioning, entanglement still occurred. Further testing using various spacer bars between lines proved impractical due to:

- Inconsistent prevention of entanglement
- Optimum solution would be high cost
- Spacer bars ultimately would reduce operational efficiency during deployment and harvesting.

Based on the challenges involved in properly measuring and creating new attachment points, it was decided that only alternate attachment points would be used, resulting in a 4m spacing being used on the grid. With hand tensioning, a single A0 size buoy was placed roughly halfway along each 50m grow line to prevent sagging below an optimal depth of ~1m. Reduced spacing halved the maximum length of grow line that could be seeded to this rig (from 1,200m to 600m) and, in turn, the annual harvest yield.

The catenary system used on this rig was designed to remain in the water year-round, which has proven to provide more space for wild settlement. Clearing fouling from the grid would take up to an entire working day utilising a vessel with a crane. Between the operational constraint of clearing the catenary system, and issues in general with deployment and harvesting rates using grids (discussed later), it is apparent this design is not commercially viable. Nevertheless, the grid is useful for experiments that do not require more than 50m of grow line per treatment.

Other grid type designs that utilise a catenary rely on the grow lines themselves to provide the catenary effect (rather than an ancillary system like ours). These designs rely on a relatively precise measurement of grow lines, and that each is attached to the right spot year on year. This is a feasible proposition for designs that utilise fewer different lengths. However, there is a more significant operational challenge for those with a greater number of different length lines, whether this is due to fitting more grow lines in a single rig and / or variations between multiple rigs. Lengths of grow lines are subject to change over their service life. This can be via creep, snapped lines being re-tied, and lines being cut for a variety of reasons. These factors cannot always be adequately tracked once lines after deployment at sea, due to the difficulty in identifying which line is being handled at any one time and an uneven distribution of creep across lines. Measurements can be taken during harvest to ensure lines remain the correct length, which can slow down harvest rates. Otherwise, measurements on land must be taken post-harvest to ensure the right lengths are used during the next deployment. This requirement to re-measure lines is true for most conceivable designs, however for catenary systems there is a layer of complication involved with the number of length variations that could exist. A mistake in this process of measuring and positioning will reduce the benefits of a catenary system.

Multiple longline

A multiple longline rig utilises two moorings and spacer bars to hold multiple grow lines in parallel. Without a permanent grid in the water, it is feasible for multiple longline rigs to have only their moorings in the water year-round. As most components are on land whilst the farm is fallow, both wild settlement is lessened and maintenance is simplified. Further, all lines have the same two attachment points to the moorings, which allows for easier access and tensioning of all lines at once. Spacing and tensioning are still important factors for these designs. In addition, the frequency of spacer bar units and the number / length of grow lines are critical. With lower tensioning and spacing, more frequent spacer bar units are required to prevent both entanglement between lines and sagging. The overall width of these designs is limited by the strength of spacer bars, as with a greater width there is more strain on these components. Additional lines added to a rig will therefore reduce the spacing that can be achieved. Longer lengths of grow line will also increase the risk of entanglement, requiring higher tensioning, more frequent spacer bars, and/or wider spacing.

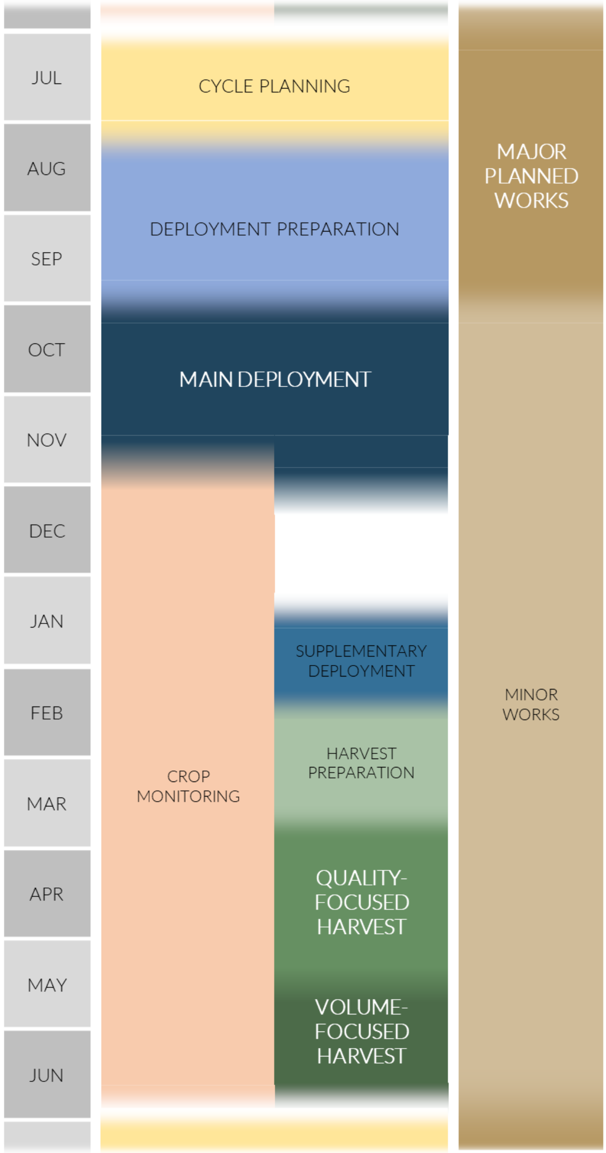
The second rig that was installed at our site utilised this multiple longline approach. Following the principle of reducing costs wherever possible, off the shelf components and minimal manufacturing was utilised in its design. Standard 6m length scaffolding poles with welded attachment points were used at opposite ends (rigid end spacer bars). The spacer bars along the rig comprised of 6m HDPE pipes with floats and chain to allow a degree of flex with wave action (flexible space bars). The flexible space bars performed well when using stainless steel chain, whilst galvanised steel chain was unreliable and degraded within two seasons. Unfortunately, both original rigid end spacer bars broke in the second and third seasons, causing the flexible spacer bars to collapse and lines entangle. However, the rigid end spacer bars could be replaced without excessive difficulty.

The first deployment was a rig with 600m capacity holding three grow lines of 200m length in parallel at 3m gaps, with flexible spacer bars every 20m. This appeared to prevent entanglement, but we recognised that tight spacing would be inefficient at scale. In later seasons, we tested the flexible spacer bar frequency and concluded that 45m spacing was suitable with 3m gaps between lines. In one deployment, we attempted to test a fourth grow line at 2m gaps to boost the line capacity of the grid. Despite complications arising from a snapped end rigid spacer bar limiting the knowledge we had hoped to gain on spacing impact on yield, we were confident in concluding that spacer bars every 30m was suitable with four lines at 2m spacing. Both our conclusions of frequency are based on the largest distances tested, so higher distances at the same spacing, or shorter spacing at similar distances could be suitable still. It is important to note that all lines were tensioned by hand. Mechanical tensioning would likely help retain intended spacing and improve durability.

In testing this rig, we found that end rigid spacer bars were challenging to handle and access once deployed because lifting one side required movement in all the attached components. Flexible spacer bars were easier to access as their joints would pivot as one section was lifted, reducing the overall load. However, flexible spacer bars would sometimes allow lines to flip over the top of others. This was more problematic in tighter spacing (i.e. 4 x growing lines at 2m gaps with shorter flexible spacer bar sections). Higher tensioning would reduce the chances of this occurring again. Overall, we concluded that a higher number of lines increases the challenge of working with this design.

PRODUCTION CALENDAR

While there will be variation year-to-year, there are clear phases of farm activity that form a growing cycle calendar. This is in the experience of the authors and relevant to our operations on the west coast of Scotland. There will be variability between locations. This includes both local variability between nearby sites (e.g. more exposure slows onset of fouling) and regional differences (e.g. earlier deployment further north as seawater temperatures cool). Any farming operation at scale will involve regular visits to farms during the harvest season, which is the time of year when close observation is required to monitor yield. The start and end of harvesting will always vary each year, with the weather over the growing season influencing speed of initial growth (determining opportunity to begin) and timing of fouling onset (the degree of which concludes the harvest season, depending on quality requirements).



Certain periods are emphasised to denote when operational resources must be focused on critical activity. Many activities will take place over lengthy periods. To an extent, it is an oversimplification to allocate a certain period to many phases because some preparation will undoubtedly be carried out year-round. It is likely any seaweed farming operation will be planning to scale up production incrementally. Therefore, deployment will need to be planned perhaps 6mo in advance to allow time for new infrastructure to go into the water (more than 12mo if the site is not yet licensed). Certainly, major maintenance activity should be scheduled over the summer when weather conditions and long days make it easier to work at sea.

This production calendar could look different were coppicing carried out and trimmed lines left to 'over-summer' for growth the following winter without new seeding. However, our experience over eight growing cycles indicates that fouling impacts during the summer means this is unlikely to be viable for commercial production at nearshore sites on the west coast of Scotland.

SEEDING

Seaweed life cycles

Seaweed life histories are complex, with a variety of cycles that go through various stages to differing degrees depending on the species. An exact description of the life cycles is beyond the scope of this report. The simplified version relevant to a farmer (for the species the writers have farmed), is that kelps have two life stages: the gametophyte stage readily grown in concentrated quantities in hatcheries and the sporophyte stage that grows into the adult forms associated with mature seaweed. During the process of seeding, gametophytes are converted to sporophytes and they attach themselves to substrates.

Hatcheries

The hatchery stage of production was not covered in this project, instead seed has been purchased from several different suppliers over the years. Therefore, the scope of this report will only include information on hatchery operations directly relevant to farmers. Currently, there are two main seaweed seed suppliers for European farmers; The Scottish Association for Marine Sciences (SAMS), and Hortimare (based in the Netherlands). Both have a strong history and proven record of supplying high quality seed and are highly recommended by the writers.

Currently, hatcheries will hold stocks of gametophytes for populations of seaweed species local to the area of farms they have supplied. This avoids the need to obtain new reproductive material from wild stocks each season, a process that can be costly and unreliable. The notice period for ordering seed is based on a hatchery's ability to propagate their gametophyte cultures to the quantities required and then induce transition to the sporophyte stage. Once this transformation process begins, it is both impossible to reverse and leaves a limited window of opportunity for seed deployment. The exact notice period and window of opportunity created are subject to vary depending on the processes of the seed supplier, which are constantly developing year on year. For the farmer, it is necessary to have as long of a window of opportunity as possible due to the uncertainty that can come with deployments.

Seeding technology options

Currently, there are two methods of seeding seaweed onto grow lines: twine and binder.

Twine method

The twine method is where twine is wrapped around spools before a mixture of seed is spread over the surface. These seeded spools of twine are then incubated in a hatchery whilst the seaweed grows out. Spools are removed from the hatchery and transported to sea in cool boxes that must be protected from the elements (to prevent excessive drying). The grow lines are then passed through the centre of the spool and a lead of twine tied on. Pulling the grow line further through the spool is sufficient to allow the twine to unwind onto the grow line. The diameter of the spool influences the number of turns and, therefore, the tightness of the rope contact. Our first trials used spools that were much wider than was ideal, creating the need to rotate the spool as the line passed through to gain a suitable tightness. This significantly slowed deployment rates. In later seasons, with discussion with our seed supplier on what was achievable at the hatchery, we began utilising 75mm diameter PVC

pipes as the spools. These have proven to be a suitable compromise between the hatchery's needs and achieving more turns per metre of grow line. Further reduced diameter could still prove to be the most favourable for the farmer, however this would require a hatchery built with longer spools in mind. To maximise the efficacy of the twine holding to the grow line, the twine should fall within the lay of the rope as often as possible. For this to occur, the twine must be wound onto the spool in the correct direction prior to seed being applied. Most 3-strand ropes have a counterclockwise lay. So, when applying twine to a rotating spool, if applied the twine from left to right the spool should be rotated counterclockwise. If the twine is applied from right to left, the spool should be rotated clockwise.

In earlier trials, we found no significant difference in yield when seeding twine onto several rope types, although this may be connected to the overall low success rate of those trials. Later, we selected ropes based on operational considerations of breaking strength, longevity, wear / creep resistance, re-useability, weight and handling. The exact requirements of each will depend on the size and makeup of an operation. Our requirements for grow lines on the multiple longline rig we discussed earlier were:

- A breaking strength of at least 4 tonnes (with scope to reduce that requirement with further testing)
- Minimum lifespan of 5 years, with a possibility of 10 if managed well
- Minimal creep and at least a moderate wear resistance
- A full 200m length being below 45kg (i.e. able to be safely lifted by two people).

For this, we have used the same ropes ubiquitous to the rest of the aquaculture industry (sold under brand names Seasteel and Polysteel). There has been no indication from other farmers or researchers that the crop would perform better on other off the shelf rope types.

After deployment of the twine to the grow lines, the holdfasts of the seaweed will grow into any grooves in the surface of the rope and around stray strands before encompassing the entire line. The initial attachment to the twine under benign conditions, and the additional growth achieved in the hatchery prior to deployment makes twine a reliable and effective method. However, the grow out stage requires temperature and light controlled conditions with filtered seawater and added nutrients. Whilst these are the same conditions that must be controlled for the year-round store of gametophytes, the twine grow out stage requires orders of magnitude more space to achieve, and for a short period of the year. This disparity in the supply chain is further discussed in the Scale disparity section.

Whilst there are nuances to the grow out hatchery stage and application of twine to grow lines, these are all be performed under controlled conditions with immediately verifiable outcomes. For example, if there is a failure of growth on twine in the hatchery, a new seeding can be initiated under different controlled conditions. Successful twine seeding onto grow lines is easy to verify: simply a tight wrap around the grow line. Because of the ease of testing and ability to test the hatchery year-round, reliable best practices of twine seed production are in place and being further developed where needed.

As growth on the twine is clearly visible, the farmer has some comfort that there are viable plants at deployment. Low coverage on the twine impacts end yield, with fewer individuals to grow there is a lower upper limit to the total yield. The lower intraspecific competition of the crop can allow individuals to grow to a larger size, which partially offsets this yield loss. Conversely, a high density on the twine may result in overcrowding of individuals, with less space for each to establish attachment points to the twine. This would result in more becoming dislodged as the line unspools during deployment. During earlier trials, growth was sometimes uneven on the twine in the hatchery, perhaps because of inconsistent seeding or imbalanced light. We occasionally saw grow lines that alternated between patches of minimal growth and full plants; this was most likely an effect of one half of the twine having a much higher density of plants at deployment. This bare line leaves space for growth of opportunistic species that will affect the harvest.

One of the main downsides of twine is the need to prevent it contaminating the seaweed harvest. As it remains on the grow lines through to harvest, improper seeding and harvesting can lead to fragments of twine remaining in the harvested material. Properly seeding lines ensures that the twine remains tight against the grow line, allowing holdfasts to form around both the twine and the grow line. By only harvesting the fronds, leaving the stipes / holdfasts, there is little chance for the twine to contaminate the harvest. Sometimes, either by improper seeding or twine snapping during the season, the twine can sag away from the grow lines. In these cases, some manual intervention is required to prevent the twine entering the harvest.

Almost all our twine was sourced from SAMS. Their proximity to our site was convenient when delays were incurred (e.g. poor weather). One growing cycle included twine from Queens' University Belfast, but logistics of delivery from Northern Ireland were challenging. There were also very small scale trials of twine supplied by Hortimare which grew well, but scaling that supply would have been a greater challenge with EU border regulations. On at least one occasion, a delivery of seed was delayed by customs for close to a week, by which time the conditions in the package had become inhospitable for the seed and a new set of seed had to be delivered.

Binder method

In brief, gametophytes that have been induced to to convert into sporophytes (seed) are added to a mixture of seawater and glue. Grow lines are then passed through this mixture, with the volume created calculated to match the length and diameter of the rope (ideally minimising waste at the end of the process). The seeded lines can then be stored for a short duration before being put out to sea. Roughly, a single litre of gametophyte culture, that can be held year-round, is enough to seed grow lines that will yield multiple tonnes of wet seaweed. If these gametophytes had been applied to twine to grow out, over 100L of hatchery space would be required to hold the seeded spools for several weeks. This difference in facilities required demonstrates how favourable the binder method can be for scaling seed supply (discussed further in the Scale disparity section). The process of mixing binder and applying it to the lines also has a few nuances.



The density of seed within the mixture and percent inclusion of glueing agent are two factors of control over the characteristics of the binder seed mixture. A higher density of seed will result in more seed material per metre of grow line, making a higher density of individuals settling across the line more likely. Excessively high density will lead to intraspecific competition and reduced growth of individuals. Lowe density will leave vacant space that will ultimately be colonised by wild settlement, which complicates harvests and reduces overall yield. The glueing agent typically comes as a powder that is then mixed with clean seawater to form the glue. The inclusion level of this powder will impact the viscosity of the glue. If too thick, a jelly-like consistency is produced that can form clumps easily pulled off the lines. If the viscosity is low, the glue runs off the lines and leaves very little behind. Whilst we theorise that slight adjustments to standard glue inclusion levels could be made to optimise seeding under various conditions (e.g. slightly higher inclusion to form a more viscous glue for higher flow environments), we have been unable to test this based on the difficulties mentioned later.

In a similar vein, the amount of the binder seed mixture applied per metre of grow line impacts the density of seed along the line. Although there is an upper limit to the amount of binder seed that any one rope can hold (depending on the diameter, material and construction of the rope), reaching that upper limit can be undesirable:

- Adhesion decreases further from the glue to rope interface
- The seed furthest from the rope in the mixture has a lower chance of reaching and then attaching to the rope before the glue is washed off (discussed later).

Too much binder seed applied per metre inevitably leads to wasted seed. The pictures below demonstrate a suitable coverage of the binder seed for the rope that we were using at the time. It was achieved by placing lengths of the grow lines into the binder seed solution, massaging the binder seed over the rope, then pulling them out through an O shape formed by forefinger and thumb. Whilst this ensures the correct application of binder seed to the lines initially, the seeded lines are sometimes then fed into a container for transportation out to site (rather than placed directly into the water). When doing this, the actual amount on each section of the line is subject to change based on its movement and points of contact with itself and the container. Winding the seeded ropes onto spools could help create a consistent impact and create a unit that is easier to transport and handle.



A further challenge with the binder is that the seaweed seed have yet to form their initial attachment points to a substrate. Unlike the twine method where the initial attachment has been made to the twine, the seaweed seed must make this attachment to the grow line directly. This is a challenge because the glue is eventually washed off the line. This is by design to prevent the glue smothering the juvenile seaweed, but also means that any seaweed seed that has not attached to the grow line will be washed off alongside the glue. The rate at which the glue is washed off will depend primarily on the movement of water at the site. Higher and more jerky movement will lead to glue being washed off faster. It is therefore important to deploy binder seed whilst the forecast predicts relatively benign conditions for the days immediately after. Whilst this can be a best practice for twine seeding too, the degree to which seed can be washed off the lines is far less for twine seed. This is one of the primary reasons why twine seeding is currently the more reliable option out of the two seeding methods. Further research into binder glue formulas and percent inclusion rates under a range of water movement environments are being undertaken but have yet to provide actionable best practices for industry. The limited seasons and sites for testing, challenges in applying lab-based learning, and inability to control in-situ factors can mean that experiments with binder seed can produce results from which conclusive evidence of best practices cannot be gained.

Seaweed seed settlement has been shown to vary in its success both in forming an initial bond, and then creating a strong attachment point, depending on the material it is settling onto and its configuration. The rugosity and water contact angle of the material are also important. has been found as key factors in this regard. This makes the selection of rope type for grow line an important factor in the success of binder seeding. Whilst the selection of twine type is important for that method for the same reasons, the seeding of twine is under controlled and relatively benign conditions, with lower additional requirements for the twine to conform to than the grow line.

Rope with a complex surface and deeper grooves provides a better area for binder to settle, allowing for a higher contact time and opportunity for seed to settle on the grow line. Polyester / polyamide blends in high strand configurations have worked well. However, this topic is likely the subject of the most development in the near future, and our findings are liable to not reflect the best options available. The same experimental challenge remains for developing these options. Besides the settlement success of seaweed, grow lines must also maintain the operational requirements previously raised. With bespoke seaweed farming ropes likely being the most optimal future option for binder seeding, questions arise over both the cost of development and the actual cost of production considering the relatively niche market.

One such bespoke example has been a ribbon developed with binder seeding efficiencies in mind. The fluffy surface, and high surface area to volume ratio ensures the maximum amount of binder could remain fixed to the line per metre without increasing the overal amount of material as much as rope would. This ribbon has been used for binder deployments in Europe in place of ropes. We saw this as an opportunity for rapid seeding; rolls can be easily soaked on each side to allow coverage of seed on each edge of the ribbon, which is not a viable option for a coil of rope. We trialled 50mm ribbon in one deployment, but our seeding was of limited success, leading to primarily operational learnings being taken from the trial. Knots in ribbon are harder to untie once tightened, leading to the need to either include rope at the ends for connecting to infrastructure or cutting the tied ribbon to detach. The cutting option severly limits re-useability, so the initial cost of adding rope is most desirable. Once cleaned and dried after harvest, the ribbon would not form back into its original shape or texture, limiting re-usablity. The design we trialled was not rated for a specific breaking strength, which creates risk if using it for lengths longer than 50m or in a structural role. Alternative designs could ensure a minimum breaking strength, however additional costs are likely to be prohibitive. Overall, there was little advantage in using ribbon and this was not pursued further during later trials.

We participated in some binder seeding trials with SAMS. However, the majority of our binder seeding used culture and protocols supplied by Hortimare, who have continously optimised their systems. The majority of deployments in some years were through binder, partly because it was easier to source smaller trial volumes. In later years our use of twine increased as we focussed on reliability of current processes, rather than optimisation of processes only relevant to future scales.

Despite the challenges, the benefits of the reduced hatchery capacity required, and relative rapidity ropes seeded on land can then be deployed on site, means that most believe that binder will be the future method of seeding once reliable practices are established. For smaller farming operations, and those attempting to scale their post-harvest supply chain, it is costly to lose crop through experiments to establish these practices. Without a substantial harvest, development of the rest of the supply chain cannot occur. It is likely that farmers will continue to primarily use the more reliable twine seeding method in the near future, before eventually pivoting to binder seed once they reach large scales where seeding efficiency optimisations have a greater impact on costs.

Scale disparity

Establishing a hatchery for a micro to small farming operation can be achieved affordably, requiring a modest budget of less than £5k. However, transitioning to sustain a small to medium scale operation introduces significant challenges and fixed costs exceeding £50k. These costs primarily stem from essential requirements such as water treatment systems, suitable location, lighting and stringent biosecurity measures.

At smaller scales, basic equipment and practices will suffice. Water collection can be managed manually or by simple pumps. Sterilisation of modest volumes of water can be done via tyndallisation and cheap mechanical filtration. Off-the-shelf temperature and light-controlled cabinets are readily available, although most are rated for a range that exceeds the needs of a seaweed hatchery. Pre-mixed nutrients can be purchased from specialised suppliers. Sterile work environments can be created using inexpensive still air boxes, and small equipment sterilisation options are available.

However, as operations expand into upper end of the small scale and beyond, these methods become impractical. Larger pumps are required for water extraction from the sea, necessitating more mechanical filtration, UV treatment and other water sterilisation systems. A holding tank will be necessary to ensure regular supply. Facilities must be outfitted with waterproofing, insulation and precise temperature controls, along with easily sterilised surfaces. While disposable plastic options exist, considerations for environmental impact may lead to the use of autoclaves for sterilising glassware. One area where cost savings can be achieved at scale is in nutrient supply, where it becomes financially viable to purchase nutrient components for onsite mixing. After these hurdles are overcome, it is a relatively low and linear continued investment for scaling to fill the capacity of the hatchery. Further investment would then be needed to expand the capacity of the hatchery.

The choices at these hurdles should be made with further scaling in mind and include items that might not see their full utilisation until the demand for seed grows. This creates a scale disparity within which there is unused capacity and a risk that demand is not reached during the lifespan of certain equipment. For operations that have invested in scaling their hatcheries, they must either sell seed at cost or take some loss to try boost the rate at which farmers may scale up. Until a substantial part of the capacity of the hatchery is being utilised, selling seed at cost is still unlikely to be at a price that is viable for farmers at any scale to pay.

This disparity is the current situation for farmers in the UK and possibly all other Western countries. Many farmers have created small scale hatcheries that are now facing that initial investment hurdle, without certainty that they will then fill their capacity. Alternatively, large hatcheries are now waiting for demand to pick up to a point where they fill their capacity. It is unlikely that farmers can justify the costs of entirely in-house hatcheries without also selling some seed created in their spare capacity to other farmers. There is scope for operations only focused on the hatchery work, overcoming the scale disparity by aggregating demand to their operation. However, both these approaches must also overcome the challenge of proving reliable supply to farmers. As an entire season is required to test a new source of seed, proof can take years to achieve.

Rates

For a day of deploying seed using a set amount of resources, multiple days will be needed to harvest and then process the resulting crop. For example, our multiple longline rig could be deployed within three hours at sea, utilising a landing craft and three staff. It would then take eight hours on the same landing craft and four staff to harvest. However, we would need to spread the those harvests across several days so as not to exceed the capacity of our processing facility. This arrangement clearly demonstrated to us that increasing the rate of deployments was less critical until we had scaled the rest of our supply chain. The points discussed in the harvesting rates section of this report could also apply to seeding.

Timing

When to deploy is a critical decision for a farmer to make year on year. They must base this decision on their experience of specific species at their sites and the forecasted conditions. The aim is to deploy as early as possible without risking the juvenile seaweed being swamped by biofouling. This allows the seaweed the longest time to grow before winter dormancy, giving it the best start when nutrients and light increase in early spring. Temperature is likely the key metric. As seaweed can withstand a lower temperature than many fouling organisms, once the temperature falls below a certain point the seaweed will outcompete anything else that colonises the lines. Alongside this point are the spawning times for fouling organisms, which whilst connected to temperature, are liable to vary in what species are spawning around or successfully settling on each unique farm site. This can mean applying knowledge from planting times at one site might not apply to another. For our Aird na Cuile site, the temperature drop occurs sometime in late September or early October (varying in exact timing year on year based on climatic differences). As previously discussed, some inference of this timing can be gained from freely available historic measurements and models. However, the most applicable method will remain measurements taken at site.

Uncertainty

Environmental conditions such as wind speed, swell, precipitation and temperature can make working at sea unsafe. Weather forecasts can predict these conditions to an extent, becoming more accurate at shorter range. This adds a layer of uncertainty to planning work at sea, which can be particularly disruptive for deployment and harvesting due to the few months within which they need to occur. All stages of the supply chain up to the point where the seaweed has been stabilised must account for these possible disruptions. Whilst delays to plans are likely the most common outcome of adverse conditions, there can be occasions where plans will need to be brought forward to ensure deadlines are met.

Seed deployed the earliest within the deployment months will typically perform the best, as is has had the longest time in the water to grow. Delays during seeding can therefore have an overall negative impact on yields. The window of opportunity to deploy seed can be shorter than the deployment season. This shorter window is determined by both the scheduling of the seed supplier and deployment method. Once beyond the window of opportunity, binder seed cannot attach itself to grow lines. Therefore, providing binder seed at any time in a deployment season requires multiple cultures of gametophytes in staggered timings, under the knowledge that some might not be used. Twine seed has a wider opportunity for deployment as the twine will hold the seed against grow lines for long enough that holdfasts can attach to the grow lines. There is still an optimum time that can be partially extended by reducing the nutrients available to the twine seed in the hatchery. Methods of extending windows of opportunity for seed deployment add substantial costs for hatcheries, which would likely be passed onto farmers.

MONITORING, INSPECTION AND MAINTENANCE

Throughout the production calendar, a farmer should expect to have to perform monitoring of the growth and condition of their crop, inspections of the condition of their infrastructure, and maintenance to correct the eventual deterioration of their infrastructure. A farmer will need to inspect and perform maintenances on their infrastructure at an intensity and frequency determined by their experience of the specific characteristics of their infrastructure and sites. The intensity and frequency of these tasks are described here to reflect the experience of the writers. Given our farming has focused on trialling different methods, the degree of monitoring, inspection and maintenance is relatively high compared to the amount of seaweed produced. Connections between infrastructure components are prone to wear, which is important to understand for scaling farm designs. Rapid identification of infrastructure wear or failures is paramount to prevent catastrophic loss.

Intensity and frequency

Inspection and maintenance of sites can be classed on a scale of Low, Medium and High intensity. The table on the following page summarises these scales, including examples.

Ideally, a farmer will perform a low intensity inspection of their site every day. Realistically, a farmer should aim to perform these a minimum of weekly and around any major storms. If issues are being frequently identified by low intensity inspections, this can indicate the need to increase the frequency of middle intensity inspections and a re-design of the infrastructure. Information gained from low intensity monitoring of a crop has little value (e.g. looking through the water in passing). As the crop is typically hidden below the water, gaining an accurate assessment of performance involves work that can only be described as middle intensity.

Middle intensity inspections and monitoring should be performed on a schedule that varies seasonally, with more frequent inspections around the deployment and harvesting. Fewer inspections, and no monitoring, is required whilst the site is fallow during the cycle planning and deployment preparation phases. The information regarding the crop that is available to the farmer is expanded upon in the Harvest section of this report.

High intensity inspections and maintenance should be planned during the major works section of the production calendar. A classic example is a mooring inspection. In an efficient operation, the work involved in monitoring a crop should not be of an undertaking that is comparable to high intensity inspection and maintenance tasks. Unless there is some form of research incentive where the required monitoring goes beyond the regularly required understanding of yield and basic crop condition.

Intensity	Monitoring and Inspections	Maintenance
LOW Incurs frequent minimal cost to the farmer to carry out.	Examples: a farmer casting an eye over the site from shore or in passing from a vessel. • Only likely to identify issues once they have become significant failures. • Unsuited for accurately monitoring the crop. • A scheduled event with minimum durations between each based on experience with rig and site.	Examples: retying loose knots and replacing worn rope. • Can be performed using on hand and unspecific materials. • Typically, either a simple fix, or a temporary fix until middle intensity maintenance can occur. • If being performed frequently on the same components, will necessitate a re-design of infrastructure and/or quality management.
MIDDLE Incurs moderate and regular cost to the farmer to carry out.	Example: a farmer spending a day on site lifting targeted sections of infrastructure or grow lines known to be either points of wear or representative of the crop. • On site inspections involving lifting of nearer surface parts of infrastructure. • Can identify issues before significant failures. • Suited to monitoring the condition and growth of the crop. • Should typically be prepared to perform some form of low or middle intensity maintenance at the same time. • A scheduled event with minimum durations between each based on experience with species being grown, rig, and site.	Examples: replacing missing buoys, snapped grow or infrastructure lines that can be retrieved without divers. • Requires more specific materials that should have spares in store. • Resets the infrastructure to as close to design spec as feasible. • If being performed infrequently on the same components, will necessitate a re-design of infrastructure and/or quality management.
HIGH Incurs substantial cost to the farmer that are irregular for maintenance and regular for inspections.	Example: divers performing an inspection of the moorings. • Ideally only for parts of infrastructure that cannot be accessed using resources owned by farmer. • Suitable for checking parts of the infrastructure that will slowly degrade over time where there is a large lag time between the first signs of wear and a complete failure (e.g. mooring chain). • Typically requires involvement of a third-party with specialist surveying equipment (e.g. divers, ROV). • Should be scheduled for months classed as for major planned works according to the production schedule.	Examples: retrieving displaced infrastructure components, mooring failures, sunken infrastructure. • Can require equipment that must be brought in from a third-party. • Materials are typically either kept in low quantities in store or must be bought in. • Even if failure occurs once, it will most likely necessitate a re-design of infrastructure to reduce or eliminate chance of failure happening again. • Includes deployment of new infrastructure. • When possible, should be scheduled for months classed as for major planned works according to the production schedule.

Monitoring yield

An assessment of the yield throughout the season is a necessary step in creating harvesting and processing plans. Without constant visual surveillance, a measurement of the entire crop is unlikely to be a viable method at even moderate scales. A farmer must judge their likely yield from selected samples. This section covers selecting the number of samples, the locations to take them from, and the metrics to use in the assessment.

The number of samples needed to gain a suitable assessment will depend on the variability across the crop, the range tolerance of the operations and the experience of farming specific species at a site. Fewer samples are required if the variability is lower, there is a higher tolerance of a wide range of estimates and with multiple years of farming experience to extrapolate from. Variability across the crop can be caused by:

- Genetics in the seed
- Differences in locations between and on sites as well as along each grow line
- Practical variabilities in seeding consistency, handling of grow lines and maintenance of infrastructure.

The tolerance to a range of estimates is dictated by the commitments to customers, ability to scale production, excess seeding to account for low yields and surplus customers that will take low quality material at cost on short notice. Ideally, sampling schedules should be more intense during the first years of operating at a site. Then, as data is collected for a site over multiple years, a farmer will begin to gain the ability to more accurately forecast their crops growth based on current state and expected conditions. Once an acceptable level of accuracy is achieved, the farmer can then reduce their sampling schedules.

As seaweed will be sold by weight, this is the metric for yield assessment. Using a kilogram per metre of grow line from the samples times the amount of seeded grow line in the water will gain this value. However, there is a challenge with the exact measurements that are taken. Taking one metre samples and weighing the seaweed is a reasonable method, but details of how that material being weighed was treated can have significant impacts on the estimate. Seaweed taken directly out the water will have a substantial amount of surface water. Most of this will drop off in a short amount of time and with agitation (e.g. onward transport). As the seaweed is held out the water, more weight can be shed as the biomass dries. This can lead to a one metre sample loosing roughly one third of the weight between immediately coming out of the water and being weighed several minutes later. The extent of the drying will vary depending on the weather conditions of the day. Moisture will be lost between the time seaweed is harvested and then delivered to a processing facility. A farmer should aim to keep a consistent approach to conditions under which their weights are taken, and adjust their estimates based on any variation to their approach. We discuss this moisture loss further in the Handling and shipping section of this report.

Drones and Remote Operated Vehicles

Drones or Remote Operated Vehicles (ROVs) can have a role to play in the monitoring and inspections of seaweed farms. Limited maintenance activities are also conceivable. At any scale, it is not feasible to monitor all parts of the farm on a regular basis. Sections of infrastructure at depth require the use of either lifting equipment or divers to inspect, both of which are expensive and not always available. Lifting lines to record crop condition and take samples for biometric analysis is time consuming and may not necessarily lead to change in plans for a season. If disease were to ever become an issue with seaweed farming in the UK, catching any outbreak as early as possible would be critical in limiting spread. As diseases can impact a small number of individuals before rapidly expanding across a farm, the degree of monitoring required to reliably catch disease outbreak early would be substantially higher than the monitoring required to gain an understanding of crop growth. As all these roles typically only require a visual assessment, drones and ROVs can be utilised.

Current off the shelf drone technology is already suitable for low intensity inspections. Aerial drones provide high resolution images of the layout of infrastructure. Polarising filters will reduce glare to aid observation of submerged lines. A farmer familiar with their infrastructure can tell from these images whether maintenance must occur. Although these images might not catch worn components before they fail, they can provide a suitable method of increasing the frequency of low intensity checks without needing to be at sea. Aerial photography can be combined with biomass sampling to gauge likely harvest.

Aquatic drones can reach greater depths than divers and do not require as much training or specialist equipment to operate. These factors increase the scope of mooring inspection programmes that can be achieved in house by farmers, both widening the area of seabed and frequency that mooring inspections can be undertaken.

More advanced and purpose-built drones and ROVs are being developed by a number of companies. Most include some form of image recognition software, automated drive and navigation systems. These innovations could significantly expand what monitoring is possible as it allows for a greater amount of data to be processed by fewer people, especially with increased utilisation of machine learning. However, these systems are currently in their early stages of development, with many critical practical challenges to overcome.

It is likely that purpose-built drones and ROVs will be an essential tool for large scale farming, where reasonably accurate projection of biomass will be important. A farming operation will need to know if they are likely to significantly deviate from their target, potentially bringing forward or delaying harvest accordingly. Sampling and direct observation alone will be impractical when farming 100s of kilometres of growing lines. However, new technology is less likely to be critical for the transition to small and medium scale seaweed aquaculture.

HARVEST

Methods

Harvesting seaweed can be broadly described as positioning grow lines at a point where the crop can then be cut into containers. The means by which the position and cutting are achieved as well as the details of the containers are variable. Ideally, positioning is mechanically aided, the cutting is fast and selective whilst the containers match the necessities of the remaining supply chain. A grappling hook on a rope is an affordable method to make initial contact with the grow line as it can be used to access any point without the need for permanent attachments rated for the maximum possible load. Claw attachments for cranes are used in South Korea and would be a worthwhile purchase for any larger farm operator from both an efficiency and health and safety standpoint. From there, the line can be lifted via crane and/or winch over a bar or roller that ensures the line remains elevated to a point that is comfortable for manual harvesting or fed directly into a mechanical harvester.

The container the crop is then harvested into can be the subject of much debate, with the ideal unit depending on a wide range of variables. While we started working with fish boxes and bags, we ended up using folding pallet boxes lined with food safe plastic pallet liners. This is due to the necessities of our situation, where the material must be kept food safe in uncontrolled environments (rental vehicles / third-party hauliers). We would also sometimes require a third-party haulier to transport the boxes from our processing facility to the landing site, for which folding pallets would take up less space and so cost less to have transported. We could also rely on mechanical lifting equipment at the landing site and our processing facility to move these large single quantities of seaweed. An operation without the need to pay per volume to transport their boxes might favour standard fish bins (e.g. 600L) due to their robustness and availability.

Timing

From deployment through to the end of the season, there are a number of stages that can be broadly categorised by the set of information known to a farmer about their crop, and the decisions they will need to make based on this information. A typical timeline of the knowledge and thought process is presented here based on our experience. The exact dates of each are subject to change depending on climatic differences across the years. For example, an abnormally warm winter and spring could speed up both the growth of the crop and onset of biofouling. Stormy weather and/or a heavily overcast early spring could slow crop growth. Further, variations across different locations can have localised influences that could also alter the timeline. For example, lower exposure sites have an earlier and more pronounced onset of biofouling.

October to Late November
Based on previous yields for each site, a farmer can estimate the total yield they will expect to harvest. For twine seeded line, an initial idea of growth coverage should be known by the end of this stage. Individuals can grow to more than 10cm length within this stage if the twine has had enough time in the hatchery. Binder seeded lines can have barely visible growth by this stage, with a biofilm forming around the lines.
December to Early January
Unlikely to see any substantial growth of the crop during this time due to limited sunlight and low water temperatures. Storm damage to the crop can occur, so regular monitoring should still be performed alongside maintenance checks during the limited hours of sunlight. It is possible to seed lines over lines that have had no growth up until this point. A moderate yield (~3kg/m wet weight) can be achieved from this under favourable spring conditions.
January to Early March
Crop should begin its exponential growth phase; however, this might not be noticeable without involved sampling. Yields will remain lower than what can be achieved later in the season. No harvest should be scheduled for this time, but a farmer should consider adjusting their harvest schedule based on the growth they see. Growth exceeding 50cm average length can be considered an indication of a decent end yield (>4kg/m wet weight). Atlantic wakame that has not grown beyond 5cm average length by this point will not produce a substantial yield (< 1.5kg/m wet weight). Sugar kelp can pull through from near nothing to moderate yields in the later stages of the season (~3kg/m wet weight).
Early March to Early April
Crop is rapidly growing with visible changes week on week. Biofouling is minimal, with none across the entire frond towards the end of this stage. Yield is at most moderate if there has been good growth prior to this stage. The yield is liable to at least double between this point and the end of the season. To harvest at this stage would require a customer that is willing to pay a higher price for premium quality than what another would for material that has been left in the water until later, Some components of the material can be found at higher yields during this stage, which could be valued by customers extracting high value components. Coppicing is possible, however the proportion of crop that is left in the water is higher than in later stages, so both yields and harvest rates will be very low coppicing at this stage.
Early April to Mid May
Growth of crop continues at fast rate, only beginning to slow towards the end of this stage. The end tips of the crop will become slightly fouled with epiphytes. This can be easily removed by trimming away during the harvest and is unlikely to represent a substantial amount of the biomass at this stage (<2%). The holdfast will be fouled with various species. It is preferable to separate the frond from the holdfast as two separate products. The holdfast can represent up to 20% of the biomass on the lines at this point. The crop should be harvested during this stage for the vast majority of uses. Towards the end the material can deteriorate to a point that it is unviable to harvest for most uses. By the time epiphytic hydrozoans appear, the crop has at most 4 weeks to be harvested before it has become too fouled to gain a harvest that is viable for most uses.
Mid May to Late June
The biofouling on the crop substantially increases across this time. The rate of seaweed growth compared to fouling growth becomes unfavourable. The most fouled parts are shed, causing the amount of viable quality material for harvesting to be reduced. The total biomass on the lines peak during this period, however this total biomass includes a high proportion of biofouling. Some end uses that are not concerned about a consistent product might be viable, however the rapid loss of biomass due to the shedding of fouled material will mean the window of opportunity to harvest at the peak biomass is short (~2 weeks).
July to September
The majority of what is left of the crop is rapidly shed at this time. Only fouling, holdfasts and some stipes remain. There is currently no discernible use for the biomass in this stage, and a farmer will likely lose money clearing the lines. Allowing some shedding to occur can help alleviate the workload, however this can also lead to more established fouling organisms that are harder to remove (e.g. mussels).

Rates

Any work done at sea involves substantially more costs than on land, so it is desirable to reduce the time spent at sea by more efficiently performing tasks. The rate at which a crop is harvested will be a large component of determining the efficiency of the days worked at sea. These rates are subject to much variation depending on the infrastructure designs, yield per metre of grow line, experience of the farmers, unforeseen complications, weather conditions and degree of mechanisation.

Accessibility of grow lines and ease by which one can travel along them are the key considerations of infrastructure design. Initial contact and setting up of a run along a grow line is time spent not harvesting, so should be minimised via ensuring the maximum length of grow line can be harvested in one go without having to do this again. Using our grid, the time taken to access the first part of the grow line, detach it, feed it into a winch and then starting cutting the seaweed could take as long as harvesting along the entire 50m length. Wind, swell, weight of lines and need to relieve pressure from both ends of attachment points would slow operations significantly. The multiple longline rig was in part designed to account for this difficulty, where a single event of detaching from the rig would allow us to run along hundreds of metres of grow line before needing to repeat the process. An alternative solution that other farmers have chosen is to use another vessel to make initial contact and detach lines whilst a primary vessel is harvesting. Although this is effective, it can often involve more of a manual element that is more limited to benign conditions. Cranes, winches/capstans and harvesting machines are all methods of improving the rate at which harvesting can be done. A crane improves the rate at which initial contact and setup of a grow line occurs. Winches/capstans improve the rate at which a grow line can be moved along to harvest the seaweed.

Whilst the yield per metre of grow line is of paramount importance for the viability of a farming operation, its impact on harvest rate is minimal. A 50m grow line bearing 400kg of seaweed will not take substantially more time as a 50m grow line bearing 200kg. Although the overall quantity of seaweed harvested in a timeframe is higher for the former yield, the total time taken to harvest the grow line is the same. This is primarily due to the rate at which grow lines can be brought on board being slower than the rate at which seaweed is cut from the line and packaged. This interaction of separate rates of the processes that contribute to the overall rate of harvest amplifies the impact of higher yields on the overall efficiency of an operation. At faster rates of bringing in the line, the limiting factor could become the rate that seaweed is packaged, in which case yield per metre will have a higher impact on the overall rate.

Additional buoyancy and / or spacer bars attached along the grow line slows harvest rates. As previously discussed, there can be challenges in accessing multiple longlines attached to each other with spacer bars. As each component is attached to the grow line with either a knot or clip, those must be accessed and removed during the harvest. This adds to the need to reduce the number of buoys and spacer bars in infrastructure designs. Larger vessels could make this process more straightforward.

Mechanised harvest

Increased mechanisation of harvesting is an obvious step to reduce costs. We never invested in a harvesting machine due to the lack of off the shelf designs, anticipated costs and complexity in developing one, as well as the relatively low biomass farmed. Therefore, we can only make comments on how mechanisation could compare to how we have harvested seaweed. The proposition of a harvesting machine would be to improve the rate at which seaweed is removed from the grow lines. As seaweed is easily cut with a moderately sharp knife, we have been harvesting by manually cutting the crop with a knife. The only strain of this approach is caused by the repeated movement. We recommend serrated bread knives for this task as they are the least likely to slip whilst cutting, do not typically have sharp ends and are readily replaced. This manual cutting can be achieved at a rate faster than the grow lines can be brought in by the typical winches and capstans installed on vessels. This means that for us to consider a harvesting machine, some form of incorporated winching mechanism capable of bringing in a line at pace would be favourable. Once larger scales are achieved with multiple grow lines harvested simultaneously, machines could present a more appealing prospect even without a fast winch mechanism.

Coppicing

Seaweed can grow back after being cut back to its meristem, just above the stipe. This allows a farmer to coppice their crop at an early stage in the harvest season and then re-harvest the same crop later. In the author's experience, comparing coppicing to a single harvest, there is no significant difference between the overall yields per metre. Harvesting a line at an early date to allow regrowth before harvesting again later or leaving that line to only harvest at the later date

sees no difference in overall yield. What coppicing can be used for is to harvest the crop at an early stage where quality is highest (i.e. biofouling is lowest) and / or there is a particularly high concentration of a desirable component. This leaves material on the lines later in the season to harvest for mid to lower quality uses, or for customers unconcerned about the concentration of the specific compound. With no overall increase in yield, the challenge of coppicing is the work involved in harvesting the same quantity of seaweed has been effectively doubled, as the farmer is travelling along the same lines twice instead of once for the same yield. Care must also be taken not to severely damage the plants during the first harvest (e.g. crushing of holdfast when taken over an elevated bar or roller).

The most appealing aspect of coppicing would be to leave the lines in the water to allow the crop to grow through the next season. This would avoid the need to re-seed lines. This form of coppicing has been demonstrated by Ocean Rainforest in the Faroe Islands and suggested as an important mechanism to reduce costs of production. Consistently, we have found a significant deterioration of plants during the summer months. There was heavy fouling by invertebrates, including mussels and tunicates. It is unlikely that this multi-season coppicing method will be viable at the farm sites we used, especially as the growth in the second year may well be a mix of species.

BIOFOULING

Biofouling is the unwanted accumulation of marine life on underwater surfaces. Typically, a biofilm will form on a submerged surface within days and this permits attachment of early colonising algae as soon as a week later. In under a month, larger animals will start to settle if their larvae are present in the plankton. Seaweeds naturally host a variety of sessile marine organisms, which are termed epiphytes when living on the plants. The unwanted growth of marine organisms is a significant factor in the success of a farming cycle. This is in relation to impacts on the farm infrastructure, complication in early growth, reduction in yield or slowing harvest.

Fouling of permanent structures

As previously discussed in the farm design section, any structure left in the sea will be colonised by marine life. Eventually, lines and buoys will be covered by large animals (e.g. mussels, tunicates) and unwanted algae (especially large brown seaweed). This will create additional load and drag on permanent surface infrastructure and must be removed periodically to avoid damage or sinking. In particular, the sharp edges of mussel shells will increase wear through rope.

Alternatively, the farm installation can be designed to accommodate the build-up of biofouling. Efficient clearing of surface grid ropes can be achieved by passing lengths through raised shackles, provided there are no other ropes tied along the length. Buoys must be lifted and scraped, with larger floats more prone to heavy fouling. Most biofouling removed from the infrastructure will sink to the sea floor close to the farm: it will not be viable to bring it back to land.

Growth on lines outcompeting target species

Any growth of non-target species will likely have a negative effect. Opportunistic seaweed species can start growing on newly deployed grow line, making it harder for the target species to establish during the crucial early phase. This is particularly problematic for binder seeding methods because the plants start at such a small size. The quicker early growth in twine deployment means that the plants soon reach a size where they can outcompete newly settled wild species. In our experience, poor early growth often saw lines taken over by Ectocarpus and similar species, although it was still possible for target species to grow to harvestable lengths. The time of deployment will also impact natural settlement, but this is only one of many factors to consider when planning a growing cycle.

Natural settlement of kelp

We regularly experienced substantial growth of furbellows (Sacchorhiza polyschides) on lines. Individuals reached 5m in length and over 1kg fresh weight in under 6 months, which is substantially larger than any Atlantic wakame or sugar kelp we grew. Sometimes individuals were mixed in with target species, but lines that were bare – especially from failed binder seeding, for example – were often covered in dense growth. This allowed us to include furbellows in some harvests, which helped us understand processing and possible future commercialisation of the species.

It is important to note that a mix of species along a grow line will hamper cultivation at scale, because automated harvesting will require manual sorting to achieve a consistent product. We often had oarweed kelp (Laminaria digitata) settle on lines, but growing relatively slowly compared to furbellows. This indicated to us that it would not be viable farm oarweed, especially given it is abundant in the wild.

Epiphytes impacting quality

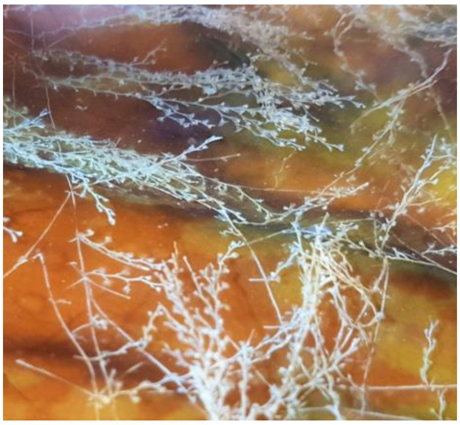
In our experience, epiphytic growth is more of an issue in sheltered environments. This is because there is less wave action creating random movement around the seaweed. A sheltered location may have high water movement from tidal flow, but this is a comparatively predictable environment. Seaweeds in sheltered habitats with strong tidal currents often carry a diverse array of marine life. Our wild harvest sites in Caithness are mostly semi-exposed, with none that we would consider sheltered from wave action. This was a deliberate choice to maximise the number of high quality plants and minimise fouling. Considerations regarding fouling are mostly connected to our experience at our Aird na Cuile site because it is where we saw vigorous growth and consistent patterns.

Hydroids

The first visible fouling would usually be hydroids (e.g. Obelia geniculate, Dynamena pumila), which would likely settle out on both Atlantic wakame and sugar kelp simultaneously. They are not a significant issue initially and we would usually process fronds with small patches of hydroids. Over time, the coverage increases and becomes more of a problem. However, this is usually when other epiphytes are more prevalent anyway.

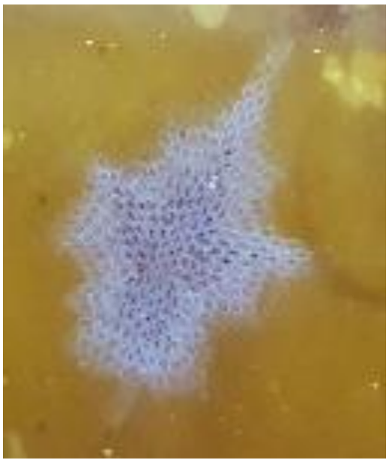
The tips of the fronds of Atlantic wakame begin to break down during April, leaving tattered ends that can be quickly trimmed off at sea. With growth from the basal meristem, it is the oldest part of the plant and so there is more time for epiphytes to proliferate. Sometimes this would be hydroids, but often small filamentous algae would also grow on the ends.



Bryozoans

Bryozoans (e.g. Electra pilosa, Membranipora membranacea) will usually start to appear in May and are a more significant issue because they form a calcium carbonate mat. This is both visible on end product and a textural problem, so presence of bryozoans would likely mean the seaweed could not be used in food applications. Colonies will eventually grow and cover large sections of frond and likely damage the underlying seaweed.


Snails and other larger animals

Settlement of snails is a significant issue for less exposed sites. For sugar kelp, Lacuna vincta is likely to be found during May. This is less of a problem for Atlantic wakame, but this species tends to drop away in quality during May anyway. In our experience, some crops of sugar kelp were rapidly colonised by Lacuna vincta in more sheltered locations (condition moving from harvestable to unharvestable within days). Although not permanently attached to the seaweed like hydroids and bryozoans, their size can make them a challenge to wash off. Barnacles will sometimes settle onto the seaweed in May or June, but in low densities so unlikely to be a significant fouling issue.

Mussel spat can settle onto the surface of farmed seaweed, which we did experience when growing in sheltered sea lochs in the vicinity of mussel farms. We occasionally found lumpsucker fish on the lines (Cyclopterus lumpus), but these wouldn't be considered epiphytes.

Ultimately, the issue of epiphytes are more pronounced in sheltered sites. By both selecting adequately exposed sites, and harvesting material before there has been substantial wild settlement will avoid most epiphytes. This is especially important for uses that can be sensitive to their presence (e.g. ensilage and acid extraction are complicated by the presence of calcium carbonate based shells).

HANDLING AND SHIPPING

Handling during harvest

Seaweed will likely dry out in warm, windy conditions. Similarly, harvesting during rainfall can leave seaweed sitting in freshwater. In contrast to the relatively short duration of wild harvest, farmed seaweed may be sat on the deck of a boat for 8 hours before reaching land. Both dessication and freshwater exposure can damage condition of the seaweed. In later years, we ensured all containers were sealed once full. This is easily achieved with large food-grade pallet box liners, designed with enough spare height to fold or tie at the top. Liners also reduce the likelihood of cross-contamination (e.g. from vehicles or improperly cleaned transport containers) and helped prevent damage to vans by retaining moisture at the bottom of the pallet box.

Harvests in early years typically used lined fish boxes (e.g. 75L). While commonly used in aquaculture and fisheries, they are too small for any reasonable scale and create an imbalanced load for onward handling.

A significant finding was the importance of achieving a reasonable packing density in pallet boxes during harvest. Inevitably, seaweed will compress during transport. Pushing down on the seaweed when a container is nearly full helps create space to add more seaweed in and, ultimately, improves density for shipping. This is particularly useful for sugar kelp as it is a light seaweed. However, squeezing the seaweed to fully maximise container volume should be avoided to prevent anoxia at the bottom (see Fresh product stablity section).

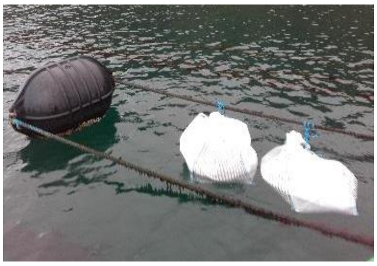
Onward transport

Transportation of fresh seaweed is critical to the success of a farming operation. A good solution for the farmer is that the customer organises and pays for uplift. However, a farming operation will benefit from control of onward transport. Considerable effort was invested in determining appropriate shipping methods during our farming trials. Fresh seaweed will likely only be accepted by hauliers in dedicated loads and not groupage (mixed consignments from different companies into the same load; also referred to as Less Than Truckload). Indeed, groupage is not practical for the farming operation as it requires more flexibility regarding uplift and delivery will be slower. There will also be fewer options in remote areas, although there may be opportunities to connect in with seafood hauliers. Moving the relatively modest amounts of seaweed we harvested and processed was awkward, because it was harder to find third parties with smaller vehicles of food-grade standard. We used a company in Oban for dedicated loads in a medium-sized refrigerated van. However, in later years we moved to shipping seaweed in pallet boxes using short-term hired vans driven by our staff. This had the benefit of complete control of movement from harvest to factory intake, including the specific handling required for loading and unloading. Most trips utilised the journey to return equipment such as containers to the Oban area. It also made it easier to isolate parts of batches reserved for processing trials at the factory.

Fresh product stability

Once removed from the sea, the seaweed species that have been farmed by the authors have up to 48 hours in temperatures of 8-18°C before the material degrades to a point where it is unsuitable for food use. This is judged by a sour vinegary smell and/or discolouration from a healthy deep brown to either light brown or any shade of green. This window is shortened with warmer temperatures, increased levels of fouling and higher packing density. Ideally an operation should plan to stabilise the material within 24 hours of harvest, the methods by which are further discussed in the Processing section of this report. Immediate chill storage will be helpful, but impractical on a small vessel.

Excessive packing density creates anoxic environments that leads to the more rapid proliferation of spoiling microorganisms. There is also greater force applied to seaweed at the bottom of the container, which may increase the amount of moisture lost. Although handling and shipping in large containers is convenient at scale, this will likely reduce the stability of the fresh seaweed. Containers of 250-300 wet kg are a reasonable compromise.



Road movement would ideally be with as large loads as possible, which may be beyond what is practical to harvest from a farm on a single day. Trials were completed in 2018 and 2019 on storage of cut seaweed in bags that were kept at sea. The condition of the seaweed remained high after 24h, as expected given the product was stored in almost the same environment experienced during recent growth. This method would have a higher risk of loss at an exposed site and there are clear inefficiencies in double handling material. Nevertheless, it is more straightforward than the equivalent seawater storage on land. Another reason for trialling this storage at site was to potentially fit in with hauliers that need to collect by the middle of a day: loading a trailer in an early evening may not always be viable in remote locations (e.g. meeting ferries).

Moisture loss during transport

Our earliest trials were inconsistent with regard to fresh weight at factory intake versus our expectations at point of harvest. As mentioned in the Monitoring yield section, there is little value to taking weights during harvesting because of the challenges of working at sea. Nevertheless, we were often disappointed by low intake weights. Over various trials where we weighed small volumes of seaweed at harvest and after transport to Wick, we would typically observe a weight loss of 20-40%. This was minimised in sealed bags, presumably because the conditions remained humid. However, in one trial we saw a difference of only 5% comparing sealed and unsealed bags. It is therefore likely that the transport conditions are an important factor, with more weight loss if a vehicle is warm. Liquid accumulating in the bottom of liners did not necessarily account for the weight loss: moisture appeared to be lost to the atmosphere.

Visual differences in seaweed sealed or unsealed during transportation were not consistent. One consignment of sugar kelp showed differences in weight between sealed and unsealed but identical quality. There appeared to be more noticeable effect on Atlantic wakame, with sealed farmed seaweed looking more like wild harvested when inspected by the factory team at Wick. On the rare occasion that seaweed was sent in sealed polystyrene boxes with ice, the quality was very good upon arrival. Despite the uncertainties around degree of moisture loss and change in quality, we strongly recommend transporting farmed seaweed in sealed containers.

One of the primary challenges of this weight loss is the impact it can have on the end sale of wet seaweed. A sale agreed on using a weight taken when loading a van could see that weight substantially reduced by the time it reaches a processing facility. Whilst there are conditions beyond the control of the farmer between harvest and weighing at a processing facility that could impact the amount of weight lost. Other industries have established practices for adjusting weights taken depending on the moisture content of the seaweed at point of weighing. However, there is currently no industry standard on how this should be carried out, or what the most desirable moisture content is for end sales. This moisture level will vary depending on the end user and their process. Driers could desire a lower moisture content so long as quality is maintained, whilst some extraction processes are facilitated by a relatively high level of moisture content.

HEALTH AND SAFETY

A system for ensuring the health and safety of staff is essential at any scale. All the knowledge surrounding the safe working of vessels at sea and mechanical equipment are gained during the process of obtaining the coding, certifications and licenses that are required for their use in commercial operations. The specifics of the health and safety systems we have had in place over the years could be considered a generic approach that all companies must follow (driven by i) overarching our Health and Safety Policy, ii) Risk Assessments compiled by knowledgeable staff familiar with the activity and iii) Safe Working Controls summarising key mitigation measures for training all staff). Based on our small scale and outsourcing marine and mechanical equipment operations to third parties, we do not consider this to be an area where our knowledge is transferrable to other operations. We therefore direct prospective farmers to find this information by contacting their relevant authorities.

PROCESSING

INITIAL STABLISATION OF FRESH SEAWEED

Stabilisation can be achieved in multiple ways that have been and continue to be explored in depth by researchers and industry. The author's primary experience is in drying and so this forms its own section. Here we consider ways to stabilise fresh seaweed: chilling, freezing, salting, fermentation/ensilage, pickling and pasteurization. This knowledge has been gained via combinations of trials, communications with experts and desktop research. All methods have their costs and benefits in terms of resource requirements, extent of stabilisation, extent of material transformation and market opportunities. However, these are not analysed in detail.

All considerations around stabilisation link to the challenge of processing the large volume of seaweed harvested in a commercial farming operation. Given the short season, it is likely that 15 wet tonnes would need be processed daily to handle 1,000 wet tonnes harvested each growing cycle. This is a significant step up from any farmed seaweed operation in the western hemisphere at present, but it is equivalent to volumes handled by processors of wild seaweed.

Delays to harvesting can result in significant disruption to processing. For processes beyond the initial stabilisation of the biomass, adequate stocks of stabilised materials can cover gaps in the harvest season and ensure processing resources are efficiently utilised. However, for the initial stabilisation step there is minimal leeway for holding stock. As discussed throughout this report, there is a short window of opportunity to stabilise seaweed for most uses. Key points when judging the various options include the speed by which this initial stabilisation can be achieved, the rapidity with which it can be scaled up or down and utilisation of equipment if there is no material to process. A higher rate of processing and scaling alongside low capital expenditure are most favourable for fitting into an uncertain time frame. As market demand ultimately dictates which process is most favourable, there is likely to be scope for multiple processes to be utilised to cover multiple eventualities. For example, drying capacity can be a challenge to scale up or down, with significant capital and time required to scale up and a minimum threshold of biomass below which performing a production run is not viable. However, dried material has historically been the most in demand due to its wider range of uses and long shelf life.

A delay to harvesting can cause there to be a lack of material to dry. When harvesting can recommence, the farmer must still harvest the same amount but now in a shortened timeframe, possibly leading to an oversupply. Harvesting large volumes in the lead up to forecasted unfavourable conditions could extend the days in which drying may take place, especially with chill storage to prevent deterioration. However, refrigeration has a similar scalability issue to drying and represents a substantial capital investment that could sit dormant throughout a season if its primary role were to only cover delays as described. Freezing is a similar prospect but at a higher cost. Ambient conditions ensilage / fermentation are promising prospects that could require minimal investment once the initial R&D hurdles are overcome. However, alternative customers would be required to take this transformed material.

Washing and blanching

Washing or blanching with just fresh or sea water alone is not a form of stabilisation, in fact it can reduce the stability of the seaweed by washing off natural antimicrobial substances. Washing is primarily done to reduce the chances of removable biofouling or detritus being present in the end product, making it a prudent step to take immediately prior to any further processing. Washing will not remove all sessile invertebrates, which are likely to be the earliest forms of fouling to appear. Our washing was not for a controlled duration. Approximately 5-10 wet kg would be tumbled through potable tap water for 20-30 seconds and either removed immediately or left for a further few minutes (e.g. if the following step in the process was delayed). Washing was always immediately prior to drying and not upon intake, because early research demonstrated negative quality impacts if washed seaweed was held for any length of time. Washing is standard in the food industry and can be readily scaled from batch through to continuous processes.

With sufficiently high temperatures and durations, blanching can be used as a method of killing microorganisms present on harvested seaweed. This will not reverse the spoilage effects such organisms can have, as the metabolites created by them are not necessarily removed. However, it can prevent the proliferation of these organisms during later processing (e.g. drying at low temperatures), or when used in certain applications (e.g. rehydrated after drying).

With the right combinations of duration and temperature, a wash / blanch can also reduce the naturally high iodine content of seaweed. Research into how these washes impact the other components of seaweed are ongoing, with initial tests demonstrating a variability in response depending on the species, time and temperature. Our research into blanching of our farmed seaweed was limited to basic benchtop trials because it was not required for our wild harvested seaweed. Introduction of blanching specifically for farmed seaweed would have created additional complications (processing, technical) for fewer than 10 processing sessions per year at trail scale. Nevertheless, blanching for iodine reduction is now widely recognised as important for ensuring sugar kelp can be consumed in reasonable quantities (e.g. greater than 1 dry gram daily).

Chilling

Cold storage was considered when designing our seaweed processing operations in 2015. Trials of holding unwashed wild seaweed at room temperature or chilled showed no significant difference in quality or microbiology over the first 96 hours after harvest (although there were negative impacts if the seaweed was washed in fresh water). Given the extra energy consumption and technical aspects of chilling freshly harvested seaweed, operations were established without any cold storage. Research indicates that chilling unwashed seaweed within

24 hours of harvest will extend the shelf life by up to a week. However, such timescales will vary according to the quality of the raw material upon harvest and some processes may need a quick turnaround to preserve target components.

Surface area to volume ratio is important for cold storage. Essentially, the centre of a large box or bin containing 250kg of freshly harvested seaweed will take a very long time to chill. The outside of the unit – assuming it is not insulated – will cool relatively quickly, but there will be minimal penetration of cold air. Much of the work we put into chill storage was for onward connection to freezing, which follows the same principles. Typically, fresh farmed seaweed was packed into food-grade plastic bags and then into crates each containing around 10 wet kg. This significantly increases the surface area to volume ratio, permitting flow of cold air around the product and rapidly lowering the temperature.

Icing was considered to help keep the temperature down during transport. However, meltwater will negatively affect the seaweed and sourcing would be an additional complication at scale. Salting alongside chilling is known to extend the shelf life to perhaps months, however the organoleptics of the seaweed are impacted and it may only be viable in small unit quantities (i.e. food retail).

Freezing

Freezing is commonly used to preserve seafood. This means that there is a wealth of knowledge and established facilities to connect into. We carried out many freezing trials on farmed seaweed, as well as on wild harvested seaweed. Freezing is an obvious logistical solution to the challenge of the farm harvest season being as short as 3 months. In a scenario where a facility aims to process 1,000 wet tonnes in a year, freezing allows quarterly capacity of 250 wet tonnes (e.g. 3-4 wet tonnes per day). If just processing freshly harvested seaweed then the facility needs to be significantly larger to process all 1,000 wet tonnes in one quarter (e.g. 12-16 wet tonnes per day).

However, blast freezing takes considerable amounts of energy and cold storage is more expensive than ambient. The issues regarding unit size and time for temperature reduction are even more acute, because freezing cycles need to be rapid to ensure the equipment is available for the following consignment. Our first trials used industry-standard fish boxes, each containing as much as 25kg of fresh farmed seaweed. The solid sides limited penetration of cold air and the centre was still above the target temperature of -20°C after 96 hours, even after attempts to increase airflow around the product. This duration is in no way aligned to a scaled process. Thereafter, freezing was completed in smaller crates with perforated sides, each with around 10-15kg of fresh seaweed inside food-grade plastic bags to prevent cross-contamination.

Controlled thawing is an important consideration. Similarly to the process of freezing, the outside of the storage unit will change temperature at a different rate to the centre. We trialled using tempering units designed to bring frozen product back to around 0°C through controlled airflow. If this process is not managed carefully, pathogenic or spoilage microorganisms can proliferate. However, the majority of our freezing trials were with Atlantic wakame transported from cold storage to our factory frozen and thawed on site prior to processing. The centre was not completely thawed by the following day, but the seaweed could be handled and washed prior to drying. This was not an optimised process, although it offered important proof of principle.

Thawed Atlantic wakame sometimes had a softer composition than the fresh equivalent, meaning that the fronds would more readily fold over each other and stick together. Another impact was a minor orange discolouration along the fronds, which was consistently seen in different batches. The cause of this was uncertain, but appeared to follow folds of bunched fronds. Both the textural and colour changes had no noticeable impact in the dried milled seaweed produced at the end of the process. However, frozen Atlantic wakame would retain a brighter green colour when thawed compared to chilled Atlantic wakame, likely because the latter would have started to oxidise.

Ensiling

A method to prevent decomposition of freshly harvested seaweed is ensiling, where water-soluble carbohydrates are converted by bacteria into organic acids under anaerobic conditions. Over time, the accumulation of acids reduces the pH of the seaweed and prevents the proliferation of spoilage microorganisms. Ensilage is a standard preservation method for animal feed and the first recorded studies of seaweed ensiling were in the 1950s. More recently, this preservation method has been a higher research priority given the clear opportunity to stabilise fresh biomass with relatively low cost in comparison to drying and freezing. This is particularly important when considering markets for seaweed that require a low cost of production (e.g. animal feed, biofuel). However, ensiling needs to be carefully integrated with end use as composition is affected (e.g. Yen et al., 2001; Larsen et al., 2021). While ensiling offers significant advantages, the method was not aligned to our existing food production operations and therefore was not trialled.

DRYING

Almost all our experience is in drying farmed seaweed because this is what our wild harvesting in Caithness is geared around. Our objective from the outset was to integrate farmed seaweed into a drying facility that would use wild seaweed as a raw material outside the farm harvest window. This format offers considerable advantages over others, including: i) precise size reduction for different applications and to increase density, ii) many years of shelf life at ambient storage, iii) efficient shipping without special haulage requirements, iv) flexibility between different markets. Of course, there is an energy cost and yield loss associated with drying, along with practical and technical challenges.

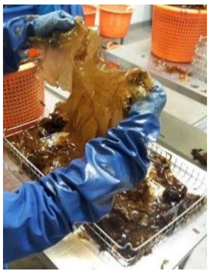
Drying at our Wick facility is a critical part of our business. While the same key concepts remain since we started in 2016, the process has been iterated considerably over time. This has led to significant improvements, mostly driven by year-round work on wild seaweed that has transferred to farmed seaweed. The continued importance of drying means that limited information will be shared to protect our working knowledge, instead focusing on our experience with farmed seaweed.

Quality of fresh seaweed

Importantly, we observed differences in the quality of Atlantic wakame we produced in our early and later years. While challenging to draw clear conclusions, individual plants tended to be shorter and thinner when grown on the leased shellfish lines we used in the first few years. Once we started growing at our Aird na Cuile site – selected for higher water exchange, full salinity and exposure – Atlantic wakame grew more vigorously. One individual would easily reach 3m in length at Aird na Cuile (vs 2m previously). More importantly, the plants were much broader (reaching over 40cm across). This morphology was previously only seen in wild plants growing in isolated patches on sheltered shores. Higher quality Atlantic wakame produced in later years was broadly equivalent to wild seaweed when handled in our factory. To a degree, this difference influences some of the conclusions presented regarding drying of farmed seaweed. However, wild harvested Atlantic wakame and sugar kelp are undoubtedly more challenging to process than other wild seaweeds.

Drying process at Wick

At our food-grade facility in Wick, freshly washed seaweed is spread onto wire racks. This offers an opportunity for inspection, more so than during washing as individual fronds are turned and moved. For farmed seaweed, operatives would typically look for fragments of holdfasts and non-target species (e.g. naturally settled furbellows amongst sugar kelp). Later in the season, fouling or tattered ends of plants would also be removed (although this would normally have been minimised during the harvest). Filled racks are stacked to be wheeled into a drying chamber.


An essential element to drying seaweed is the depth of the bed, whether through a batch process or continuous system. Many species of seaweed sit on a flat surface in a way that allows air to move around individual plants. Most wracks will cluster together but not form layers as they dry (e.g. air bladders in Ascophyllum help maintain gaps between fronds). Unfortunately, the farmed kelps have a flatter shape and create layers that trap moisture. This is a significant issue for drying, both in terms of cycle duration and risk of microorganism proliferation (some parts of the batch will be completely dry while adjacent fronds will still be damp. In our experience, wracks could be stacked at densities of 6kg per m^2 in our baskets and dry successfully. We would typically operate at a stacking density of only 3kg per m^2 for farmed seaweed to ensure effective drying. Obviously, a layout where individual plants are carefully spread to allow airflow completely around the product will permit rapid drying but is an extremely inefficient use of capacity. Turning seaweed during drying will obviously help expose surfaces, but this is labour intensive or difficult to mechanise.

Our seaweed is dried within chambers containing dehumidifiers and fans to maintain strong airflow around the chamber. At the end of the cycle, the temperature is raised to around 40-45°C. All our seaweed is dried to below a water activity (A_w) of 0.60, below which microorganisms cannot proliferate. Indeed, typically our seaweed is down to 0.30-0.45 A_w when removed from the drying chambers.

Once dry, seaweed is removed from the wire baskets. Again, this step tends to be more difficult for farmed seaweed. Typically, the stickier composition of farmed seaweed means parts of the fronds are more likely to adhere to the wire baskets than wild seaweed. This not only causes a small yield loss, but also complicates post-production hygiene. This led us to dry farmed Atlantic wakame on non-stick mats, which significantly reduced processing times. However, the quality of the plants generally improved in later years and the non-stick mats were less critical. At this stage, the seaweed is essentially in whole leaf format, but not in a consistent size. Our attempts to manage the size of fresh seaweed never provided efficiencies in handling once dry because fronds tended to stick together during drying. Indeed, a smaller particle size typically made the problem worse because there was increased layering during the drying process.

Other drying systems

We recognised at the outset that the drying capacity of our facility at Wick was small in comparison to the daily harvest volumes required to make farming commercially viable. Seasonally high throughput of farmed seaweed would not easily align with processing wild seaweed. Therefore, we explored options for contract drying, with the ideal solution being an industrial scale operation with downtime during the farm harvest season.

We trialled drying farmed Atlantic wakame on a continuous belt dryer. It applied air at around 65°C (heated by natural gas) over the product spread thinly onto a belt approximately 1.5m wide. It was a multi-layer design, meaning the wet seaweed was conveyed to the top and then moved down a series of belts to discharge at the base. This provides a rotation of the product during the drying process, helping to expose different parts to the warm air. Unfortunately, this design was ill-suited to drying farmed Atlantic wakame. The seaweed formed into clumps as it fell down to the belt below, which resulted in blockages and frequent damp patches within the batch because air could not penetrate. This is obviously a significant issue for a continuous automated system. The problem was likely exacerbated by the sticky nature of the farmed seaweed. Indeed, when wild harvested Fucus species were trialled on the same equipment there was no clumping and the seaweed was dried successfully (mirroring our experience at Wick that wild seaweed is generally easier to handle and dry than farmed seaweed).



A single-level continuous belt would overcome the inconsistent drying caused by clumping. However, the seaweed would need to be spread very thinly to ensure sufficient airflow over the product. Turning during drying would also be effective, although challenging to automate. There are a wide range of drying technologies available. Most operate only with large volumes because of the time needed for start-up and clean down, which meant the quantities of seaweed we farmed were too small for meaningful trial.

We never considered drying seaweed in on external surfaces or within polytunnels. This is partly because of the difficulty of maintaining food quality and safety standards in such environments. However, the critical factor is inconsistent drying conditions with uncontrolled temperature and humidity. This will result in unreliable drying cycles and would have been particularly challenging for scaling processing operations in Scotland. Overall, it is unlikely that such methods will be useful at any significant scale.

Yield from wet to dry

The yield of dry seaweed product from fresh intake is a critical factor for a successful operation. We have consistently seen a lower dry yield in farmed seaweed compared to wild. This is distinct from general patterns between species that are farmed and species that are wild harvested. The dry yield for wild harvested wracks is typically 20-25%. This varies between batches, with upper shore species harvested on a dry windy day often showing significantly higher yields. For example, our average yield for Pelvetia canaliculata is around 33%, but it ranges from under 20% to over 50%.

We saw a lower dry yield for farmed Atlantic wakame than wild Atlantic wakame every year. Across all our production to date, the average yield for wild harvested Atlantic wakame is 14%, whereas farmed Atlantic wakame is only 11%. This is equivalent to 21% less dry output for the same input, which is a significant extra cost element. This pattern was also seen in sugar kelp (wild: 13%, farmed: 9%), although this should be caveated by the fact that fewer batches of this species were processed over the eight years of operation. We came to expect a lower dry yield for farmed sugar kelp than farmed Atlantic wakame. Some seasonal differences were observed, but nothing significant.

Yield of Atlantic wakame [a]

Harvest year	Farmed	Wild	Reduction for Farmed
2016	8.3%	14.9%	-44.2%
2017	9.6%	14.6%	-33.9%
2018	10.1%	14.1%	-28.3%
2019	11.5%	13.7%	-15.5%
2020	11.9%	13.2%	-9.9%
2021	11.9%	13.8%	-13.9%
2022	11.4%	16.3%	-30.3%
2023	10.2%	13.5%	-24.4%
All years	**11.2%**	**14.1%**	**-20.6%**
	28 batches	227 batches	

Yield of sugar kelp [a]

Harvest year	Farmed	Wild	Reduction for Farmed
All years	**8.5%**	**13.2%**	**-35.6%**
	7 batches	12 batches	

[a] As dry output from fresh weight taken at factory intake prior to processing, not weight at point of harvest.

The reason for the marked difference in dry yield is unclear. We carried out no experiments to try and determine the cause. It may relate to loss of components during transportation. Yet this may itself also be connected to farm origin. Wild Atlantic wakame plants are exposed on spring tides, perhaps spending 10-20% of each year out of water. In comparison, the first time farmed plants leave the water is the moment they are harvested. This may result in changes to the composition that means wild plants are able to retain components better than farmed plants. There may also be a degree of drying for wild seaweed immediately prior to harvest as the plants are generally cut when exposed to the air on a low tide.

Initially, seaweed was transported from farm to factory unsealed because our research showed that fresh seaweed spoiled more quickly in sealed containers. Once we moved to sealed units, the condition of the seaweed upon arrival at Wick improved. However, it is difficult to dissociate this from the general increase in product quality as our Aird na Cuile site came into operation. Upon inspection at the factory, there was always a pool of liquid at the bottom of a sealed unit. This would be under 100ml when farmed seaweed was transported in smaller bags, but 10-20L would be at the bottom of a large container. The liquid was green/brown in colour and likely contained carbohydrates that may have been part of the dry output had they not been lost prior to processing.

It is important to recognise that moisture loss between harvest and processing is unlikely to provide an advantage regarding drying. Intuitively, a modest reduction in water content would mean there is less to remove during the drying process, but there are three points against this:

- In our operations – and in many processes – the seaweed is washed prior to drying. This will usually add water back to the seaweed.
- Materials dry in a non-linear manner. The first part of the curve sees a rapid moisture loss. This means any weight loss during transport would likely have been quickly removed during drying anyway.
- During processing, we often observed poorer quality in batches where there was a high moisture loss. This meant we prioritised minimising moisture loss post harvest.

Ultimately, it is important to make conservative assumptions about dry yields when modelling. We would expect a yield of 10% when processing batches, usually seeing Atlantic wakame come out slightly higher and sugar kelp slightly lower. This is a significant multiplier of cost to produce the fresh seaweed.

SIZE REDUCTION AND STORAGE

At our Wick facility, seaweed will almost always go through a degree of size reduction immediately after drying. Ideally, we would instantly take seaweed down to the particle size needed by a customer. This can be problematic as customer requirements can change. Moreover, milling to a fine size may be a rate limiting step that slows the overall process. Generally, we would take whole dried seaweed to a medium particle size, which is reasonably quick and offers further opportunities for size reduction if required.

Improved density for storage and shipping

Size reduction increases density, which is vital for well-organised storage. Almost all dried seaweed is stored in food-grade HDPE kegs with open top lids. Larger cuts will be stored in 220L kegs, but these become unwieldy when used for smaller particle sizes. Without implementing mechanical lifting throughout warehousing and processing, 30L and 60L kegs are better suited for storage.

Many of our customers require the seaweed to be packed into food-grade LDPE bags, because they take parcel quantities or want to draw down stock for their production. However, some customers are able to receive dried seaweed in the kegs we use for warehousing. This simplifies order preparation and the cost of the kegs is passed on.

Kegs will securely fit onto a pallet, although sometimes a degree of overhang is necessary. Packing into bags or sacks is the most efficient use of shipping unit volume. A pallet of fine milled Atlantic wakame or sugar kelp would be around 400-600kg (substantially less than wracks due to their lower density). Perhaps just 100kg of whole leaf dried seaweed will fit on a pallet. To date, over 95% of our dried seaweed sales have been milled to some degree, with whole leaf sales generally restricted to high value species. We have avoided supplying seaweed in large one cubic metre bags because of the lack of moisture control and risk of damage.

ORGANIC STATUS

We designed our wild harvest operation around organic principles. Our vision was seaweed for food uses and we recognised the importance of organic accreditation as mark of quality and sustainability. We achieved accreditation by Soil Association Certification (GB-ORG-05) in 2016, which has been certifying organic farming for over fifty years and is subject to inspection by the United Kingdom Accreditation Service (UKAS). All accreditation is under the company name New Wave Foods Ltd, with separate certification for wild harvesting production (AK25124) and seaweed processing (DM25124). All approved organic wild harvest sites around Caithness are listed on an information schedule; all species approved for sale and activities (e.g. processing, packing) are listed on a trading schedule. This approach would be mirrored for farmed seaweed: sites at sea and shore facilities will also need approval.

EU Regulations 834/2007, 889/2008 and 1235/2008 were the legal basis for the control of organic production, processing and labelling within the EU and were retained in Great Britain (GB) after 31st December 2021, as set out in The Organic Production and Control (Amendment) (EU Exit) Regulations 2019. Soil Association Certification have specific standards for seaweed production.

Constraints of organic standards

There are many general requirements for organic production that must be followed, including record keeping, labelling, separation and cleaning. These elements of the standards all need to be integrated into operational systems. This means written procedures, staff training and evidence of compliance. There are also higher requirements specific to the Soil Association standard that are above legal minimums (e.g. protecting human health, safeguarding the environment). While this is aligned with our wild harvesting operations, the seasonality and evolving methods of farming would have been more awkward for organic certification. However, the additional demands are not especially problematic.

Organic products exported from GB to the EU, Norway, Iceland, Liechtenstein and Switzerland require a Certificate of Inspection. This creates significant additional burden for both the seaweed producer and the customer receiving the goods, with both parties needing to register details of the consignment on the EU's TRACES NT system. In effect, this makes it harder for a European customer to source organic seaweed from GB and increases the likelihood of them sourcing within the EU. There are logistics solutions available at a cost and clearly efficiencies can be achieved with larger order volumes. Unfortunately, organic certification is often an essential requirement.

The critical phase for organic seaweed farming is the hatchery, which is treated as land-based cultivation for the purposes of the standards. There are two important restrictions relating to the use of fertilisers: i) producers are limited to using only nutrients listed in Annex 1 of the standard and ii) discharged seawater cannot be nutrient enriched. Boderskov et al. (2022) investigated the response of sugar kelp in the key hatchery phases to nutrient sources approved for organic seaweed production. Unfortunately, the performance of approved nutrients was suboptimal and it is clearly not ideal to rely solely on the nutrients naturally present in seawater pumped ashore. Given the relatively small amounts of artificial nutrients needed to produce many kilometres of seed for deployment at sea, these constraints could be seen as excessive. Indeed, the majority of the growing cycle is adhering to these principles because there is no additional input of nutrient applied by the farmer.

MARKETS

Given Horizon Seaweed continues to wild harvest, there is a limited amount of information to share in this section. For example, we do not provide commentary on which applications or sectors may be able to pay a premium to support the higher costs associated with farming. Our push on farming was driven by projected internal requirement for Atlantic wakame for food applications. This did not materialise to the extent where cultivation was necessary to fulfil demand.

Since operations commenced in 2016, around 5% of our sales by volume have been Atlantic wakame or sugar kelp. Where we have had interest for pallet quantities of these two cultivated species, organic certification was important and so these orders were fulfilled with wild harvested seaweed. It is possible that organic accreditation will unlock opportunities for farmed seaweed, but in our experience the critical factor has been the limited interest in Atlantic wakame and sugar kelp. These species are also being farmed on a larger scale in Europe and the efficiency gains allow them to be sold at a lower price than can be sustained by the modest volume production currently in the UK. We have sold pallet quantities of oarweed kelp (Laminaria digitata). This is a species that can be farmed, but these sales were at a price viable for wild harvesting and not sustainable for farming.

Challenges of selling fresh

As outlined in the shipping and handling section, there are logistical considerations when selling fresh seaweed to customers. Even if these are overcome, supply of fresh seaweed will always be seasonal, thereby presenting a processing challenge. Currently, quality farmed seaweed could realistically be supplied from Scottish farms between March and June. This short window might be extended in the future with wider species options, but it is likely to remain within 5-6 months. There are food applications that utilise fresh produce and, therefore, accept seasonality. In our experience, these markets are of limited scale.

To date, approximately 98% of our sales by volume have been dried seaweed. We have engaged in dialogue with many potential buyers who want fresh seaweed, extending to lengthy projects in some cases. However, the seasonality of fresh seaweed is difficult to resolve. Dried seaweed can be rehydrated into a form sufficient for many applications where fresh would be preferred. Importantly, farmed species can be supplied year-round if dried. We made little progress in selling frozen seaweed, because of difficulty meeting customer specification and cost of storage. Our research into freezing was directed towards thawing for drying to lessen seasonal bottlenecks.

Variable customer requirements

Many of the markets for farmed seaweed are nascent, which means that product specifications are not necessarily fixed. This makes building sales more challenging. Holding dried seaweed stock provides more options in terms of continuity of supply, flexible particle size and secondary processing. However, drying carries significant additional costs and constrains cashflow. Dried seaweed certainly provides the most options regarding markets because it is a conventional format for seaweed and is readily shipped.

ENVIRONMENTAL AND SOCIAL EFFECTS

The possible environmental and social benefits of seaweed farming have been some of the primary drivers of industry growth in the west. The potential for seaweed to provide a low impact source of nutrition and feedstock for higher value products has been an appealing message to present. Because of this, there have been many studies and opinion pieces created across published literature that explore many of these effects. These topics can and have been large reports in themselves, so covering every aspect in detail is beyond the scope of this report. We will therefore only discuss specific parts of the topics that we believe our perspective could add to the overall conversation.

CLIMATE CHANGE

There are several qualities of seaweed species that make them an interesting proposition for anyone looking at atmospheric carbon dioxide removal (CDR). The approach to utilising each characteristic can be mutually exclusive from another approach and the extent to which any one aspect can feasibly be utilised will be limited. From our perspective, these limits have often been understated in the information put forward in the past few years. Recently, a more realistic outlook is being presented, recognising that the majority of carbon fixed by seaweed is stored on a short-term basis. Only a small proportion of the carbon within seaweed is likely to be sequestered.

Replacement

Seaweed derived products can be used to replace products made from fossil fuels. Both plastics and biofuels are the most cited. There is a substantial economic challenge for these products to replace fossil fuel based ones at sufficient volume to significantly impact climate change. There is a further challenge in competing with other similarly low carbon – or even negative carbon - products. There are already niche markets for seaweed derived products that perform significantly better than fossil fuel based ones, thus justifying their higher price point. The prospecting of many seaweed species for such products is progressing in laboratories across the world. Scientific understanding is developing and it is fair to say that approach has yet to reach its full potential.

Unfortunately, seaweed farming does carry a carbon footprint, principally due to:

i) Use of fossil fuels by marine vessels (potential for hydrogen or electric powered boats, but this may be decades into the future).
ii) Use of materials for farm infrastructure (concrete, steel, plastic are all challenging to replace)

This is excluding energy use associated with the stabilisation of raw material, which will be essential to retain carbon within the seaweed. There have been recent estimates of greenhouse gas emissions associated with seaweed farming in northern Europe. Most of the work has been on sugar kelp, with cradle-to-gate emissions of 55-174kg CO_2e per tonne of fresh weight for farms in Sweden, Denmark and Ireland (Thomas et al., 2021; Nilsson et al., 2022, Zhang et al., 2022a, Zhang et al. 2022b). One study of Atlantic wakame farmed in Ireland calculated cradle-to-gate emissions of just 14kg CO_2e per tonne of fresh weight (Collins et al., 2022), but it is unlikely that the species is materially lower impact than sugar kelp. While the emissions for the fresh material are relatively low compared to conventional agriculture, the seaweed is then dried for most applications. This carries an energy cost and a dry yield multiplying effect (e.g. 100kg CO_2e per tonne of fresh weight immediately becomes 1,000kg CO_2e per tonne of dry weight, assuming carbon-free drying and a 10% yield).

The greenhouse gas emissions per tonne of seaweed produced in our trials was undoubtedly very high due to the small volumes grown. This will certainly reduce with increasing scale efficiencies to the point where dried farmed seaweed will have a low footprint compared to terrestrial agriculture. In contrast, there are no emissions associated with the growth of wild seaweed. While we use conventional vans at present for harvesting at Wick, a switch to electric vehicles powered by on-site renewables would mean practically zero impact up to the point of factory intake.

There are significant opportunities to displace intensive materials in conventional supply chains. Accurate life cycle analysis will be important in justifying the use case of seaweed as a low carbon ingredient or material.

Carbon shedding

The concept of seaweed shedding carbon that is then sequestered into sediment or the deep sea has been presented several times. Some amount of particle organic carbon (POC) is lost as seaweed grows out, but the majority of POC is shed as it dies back towards the end of its season. Kelp left on lines through the summer will degrade significantly. Both POC loss during growth and dieback represent a loss of yield for a farmer. Dissolved organic carbon (DOC) can also be lost during growth. The form this idea has been presented in is for either farmers to gain credits based on the shedding during the grow out, or non-farmers who have built artificial reefs to gain credits based on all the shedding. The methods of proving and then quantifying the carbon sequestration of these processes have yet to be developed. There are serious ecological questions over whether increasing the load of seaweed fragments in the deep sea should be undertaken. This will only be feasible to achieve in certain areas where transport to suitable areas of the deep sea reliably occurs.

Intentional sequestration

To overcome the limited reliability of letting seaweed naturally sequester, some have presented the idea of harvesting a crop to then sequester the biomass intentionally. This could be via sinking to the same or similar areas the fragments could naturally settle, or some form of burying on land. The sinking would pose as much of an ecological question as increasing the quantity of fragments. Transporting such quantities to adequate deep sea sites involves significant energy. Burying on land is a conceptually promising prospect if it can add value beyond the carbon. This would most likely come in some form of soil benefits for farmers and / or conservation. Pyrolysis transforms biomass into biochar, which fixes carbon. Seaweed biochar is an interesting feedstock (Roberts et al., 2015). The high mineral content has advantages (traces of potassium, calcium) and disadvantages (sodium), but will work well blended with biochar produced from woody material. Unfortunately, tens of tonnes of fresh seaweed are likely to be needed to produce one dry tonne of biochar. Therefore, it is hard to imagine a substantial market for such a carbon sequestering product without significant incentives.

Value to farmer

Overarching all these points is the fact that farmers must look to maximise the value they gain from their crop. All prospects previously mentioned will require cheap biomass to be successful, but what is the value of the carbon absorbed by farmed seaweed if traded as carbon credits? There are various assumptions that must be made to answer this question, to the extent that any scenario is inherently hypothetical. This is particularly the case when considering the amount of carbon to which carbon credits can be applied.

The price of one tonne of CO_2 in January 2024 was £50-£70 in the EU Emissions Trading System, down from a peak of around £90 per tonne in February 2023. The candidate kelp species for farming at scale in northern Europe are approximately 3% carbon by wet weight (sugar kelp, Atlantic wakame). Therefore, 1 wet tonne of seaweed contains 30kg of carbon at point of harvest. This carbon content converts to 110kg of carbon dioxide (x3.67). Even assuming the optimistic scenario of i) a zero carbon farming operation (i.e. 0kg CO_2e per tonne of fresh weight harvested), ii) 100% of the carbon content of the farmed seaweed qualifying for the credit and iii) the record high carbon price of £90 per tonne, the carbon credit value of one tonne of fresh seaweed is just £10. Scaling up to a large operation of 1,000 wet tonnes annually would yield the farmer around £10,000 of carbon credits. This is not a significant enough revenue stream to influence commercial strategies: it is inconceivable that a farmer could run an operation based on the sales price of carbon in seaweed alone.

1,000
WET TONNES
=
£10,000
CARBON CREDITS
IN OPTIMISTIC HYPOTHETICAL SCENARIO

There is also the question of who gains the credit for that carbon sequestration in the value chain. In the case of replacement, should it be the farmer growing the seaweed, the company that creates the product from the seaweed or the end user of the product? Ultimately the value to the farmer is likely to lie in the increased price achieved for an environmentally sustainable, low impact product than any carbon credit in the seaweed itself.

BENEFICIAL ENVIRONMENTAL EFFECTS

Bioremediation

As previously explored in the Co-location with other aquaculture section, seaweed can remove anthropogenic nutrients from marine ecosystems. Attention would need to be given to aligning the locations and timings of nutrient inputs to the seaweed growth season. A misalignment could result in nutrient inputs having an impact on the ecosystem before the seaweed growth is able to remove them, and / or the seaweed growth only removing naturally occurring nutrients from an unrelated section of the sea. Further, the impact on the composition of the seaweed itself and the end use of the biomass should be considered. For example, if seaweed were placed at the outflow of a sewage plant, there would be a higher risk of pathogenic microorganisms, meaning further processing would be required to ensure the crop is food safe. Indeed, such bioremediation scenarios may be prone to perception challenges that limit market opportunities. Additionally, many uses of seaweed are likely to eventually return those same nutrients to the environment.

Prospective farmers should search for opportunities to make use of anthropogenic nutrient inputs that could benefit their crop. As previously explored in Fossberg et al. (2018), there are real yield benefits from locating a site within the proximity of finfish aquaculture. The eventual scales at which a developed seaweed industry in the UK can reach are likely to impact the nutrient levels in our coastal waters. This can be of benefit where anthropogenic nutrient inputs are excessive. However, as an endeavour in and of itself, the model of farming seaweed only to remediate waters has yet to present an economic model that is more appealing than those that have higher value uses in mind. Whilst these higher value uses can temporarily remove nutrients from the ecosystem, many conceivable uses will result in them eventually finding their way back into the ecosystem on a timescale that makes its removal irrelevant for sequestration.

Habitat creation and ecosystem services

Seaweed farms provide habitats for a wide range of seaweed species. As outlined in the Biofouling section, over the years we have found on our infrastructure juvenile lump suckers, small crabs, brittle stars, tunicates, amphipods, bryozoans, barnacles, mussels, clams and a range of naturally settled seaweed species. In a similar approach to terrestrial ecology practices, many are looking to seaweed farming as a means to foster improved biodiversity and regenerative effects for marine habitats. To this end, there is a large body of research being built looking at the ecosystem services seaweed farming could provide. Although these studies are in the early stages of establishing best practices for study design, there are already indications that seaweed farm services are distinct from established wild kelp forests.

From our perspective, we can see several reasons for this outcome based on the approaches farmers might take. As previously discussed, components that remain in the water year-round will result in some form of wild seeded community establishing itself on them. Accounting for these in the initial infrastructure designs can lead to long term communities that will provide ongoing ecosystem services more similar to established kelp forests. However, this approach increases the specification to which designs are made and heavier individual components complicates access. These challenges can lead farmers to regularly clear their infrastructure of wild settlement, with the marine organisms falling to the seafloor around the farm. In these cases, the short-lived communities that establish themselves are primarily made up of pioneer species. These communities can still provide ecosystem services of their own, and it is a part of natural ecosystems to have these pioneer communities present in the wild.

The positioning of farm infrastructure within the water column differs to the typically benthic positioning of substrates in the wild. The substrates at farms (majority ropes) can be seen as a series of single dimensional lengths. Wild benthic substrates are typically spread across two dimensions with a higher variation of substrate types. These differences will select for different adaptations and so impact the end communities that can grow on each. Species without a pelagic stage in their lifecycle are only likely to interact with the anchors of a seaweed farm. They will therefore most likely be excluded from most wild settlement communities created by seaweed farms. Species that require flat areas and / or the varied benthic environments created by rocks and boulders will similarly be excluded.

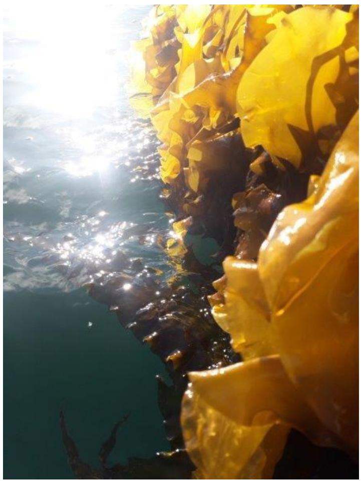
ADVERSE ENVRIONMENTAL EFFECTS

Nutrient removal

It is impossible to state the bioremediation capacity of seaweed without also recognising that this same propensity for nutrient removal can negatively impact the environment. Even within an area of high anthropogenic nutrient inputs, it is unlikely that the entire set of nutrients required by the seaweed are being provided by anthropogenic sources. Therefore, to varying degrees depending on the exact type and amount of anthropogenic nutrient sources, seaweed growth at farm sites must always rely on naturally occurring nutrients. This can place farmed seaweed in direct competition with wild populations of algae in the vicinity of the farm that also use those nutrients.

Although this can prove to be an adverse environmental effect, it should be noted that the question of scale must still play a critical part in this discussion. Combining the Fossberg et al. (2018) study calculations and the Marine Directorate definition of farm scales, the upper end of the crossover point from Small to Medium-Large (80 tonnes fresh seaweed produced per annum) would represent under 0.01 % of the seaweed that would need to be grown to absorb the excess nitrogen released by a single average sized salmon farm in a year. Using the definition of a Large scale we have provided in this report, the excess nitrogen output of a single finfish farm could support the growth of seaweed needed to sustain over nine times the number of large-scale operations (>9,000 tonnes fresh weight annual seaweed production). However, it should also be recognised that this is both only one specific component taken up by seaweed and one component released by finfish farms. It does not entirely account for what might be added to or taken from the natural environment.

Shading



The canopies created by seaweed farming prevent some light from reaching lower depths. These shaded areas could impact phototrophic species living below. The degree to which this effect can be negative will depend on the density of farm infrastructure, water depth and the habitats they are placed over. Most of this shading effect is from the seaweed crop itself. Therefore, it is limited to the end of the growth period, whereupon it is removed during the harvest. Whilst this limits the duration that shading occurs, this is also a critical time for most phototrophic species. Well-mixed nutrients and lengthening days create the same conditions for rapid growth in wild populations as it does for farmed seaweed. Limiting light during this period can prevent wild populations from making the best use of this optimum growth period. Habitats with light sensitive species should therefore be avoided as sites for seaweed farms. Specifically, areas above wild seaweed, maerl beds, and seagrass meadows should be avoided. Most research into shading effects of seaweed relates to warm-water cultivation of red seaweed in shallow lagoons: a markedly different scenario to kelp aquaculture in the UK.

Phytoplankton have also been cited as possibly being negatively affected by shading. The degree of this impact would depend on how long the phytoplankton will remain under the canopy of the seaweed farm. Higher water exchange and infrastructure spacing will reduce the time phytoplankton are impacted.

Plastic

The consistency, ready supply, longevity, versatility and costs of the plastic components of seaweed farming infrastructure are superior to the same components made from alternative materials. Some specific elements are better suited to metal, stone or concrete due to their density and resistance to wear. However, most components of seaweed farms will be made of plastic for the foreseeable. It is therefore inevitable that some form of plastic pollution will come from seaweed farming from i) direct loss of plastic items at sea, ii) degradation to microplastic, iii) the inefficiencies in disposal when recycled or not. The exact extent to which seaweed farming will contribute to plastic pollution is yet to be determined and will be subject to high variability between different approaches.

The estimated weight of various plastic components on our multiple long line rig is as follows: ~150kg ropes (including grow lines), ~80kg spacer bars, ~70kg buoys. Each of these components are expected to last five to ten years before requiring replacement. The yield of this rig is expected to average 6 wet tonnes per annum, i.e. 30 to 60 wet tonnes over the course of these components' lifespan. This translates to an average of 7.5g of plastic waste per wet kg of seaweed produced from the rig components, or at least 7.5 tonnes of plastic waste produced by a large-scale operation producing 1,000 tonnes of wet seaweed per annum.

The direction of our infrastructure testing has been to reduce the quantities of these plastic items. Smaller diameter ropes, fewer buoys and spacer bars placed at higher spacing between each would all substantial reduce the amount of plastic. Reusing each component also helps reduce the overall quantity of plastic waste. Longer lengths of rope can be cut to shorter lengths (e.g. retired grow lines can become buoy ropes). Spacer bars can be cut to shorter lengths and filled with concrete to use as weights. It would not be unreasonable to assume half the weight of plastic waste could be achieved whilst maintaining the same yield. This is especially the case for less exposed sites where components are subject to less wear and can be of a lower specification.

However, this calculation does not account for losses of components at sea. Large storms and sustained poor conditions can disrupt maintenance regimes and exacerbate wear points. Both of which can lead to broken infrastructure and components becoming detached and either sinking or floating from the site. Whilst inbuilt redundancies reduce the likelihood of this occurring, there will likely always be some losses due to human error and the difficult task of predicting natural movements at sea. Due to the variation in this route for plastic waste generation, we cannot currently account for them in our estimate. Single large scale failure events could create significant amounts of plastic waste. Simply increasing redundancy to reduce the likelihood of lost components increases the quantity of regular plastic waste created by components reaching the end of their service life. A balance of redundancy and risk must instead be found for each operation.

Recently, Crown Estate Scotland introduced a plastic reporting programme for all aquaculture companies. Operators should report their use of plastics at their leased sites, and the disposal methods they have used for any waste. Parts of these reports will be published for public viewing. These could act as a suitable method of comparing different production methods in the future.

EMPLOYMENT

Seaweed farming presents a promising number of employment opportunities directly to rural and coastal communities, with wider value to be gained across industries that can rely on seaweed biomass at scale. Due to the site selection and time to stabilise requirements previously discussed, it is likely that most work involved in farming and the primary processing of seaweed will be within rural coastal communities. Moderate to highly remote areas will be the most favourable due to the low risk of anthropogenic challenges. Much like other primary production industries, this can be a source of new capital being brought into communities that will help both sustain and grow their service industries.

Seaweed farming has an innate capability to be a sustainable venture. Utilisation of the existing skills of the established marine workforce of Scotland could bring another level of non-disruptive resilience to communities.

Credentials to work at sea

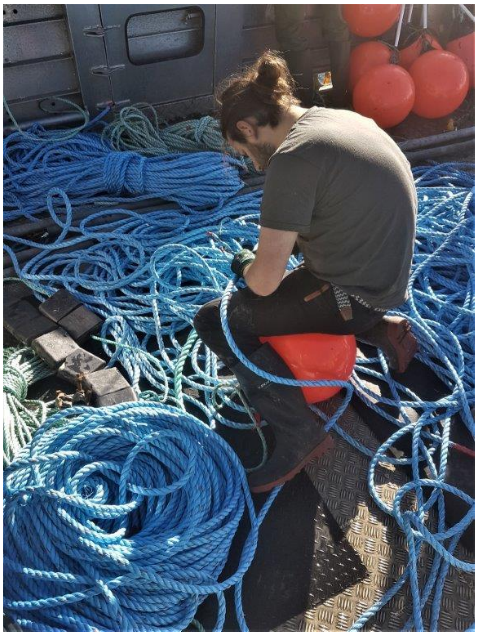
Working at sea is an innately challenging activity. Commercial operations require staff with a minimum of several qualifications to work at sea. The level of these required qualifications expands alongside the complexity and risks of the work involved. With Scotland's existing marine workforce, there is a population that can be drawn on with appropriate qualifications. This allows smaller farming operations to work with a wider pool of staff than in many other areas of the UK or Europe, potentially saving costs in early phases. Beyond a certain scale it is likely that providing the means for staff to gain these qualifications with the farming companies will be required.

Seasonality

Following the production calendar previously presented, there is a variation in the number of staff required to carry out each stage:

- The fewest staff are required during cycle planning and crop monitoring.
- Moderate levels of staff are required during preparation stages, with more needed leading up to deployment than harvesting.
- The most staff are required during deployments and harvesting, with more required during harvests due to the quantities of material being handled.

The high seasonality means it is clear employing a fixed team year-round will be inefficient. However, staff retention between growing cycles is essential for continuous improvement. At smaller scales, a minimum of one staff member should be familiar with working at sea and be adequately qualified to operate a vessel and associated equipment. The specific qualifications will vary depending on the size of vessel, types of equipment and intended operational plans. With larger scale operations typically needing more highly qualified staff to operate larger vessels, more complex equipment and under a greater range of conditions. Larger scales will also require more staff members with similar experience and qualifications. The type of work these full time staff will be expected to perform will change with the stages of the production calendar. Whilst the site is fallow, most work will involve onshore processes of resetting equipment for the next season. The best approach will be to have a small core team with a variety of skillsets and then recruit seasonal employees or contractors on an ad-hoc basis.



At all scales, farmers will need to be able to increase their staffing during busier times of year. This mirrors challenges we experience with wild harvesting in Caithness, because there are months where more harvesters are required. However, the difference with farming is that there are prolonged periods with less activity. This makes it difficult to train staff and build on that knowledge year-on-year.

Whilst a number of third-party aquaculture companies offer marine services, most are geared, costed and scaled for the salmon industry. We have found that working with third-party marine operators offers connections to a network of competent contractors. This was a better solution than our attempts to recruit a cohort of part-time employees to work on a flexible basis; invariability, their availability did not align with our planned deployment and harvesting.

Future scaling will undoubtedly require mechanisation of deployment and harvesting to achieve economic efficiencies. In our projections for future growth, we assumed increasing production without commensurate increases in number of staff. A farming operation employing 5 people (on a Full Time Equivalent basis; FTE) to produce 100 tonnes a year will not be viable if it needs even 20 FTE to scale up to 1,000 tonnes. It is more likely that efficient production of 1,000 tonnes a year will need to utilise fewer than 10 FTE, which clearly requires a level of mechanisation beyond current industry practice.

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