BLUE FORESTS

A review of carbon offset strategies with seaweed aquaculture – feasibility, current knowledge, and suggestions for future research

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Glossary

Macroalgae – Marine photosynthetic multicellular algae which fall within three broad groups: red, green and brown algae. Macroalgae inhabit the littoral zone from the intertidal to depths where light is still available. Also referred to as seaweeds.

Microalgae – Microscopic photosynthetic algae, generally unicellular and invisible to the naked eye, often discussed as phytoplankton which can be both pelagic (found within the water column) or benthic (living on the seafloor).

C – Carbon, **O** - Oxygen, **P** – Phosphorous, **N** – Nitrogen. Key elements referred to in the text and essential in nutrient turnover in the oceans.

Blue Carbon – The Scottish Blue Carbon Forum defines blue carbon as 'the carbon captured and stored in marine and coastal ecosystems that accumulates over long timescales through natural processes.'

MA – Macroalgal Aquaculture.

OC – Organic Carbon, the carbon component of organic compounds such and carbohydrates, lipids, proteins and amino acids.

IC – Inorganic Carbon, in the atmosphere is predominantly CO_2, in water there are carbonate ions and in sediments it can consist of calcium carbonate ($CaCO_3$).

POC – Particulate Organic Carbon, often referred to as detritus.

PIC – Particulate Inorganic carbon.

DOC – Dissolved organic carbon.

DIC – Dissolved inorganic carbon.

CO_2e – Carbon dioxide equivalent, often used when converting other carbon containing greenhouse gasses for example, methane (CH_4) into the relative mass of carbon dioxide. Also used when converting carbon estimates in seaweed biomass into relative CO_2 units.

LCA – Life Cycle Assessment

Executive summary

In September 2022, a group of international collaborators gathered from six European countries (hereby referred to as the 'working group') to take part in a workshop at the Scottish Association for Marine Science (SAMS), Oban.

The workshop was funded as part of Marine Scotland's Blue Carbon International Policy Challenge (BCIPC). The main aim of the workshop was to produce a document outlining the potential for carbon offset by macroalgal aquaculture. The discussions held at the workshop focused on various concepts and hypotheses surrounding carbon drawdown by seaweed aquaculture and the potential for mitigation of atmospheric CO_2. The key points of these discussions have been compiled into a policy brief which aims to highlight important areas for future research, uncertainties and challenges faced by the industry, policy makers and other stakeholders.

Multiple concepts are discussed in this report, but broadly the focus is on two main threads:

1. Growing and sinking seaweed biomass in its entirety to lock carbon dioxide (CO_2) away in the deep ocean
2. Mitigation of atmospheric CO_2 and reduction of CO_2 emissions through seaweed aquaculture of which multiple pathways exist from product and food replacement to biofuels.

The main concepts discussed were:

1. growing and sinking seaweed biomass
2. replacing/supplementing human food products with seaweed based products
3. replacing/supplementing agricultural food and fertiliser with seaweed based products
4. the potential for bioenergy produced by seaweed biomass
5. other products such as plastics that could be replaced with seaweed based polymers
6. the direct contribution to sediment C stores and protection offered to sediments by infrastructure around macroalgal aquaculture.

The following conclusions and recommendations were formed

- **Grow and Sink Not Recommended**
  Growing seaweed specifically for the purpose of sinking the biomass is shrouded by scientific uncertainty, moral concerns, a lack of legal and regulatory frameworks and is currently inadvisable in Scotland.
- **More Research Needed**
  There is still a need for robust, scientific evidence of carbon offset via macroalgal aquaculture.
- **Full Life Cycle Analysis Needed**
  Any carbon offset strategy based on macroalgal aquaculture should be coupled with a full life cycle analysis (LCA) which incorporates the bigger picture of the entire process from seed to shelf (also referred to as cradle to grave).
- **Upscaling Concerns**
  If demand for cultivated macroalgal species in the UK increases, upscaling production will need to carefully address social concerns, regulatory and legal streamlining processes, multiple user interactions and environmental concerns including nutrient competition with other primary producers (i.e., phytoplankton), the potential introduction of non-native species, and population genetics. Upscaling will also need to be coupled with establishing effective supply chains as well as streamlined logistics and processing facilities to meet demand.
- **Product Replacement (Excluding Fuels and Foods)**
  The project working group recognised the potential offset of emissions through various products which incorporate seaweed biomass such as bioplastics. By reducing the amount of CO_2 in the production process there is scope to mitigate CO_2 emissions. Careful analysis of LCAs behind replacement products is advised and work remains to be done to establish consumer and industry confidence in innovative products.
- **Fuel Replacement**
  There is good knowledge of how to produce biofuels from macroalgae. As well as the overarching upscaling concerns, optimising the cost-effectiveness and productivity of MA to replace the fossil fuel industry is paramount.
- **Food Replacement**
  Incorporation of seaweed into human food is a complex area with uncertainties around nutritional content and health benefits, protein content and the effectiveness of such a transition.
- **Animal Feed Replacement**
  While evidence exists of macroalgal enhancement in animal feed leading to reduced CH_4 emissions in cattle ruminants, uncertainties remain around the upscale of production of certain species (namely the red algae Asparagopsis taxiformis, or red sea plume), the health and wellbeing of cattle, biosecurity concerns and effectiveness of delivery in foods in certain grass-fed systems.

Introduction

Macroalgae are large photosynthetic marine, red, green, and brown algae. While the term "seaweed" refers to macroscopic, multicellular marine algae within the same red, green and brown groups, it is often more accurate to use the term macroalgae since red, green and brown seaweed groups all have microscopic or unicellular representatives (Hurd et al., 2014).

Macroalgae are large photosynthetic marine, red, green, and brown algae. While the term "seaweed" refers to macroscopic, multicellular marine algae within the same red, green and brown groups, it is often more accurate to use the term macroalgae since red, green and brown seaweed groups all have microscopic or unicellular representatives (Hurd et al., 2014). Globally, the production of macroalgae through aquaculture has seen a rapid increase in the past 60-70 years. For example, worldwide cultivation of brown macroalgae in 1950 was recorded at 13,000 tonnes, in 2019 cultivation was recorded at 16.4 million tonnes, an average of 10.9% annual growth in production (Lovatelli et al., 2021). The main producers of this biomass are China, Korea and Japan. In Europe annual production is closer to 1,500 tonnes and the industry is currently considered small but nascent (van den Burg et al., 2021). Farming of temperate and warmer water species has seen a recent surge in interest in parts of Europe (FAO, 2020).

Macroalgal aquaculture (MA) in Scotland is also in the developmental stage with a few businesses operating at small scale. Although MA represents an attractive alternative to terrestrial agriculture because MA farm sites do not require fertilizer, feed, and little land-based space to grow (Krause et al., 2022; Naylor et al., 2021). A recent review outlined the various challenges faced by Scottish macroalgal cultivation and highlighted concerns such as large startup investment costs, low value of final products, uncertainty of markets, the need for scale-up mechanisms to achieve economic viability and the poor supply chain and infrastructure in place (Scottish Government, 2022). In Scotland most of the seaweed used in industry is still wild harvested, in spite of the growing interest in MA (Araújo et al., 2021; Scottish Government, 2022). Macroalgae rapidly draw down carbon dioxide (CO_2) through photosynthesis, storing it as sugars and other compounds in their tissues. It follows that there is great interest and attention on MA for its potential to remove atmospheric CO_2, a greenhouse gas implicated in global warming (Laruelle et al., 2018)....

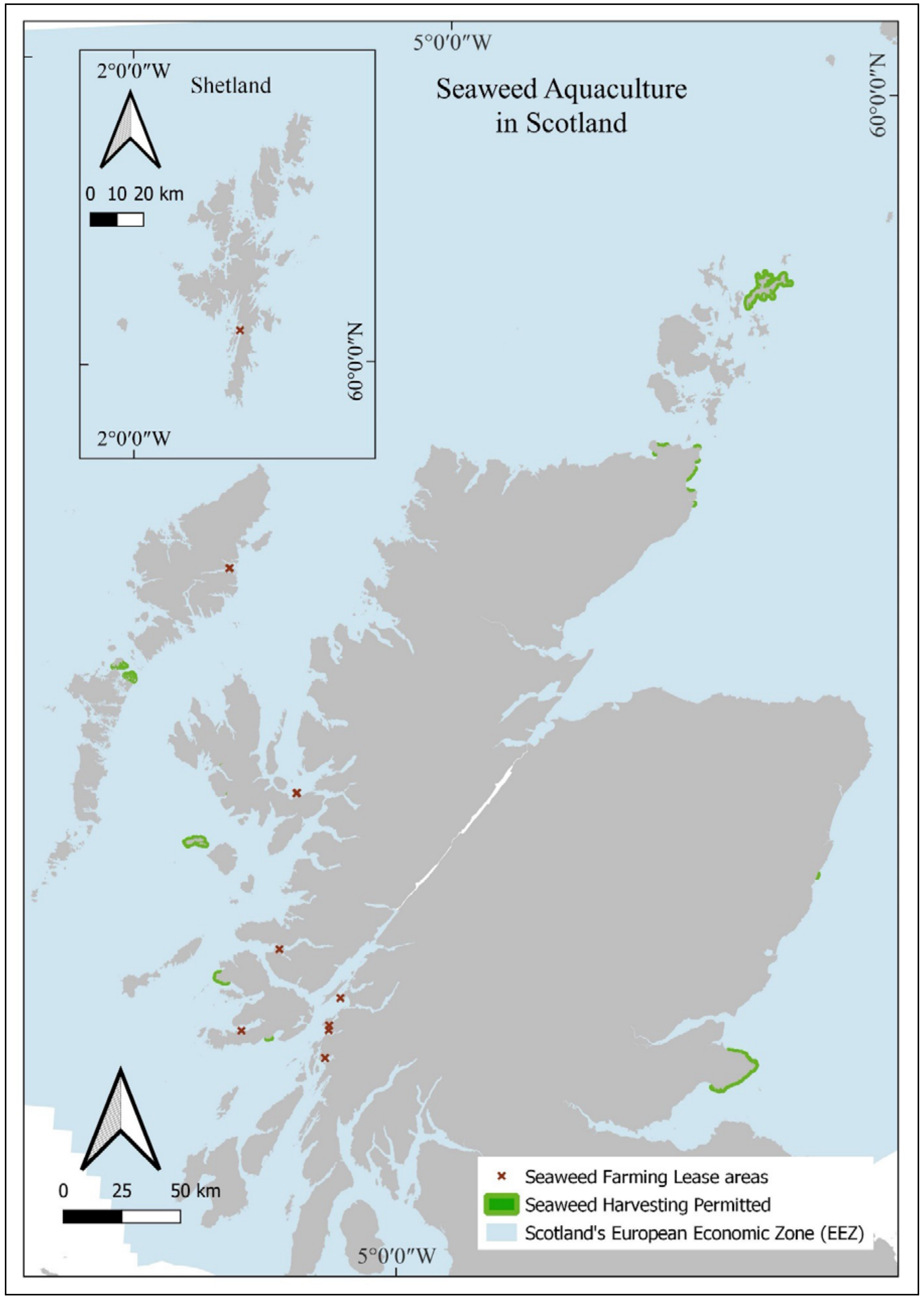


Figure 1.

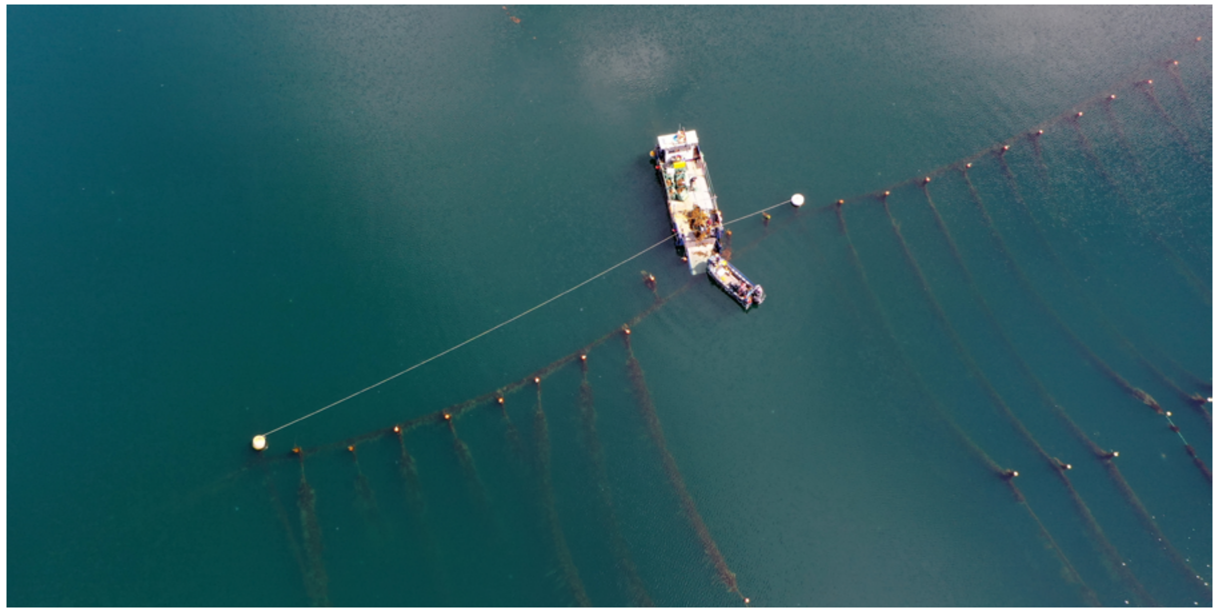
Currently (last updated April, 2022) 10 sites have been leased in Scotland for the purpose of seaweed aquaculture totalling 1.8 km² (180 hectares) from Crown Estate Scotland. While 1.8 km² is leased from CES, not all of the leased area is occupied by seaweed lines. Seaweed harvesting is permitted at 11 sites in Scotland covering an area of 34 km² (3400 hectares).

Introduction continued...

Some uncertainty surrounding the benefits of aquaculture development and carbon offset potential remains, which is demonstrated by contrasting arguments in the literature.

These arguments range from optimism and the establishment of blue carbon offset credits in net-zero frameworks through voluntary offset markets (Kuwae et al., 2022) to cautious reality checks surrounding the recent surge in publications that offer a 'silver bullet' solution to the global food, carbon, and climate crisis (Costa-Pierce & Chopin, 2021; DeAngelo et al., 2023; Williamson & Gattuso, 2022). There is a clear need for a balanced approach to the topic and perhaps, it is necessary to break down the potential risks and benefits of seaweed farming into manageable subject areas recognising the subject is multi-faceted with potential benefits and negative impacts to the marine environment, society, and climate regulation. (Duarte et al., 2021). Here, the potential for a policy framework surrounding carbon sequestration and emissions reduction by seaweed aquaculture is discussed. Other benefits, such as health benefits (Kazir & Livney, 2021), job provision, economic and welfare (Duarte et al., 2021; Valderrama, 2012), and biodiversity provision (Corrigan et al., 2023; Harbour et al., 2021), while recognised, are not the focus of this brief but where they are relevant, are discussed.

It is necessary also to recognise the importance of wild (not farmed) macroalgal ecosystems in Europe and the essential services that they provide (Hamilton et al., 2022; Hynes et al., 2021). In addition to wider ecosystem services, there is a growing body of evidence that these systems contribute to 'blue carbon', carbon sequestration through the provision of a carbon source to benthic areas and the transportation and subsequent burial of detritus (Anglès d'Auriac et al., 2021; Krause-Jensen et al., 2022; Lewis, 2020; O'Dell, 2022). This body of evidence demonstrates the importance of protecting wild seaweed ecosystems and the habitats they provide.



It is equally as important to acknowledge the differences between macroalgal aquaculture and wild macroalgae, particularly when it comes to carbon sequestration. Carbon storage by macroalgae is dependent on the production and fate of detritus (Krause-Jensen et al., 2018; Krause-Jensen & Duarte, 2016; Krumhansl & Scheibling, 2012). While there is still considerable production of detritus during the growth phase (see section 2.6 and also (Broch et al., 2022), the main objective of macroalgal aquaculture is to harvest biomass before detritus is produced (i.e., produce maximum yield of product), therefore removing a major mechanism of natural carbon sequestration by macroalgae.

This brief will discuss current suggestions for carbon mitigation strategies and seaweed aquaculture and provide evidence-based suggestions for future practices. By bringing together an international group of scientists and practitioners from diverse backgrounds, this report will draw upon knowledge and data from existing practices noting the successes, failures and uncertainties uncovered.

Evidence to inform robust carbon accounting from macroalgal aquaculture

Globally, there is a push to reduce the amount of emissions of greenhouse gasses each nation makes to zero (to achieve a so called net-zero emissions), individual nations have set their own national targets.

For example, the United Kingdom aims to meet net zero emissions by 2050, Scotland by 2045 (Acts of the Scottish Parliment, 2019; Great Britain & Department for Business, 2021). The removal of atmospheric CO_2 therefore is a key aspect of net-zero targets, as is accurate budgeting of existing carbon cycles and the dynamics of carbon turnover through wild ecosystems. To accurately budget national carbon turnover, a full understanding of all aspects is required.

Macroalgae use carbon dioxide (CO_2) and sunlight for growth. Through photosynthesis, macroalgae remove significant amounts of CO_2 from seawater and in doing so, facilitate a 'draw down' mechanism of atmospheric CO_2 into the ocean (Clements & Chopin, 2017; Costa-Pierce & Chopin, 2021; Gao & Beardall, 2022).

The amount of carbon fixed annually by seaweed aquaculture can be calculated from measurements and models and converted to CO_2 equivalents (CO_2e). Total solids in macroalgae are approximately 15% of the fresh (wet) biomass and the amount of carbon in forest forming macroalgae in Europe is well documented at around 30% of dry mass (Krumhansl & Scheibling, 2011; O'Dell, 2022; Schiener et al., 2015). However, growth rates vary by species, and annually with various factors that influence the productivity of farmed species (Bartsch et al., 2008; Smith, 2011; Vadas et al., 2004). Nonetheless, biomass is generally measured during harvest and the mass of carbon produced can be easily estimated at approximately 4.5% of harvested wet weight and converted to CO_2 equivalent or measured directly analytically.

The carbon export from algal farms to adjacent natural environments (the fractions lost from cultivation that needs added to the carbon budget) has been estimated empirically and shows large variation across cultivation practices, latitudes, growth stages and seasons (Fieler et al., 2021; Mortensen, 2017; Xiao et al., 2017; Young et al., 2022; Zhang et al., 2017). Ongoing research has documented the potential for carbon sequestration directly beneath macroalgae farms at some sites around the globe but also large variability between sites (see section 2.1, Duarte et al., 2023).

However, the fate of MA biomass is key to the storage of carbon and there are multiple uses of MA such as food, fertiliser, bioenergy and high value compounds that all have different end products. Therefore, to assert that 4.5% of aquaculture produced biomass is carbon that has been removed permanently from the atmosphere would be misleading. There is, therefore, a significant difference between seaweed farming for carbon sequestration and the amount of carbon that can be sequestered by seaweed farming alone, considering the product chains and fate of the biomass generated (Hasselström & Thomas, 2022; Troell et al., 2022). Much of these estimates depend upon accurate calculations of the full life cycle of macroalgal production from seed to shelf, termed Life Cycle Analysis (LCA) (Thomas et al., 2021).

There is also a current demand for carbon accreditation, with multiple industries wishing to offset their emissions (Blaufelder et al., 2021; Steven et al., 2019). Carbon credits from macroalgae aquaculture can be awarded when accurate carbon content is measured for the individual seaweed species cultivated and the amount of atmospheric CO_2 that is offset is certain. This requires a) analytical steps to ascertain accurate C content, b) LCA to ascertain carbon footprints of individual operations and c) robust scientific evidence of C sequestration (or removal of atmospheric CO_2e for geological timescales). With uncertainty surrounding the overall contribution to CO_2 removal through MA, and a desire to inform or produce viable carbon offset credits, the main questions to address therefore are threefold.

1. Can seaweed aquaculture make a significant difference to atmospheric CO_2 levels?

2. Can a carbon accreditation system be formed through seaweed aquaculture?

3. Does macroalgal aquaculture as it stands reduce carbon emissions?

Carbon credits can be awarded when accurate carbon content is measured for the individual seaweed species cultivated and the amount of atmospheric CO_2 that is offset is certain. This requires a) analytical steps to ascertain accurate C content, b) LCA to ascertain carbon footprints of individual operations and c) robust scientific evidence of C sequestration (or reduction of atmospheric CO_2e).

Below the concepts that might result in the development of policy in this way are discussed, where possible, evidence is provided to give context and background for the reasons behind each concept. Any aspects which are unknown are outlined and suggested actions are given (to do list).

Grow and sink

Concept

The main concept behind the grow and sink strategy is that increasing primary productivity at surface levels and exporting the organic carbon to substantial water depths (e.g. over 1,000 metres) will remove atmospheric CO_2 for significant timescales (Baker et al., 2022; Fieler et al., 2021; Krause-Jensen & Duarte, 2016). Therefore, harvesting large quantities of rapidly grown biomass and sinking it to depths will potentially 'sequester' carbon. There are suggestions that this market has already begun to operate (Ricart et al., 2022), and in parts of the Caribbean, methods to mitigate potentially harmful Sargassum spp. matts on beaches by forcing it into deeper parts of the ocean are actively in development (Gray et al., 2021).

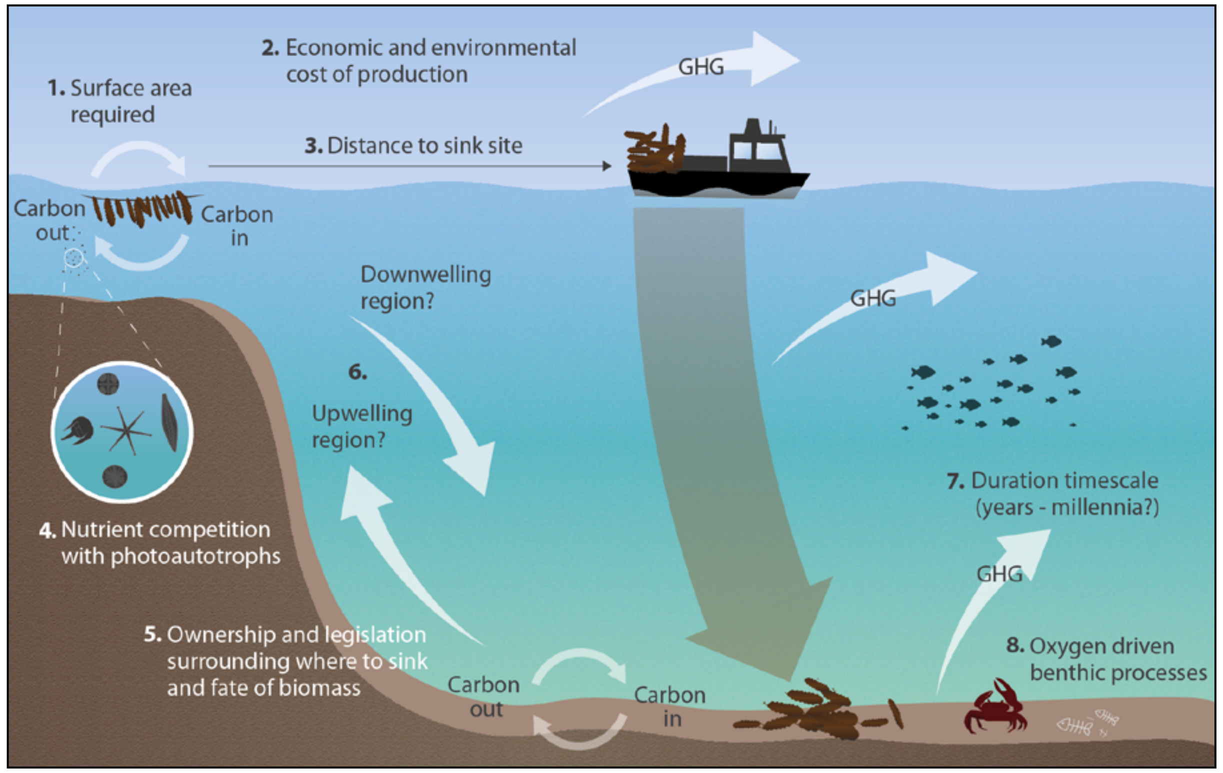


Figure 2.
The 'grow and sink' concept remains largely uncertain, particularly within the scope of Scotland's continental shelf zone. Unknown aspects such as release of C (in greenhouse gas form) while sinking, degrading and through transportation are highlighted as well as the dynamics of sea-surface interactions with nutrients and other user interests.

Evidence

There are some general assumptions which are widely accepted in the literature. Specifically, that in shallow water depths within the mixed layer (1-100 m deep) remineralisation of POC will result in rapid atmospheric exchange within a year, whereas below the mixed layer in the upper mesopelagic (200 – 500 m), POC will be removed from atmospheric exchange for decades, and in deeper waters in the lower mesopelagic (500 – 1,000 m) and below, POC may avoid atmospheric exchange for 100 years or more (Antia et al., 1999; Baker et al., 2022; Lampitt et al., 2001; Lampitt et al., 2008; Robinson et al., 2014).

From a legal perspective, depositing substances or articles at sea in Scottish waters can only be performed with a licence from Marine Scotland. Who may include provisions on the licence in order to protect the environment. Depositing organic matter such as kelp is not exempt from this licencing process and the process will need to follow the guidelines set out in the Dumping at Sea Act (1974). The need to protect the marine environment from adverse consequences of dumping is a key part of the licensing process. There are also significant challenges involved in sinking biomass outside of territorial waters. The London Convention (1972) was modernised under the London Protocol (1996) which prohibits the dumping in the ocean except for 'organic material of natural origin'. Ricart and colleagues (2022) point out that farmed macroalgae offshore, specifically grown for the purpose of carbon offset might also be considered waste (Ricart et al., 2022).

The Intergovernmental Panel on Climate Change (IPCC) set a time scale of 100 years for the removal of carbon dioxide from atmospheric exchange and interaction for climate-relevant sequestration (IPCC, 2018). However, sequestration timescales in the deep ocean are uncertain (Gattuso et al., 2021) and models have predicted that 60-70% of remineralised carbon from sunk biomass will re-enter atmospheric exchange long before the 100-year threshold set by the IPCC depending on sinking location and on how deep into the water column POC is injected (Robinson et al., 2014; Siegel et al., 2021). Furthermore, scientific evidence related to the efficiency and impacts of large-scale seaweed sinking is scarce and certain moral and ethical issues remain which are discussed below (Ricart et al., 2022), as well as the impacts of large scale growing in coastal or offshore areas. Below, we discuss both processes (grow and sink), through the lens of different aspects related to carbon dynamics, environmental impacts, logistics, legal and social issues, to identify the knowledge gaps and what are the most urgent actions.

Grow & sink continued...

Unknowns

There are overarching ecological, feasibility and legislative factors that remain uncertain.

The following questions surrounding the sinking of seaweed biomass need to be resolved, there are also evidence gaps around how these points might vary at a species level and under different environmental conditions.

1. what happens during the sinking process including rates, carbon (POC and DOC) loss on the way down?
2. what depth is required for long-term sequestration that is in line with IPCC guidelines, and how much is remineralised and lost to the atmosphere at which depths?
3. what are the kinetics of degradation on the seafloor and what is the amount of refractory material that will remain?
4. how much biomass is incorporated into sediments?
5. what is the carrying capacity of the deep sea and what are the impacts of adding substantial amounts of organic matter to deep sea benthic ecosystems that are adapted to a carbon limited environment?
6. from a legal perspective, who owns the biomass once it is on the seafloor and who is responsible for the consequences which are unknown?
7. where are the optimal sinking sites given various physical, chemical and environmental processes that might disturb sunken biomass?
8. What are the associated costs, energy and materials needed to sink and maintain the grown biomass at depth?

...The biomass produced in seaweed aquaculture has considerable value, some argue that sinking this biomass is a waste of a resource that could be better utilised elsewhere (Costa pierce and Chopin 2021; Ricart et al. 2022). For example, the reduction in nitrates released to the atmosphere by using seaweed based fertiliser vs synthetic or animal based slurry (López-Mosquera et al., 2011) and industrial use, as well as using macroalgae for food and feed (Troell et al 2022).

The outcome of sinking organic matter at this scale can, realistically, only be modelled. Therefore, a considerable degree of uncertainty and numerous caveats will remain. From existing bathymetry data, effective sinking of macroalgal material in Scotland could only happen beyond the Rockall Trough region (between 100-150 km from the Outer Hebrides). The carbon footprint of transporting seaweed detritus this far would be significant and the greenhouse gas emissions will largely depend on transportation mode and energy sources. Additionally, surface currents in the region would potentially drive sinking biomass northwards which, depending on sink site, might send sinking biomass away from territorial waters or into areas which are not considered deep enough (Kämpf & Chapman, 2016).

Next steps

Uncertain aspects outlined above need to be researched and resolved prior to the acceptance of the 'grow and sink' process as a reliable offset strategy. In addition, there is a need for regulatory framework regarding large-scale plans particularly regarding the ownership and responsibility for the sunk biomass. Third party verification pathways for carbon offset which include all C sequestration pathways which will likely involve LCA analysis of costs and carbon footprint.

Product replacement

Concept

The main concept behind product replacement for emission reduction is the reduction of CO_2 emissions by switching market demand from products that are energy intensive and have large carbon footprints, to products that are less synthetic, more easily degraded (have shorter half-lives), and are less energy intensive to produce. Replacement of products that are energy intensive and hard to degrade may reduce emissions but might not actively remove atmospheric CO_2.

Evidence

Globally, roughly 400 million tonnes of plastic is produced and circulated through various uses annually (Geyer et al., 2017) and CO_2 released during manufacturing of plastics can be significant. For example, one tonne of polystyrene production has been shown to produce up to 1.9 tonnes of CO_2 through the production process (Patel, 2003). The UK is estimated to use 5 million tonnes of plastic annually (Smith, 2022), of which 2.5 million tonnes becomes waste and is not recycled (DEFRA, 2022). An alternative to petroleum-based products in the form of biopolymers made from algal hydrocolloids has potential to reduce CO_2 production during manufacturing and the resulting more biodegradable end-product (Lim et al., 2021; Rajendran et al., 2012). Certain lectins or carbohydrate-binding proteins have recently been noted for their moisture-barrier properties, making them suitable for (rapidly) biodegradable and even edible packaging (Praseptiangga, 2017).

Unknowns

The market acceptance of packaging that is short-life and rapidly biodegrades remains a large uncertainty. Replacing reliable long-life plastic packaging with alternatives and establishing consumer confidence in such products will be a challenge. Three main aspects discussed in the literature are confusion among consumers about the benefits of bioplastics, value-action gap (the difference between the value perceived and the lifestyle choice or change) and unrealistic expectations of the products (Fletcher, 2022). As with most concepts discussed here, upscaling to meet consumer demands if/when products become incorporated into everyday use is also key to this process.

Next steps

The aspects of product replacement from a social perspective (i.e., social perception of such products and industry willingness to transition to these products), as well as biochemical extraction and production methods require research and development.

Food replacement

Concept

Evaluating the health and environmental benefits of switching diets away from red meat, to other sources has shown that aquaculture requires less feed-stocks and terrestrial land space (Froehlich et al., 2018; Gephart et al., 2021; Springmann et al., 2018; Willett et al., 2019). With the additional uptake of CO_2 by seaweed aquaculture, there is potential to reduce emissions directly (Collins et al., 2022) as well reducing the methane emissions by drawing demand away from ruminants (discussed in page 22 but also see, Glasson et al., 2022). The low protein content of most macroalgae means it is unlikely to replace meat as a protein source entirely, but it could contribute other nutritional functions (such as a vitamin supplement) while also playing a flavour enhancing role as an ingredient in vegetarian alternatives.

Evidence

There are many challenges associated with human consumption of seaweeds although seaweed is well integrated into diets in other nations. Studies have found that shifting to vegetarian diets could be a key strategy to reduce carbon emissions (Willet et al., 2019; Chen et al., 2022). Evidence showing the human health benefits of consuming seaweed products has been found and some studies have demonstrated a positive attitude towards seaweed consumption in European nations (Italy and Sweden respectively see, Palmieri & Forleo, 2020; Wendin & Undeland, 2020). Of the so called 'blue foods' farmed seaweed and bivalves have been shown to generate fewer stressors than crustacean and finfish aquaculture (Gephart et al., 2021).

Unknowns

Key factors limiting the consumption of seaweed in studies conducted in Australia were found to be poor accessibility to seaweed products, high costs and undesirable packaging (Young et al., 2022) further supported by studies in Italy that interviewed 257 consumers found accessibility to be an issue but there is potential for increasing production (Palmieri & Forleo, 2020, 2022). Both aforementioned studies point out that superficially, if seaweed was more available and, on more menus, the general public would likely be willing to consume it. However, this apparent willingness to consume seaweed products in Europe has not translated into a widespread integration of the products into mainstream supermarkets or day-to-day diets.

There are concerns around food safety, considering some species accumulate halogens such as iodine and some heavy metals (Blikra et al., 2021; Kumar & Sharma, 2021; Løvdal & Skipnes, 2022). Nutritional content and bioavailability of species of seaweeds can be highly variable depending on season, species and other environmental factors making nutritional labelling difficult for mainstream consumer products.

Next steps

Market interventions including promotional and information provision strategies need to be applied to encourage consumption of seaweed-based foods. The solution to encouraging the consumption of seaweed-based products is somewhat cyclical. The market cannot upscale efficiently until demand for products is present yet demand at this scale may not occur until the availability of seaweed foods is improved and knowledge of products is encouraged by investing in marketing. Key questions remain, and investment by industry carries risk - should the industry invest in marketing strategies to encourage desirability of seaweed products, or investment in product development and supply chain processes that might exceed current demand? Both strategies will likely be needed to encourage dietary transitions in western societies.

Food safety concerns can be addressed experimentally, analysis of heavy metals, halogens and other toxins which might be present as well as the vitamin and mineral (and protein) content can be analysed and researched in a lab setting. Dietary studies which explore the health benefits of partial, or complete inclusion of seaweed in certain food types will also be key.

Bioenergy

Concept

The consumption of fossil fuels to produce energy requires the re-circulation of geological carbon reserves and thus, increases modern day atmospheric CO_2. Removing or reducing the current dependence on fossil fuels and replacing them with bio-alternatives (such as biofuels produced with seaweed biomass) will reduce net release of CO_2 by shifting from long-term carbon cycles to short term carbon cycles.

Evidence

The production of biofuels from seaweeds is well studied, methods such as anaerobic digestion (AD), chemical extraction and transesterification, conversion using heat such as combustion, liquefication, gasification and pyrolysis are all areas of active research (del Río et al., 2020; Hessami et al., 2019; Michalak, 2018). The conversion technologies themselves are well understood, and producing fuel from macro and microalgal biomass has been successful (Chen et al., 2015). Initial attempts to produce large amounts of macroalgae for biofuels in the 1960's failed largely due to engineering challenges of farming offshore, the ideas have been re-addressed since and conservative estimates of biogas from macroalgae are in the region of 22 m3 per tonne of wet weight yielding 171 GJ per hectare (Gigajoules or a thousand million joules of energy) (Hughes et al., 2012).

Unknowns

While conversion technologies are well understood and active research is ongoing, regulation, upscaling and competition with other renewable sectors, as well as the transition logistics of an industry that is currently producing seaweed for small-scale high value products to large-scale bulk (biomass focused) production are all unknowns. While technically biofuels have been produced from MA, reducing costs during biomass production and improving the overall cost-effectiveness of biofuels from MA has been a challenge but macroalgae are considered more cost-effective than microalgae (Gao et al., 2020).

Next steps

Optimising the cost-effectiveness of MA while maximising productivity is paramount (Gao et al., 2021). Various scientific, regulatory, and social challenges remain. A number of regulatory reviews are ongoing in Scotland which encompass MA and live harvesting of wild stocks many of which are discussed in the recent Seaweed based-industries report (Scottish Government, 2022). Licencing requires streamlining, while regulatory frameworks for seaweed farming at scale are not in place, as well as the renewable energy consent and planning application process, which could act as a baseline for seaweed aquaculture regulation (UK Government, 2013). Any regulations will also need to consider assessments such as the Strategic Environmental Assessment (SEA) which considers environmental aspects of upscaling and energy production as required by the Environmental Assessment (Scotland) Act (2005). Considering seaweed aquaculture is currently in active research and development it could be necessary to adopt 'design and monitor' or 'design envelope' approaches which allow lease holders to develop and test a range of approaches within a plan while developing designs and optimising solutions and business plans. Offset or emissions reductions can be calculated using LCA analysis (Czyrnek-Delêtre et al., 2017).

Fertiliser & cattle feed enhancement

Concept

Methane is a greenhouse gas and current agriculture and forestry practices in Europe are potentially a source of CO_2 and CH_4 (Schulze et al., 2009). Again, the replacement of fossil fuel intense practices to produce synthetic fertiliser and manufacture cattle feed is reported to reduce emissions of CO_2e (Raghunandan et al., 2019). Emissions during seaweed production are low when compared with other food types (Gephart et al., 2021). The use of seaweeds as natural fertilisers has potential to reduce the number of synthetic compounds, and the amount of energy consumed during manufacturing/processing of synthetic fertilisers (Raghunandan et al., 2019). As a low trophic species, the extraction of nutrients by seaweed as it grows can also mitigate eutrophication (and thus reduce other GHG emissions) while closing the loop on phosphorus, bringing it from where it is diffuse in marine environments back into human consumption systems (Thomas et al., 2022). Similarly, the production of CH_4 by cattle is also dependent on diet and can be reduced using seaweeds (Jentsch et al., 2007).

Evidence

Enhancing a small portion of cattle feed with certain algal species can reduce CH_4 emissions significantly (Paul et al., 2006). For example, the red algae Asparagopsis taxiformis contains bioactive, anti-methanogenic compounds such as bromoform, which has been shown to reduce methane production by as much as 98% when cattle feed was supplemented as little as 0.1-0.2% with A. taxiformis (Kinley et al., 2020; Roque et al., 2021). Cattle feed enhancement therefore has potential to mitigate harmful greenhouse gas emissions and 'low-methane' beef is already for sale in parts of Europe (Taylor, 2021).

There is a large variation in herd sizes and structure of cattle numbers and types in farms and crofts across the country, with individual businesses having anything from a single animal to thousands making application of macroalgal supplements challenging (Thomson et al., 2021). If Scottish cattle (estimated at 1.721 million) were fed proportions similar to those of New Zealand cattle (20%) on the assumptions of 10-15 kg DMI day^{-1}, this would require 13,768-20,652 tonnes (dry weight) of Asparagopsis sp. (containing 6550 ppm bromoform and supplementing feed at 0.2% OM inclusion) annually (Agriculture and Horticulture Development Board, 2022; Glasson et al., 2022).

Unknowns

Upscaling production of red-algal feed supplements to the required biomass has again been the key focus of discussion. The majority of production currently takes place in parts of Sweden (city of Lysekil) but land-based operations are under development (Nilsson & Martin, 2022). LCA assessments have found that sourcing key components such as salt, and water as well as a large thermal demand have the biggest footprints on A. taxifomris production, and need addressing before carbon neutrality can be achieved (Nilsson & Martin, 2022). The health and wellbeing of cattle, arsenic content of seaweeds and food standards (Navratilova et al., 2011; Rose et al., 2007), gut-bacterial resistance and evolution remain key factors that warrant investigation before large scale implementation of this practice. There are various biosecurity concerns about the large-scale production of a warm-adapted, non-native seaweed species in both temperate regions (for example, Northwest Europe) as well as warmer regions (Mancuso et al., 2022).

Next steps

The research that has been done to date has limited application in a Scottish system, however, work can be performed to establish the effectiveness of other UK, native species which have similar bromoform content. Work on optimising the processes for land-based operations and minimising environmental impacts as well as upscaling production of A. taxiformis needs to be carried out with strict guidelines in place to ensure biosecurity is maintained. There are also challenges involved with incorporating supplements to feed systems, particularly in free-range grass fed herds.

More work is needed to reduce the uncertainty around CH_4 reductions, which will likely evolve if widespread implementation of A. taxiformis occurs. Once CH_4 reductions are established, policy can be developed around how to apply the CO_2e offset, and answer key questions such as; do credits apply to cattle farmers, seaweed producers or feed manufacturers?

Sediment protection & enhanced carbon storage

Concept

Marine sediments are the largest reservoir of organic carbon in the sea, sediments underneath or close to vegetated ecosystems can store significant amounts of organic carbon in the long term (Estes et al., 2019). However, only a small portion of sediment carbon stores are within protected areas globally (Atwood et al., 2020). Physical disturbances to these sediments, such as boat anchoring or intensive trawling, are a threat to buried organic carbon and may potentially lead to CO_2 emissions. This is because oxygen is introduced into the system which enhances the metabolism of organic carbon in sediments (Sala et al., 2021; Serrano et al., 2016). The amount of carbon that is potentially converted is dependent on many factors such as the sediment type, the age of the carbon and where it originated. To site a seaweed farm, an area of seafloor is leased and therefore becomes closed to activities that disturb the seabed, thus the sediments and organic carbon they contain, could be considered safeguarded. Detritus produced by natural kelp forests can be a significant source of organic carbon to sediments, and harvesting before the onset of this detrital production minimises the potential contribution. However, particulate and dissolved organic carbon are often produced continuously during growth. Seaweeds can release up to 20-40% of their production as DOC which may also contribute to carbon stores (Gao et al., 2021; Paine et al., 2021). There are however, associated risks with excess DOC and POC produced during growth, particularly at large scales which include aspects of anoxia and impacts to benthic communities (Ross et al., 2022).

Evidence

The delivery or enhanced downward flux of nutrient rich detritus are is unlikely to negatively affect sediments and could be beneficial to benthic organisms (Campbell et al., 2019). Thus large scale cultivation of seaweeds has been suggested as a mitigation strategy for removing excess nutrients from target areas (Fei, 2004; Racine et al., 2021; Zhang et al., 2022). A recent study that looked at over 20 seaweed farms and found that on average 2.1 tonnes CO_2e per hectare of farm (range of 0.06-8.99 tonnes CO_2e) was buried annually. The amount was largely dependent on farm location, sediment type beneath the farm, and yield of seaweed produced (Duarte et al., in review). In addition, a proportion of organic matter (seaweeds) from farms is expected to deposit on the seafloor in adjacent environments as large fractions of exported seaweed debris can be transported away from the farm site (up to hundreds of kilometres, Broch et al., 2022).

Unknowns

Seaweed detritus has been tracked moving many miles from source due to ocean circulation patterns (Queirós et al., 2019, 2022). While it is likely that 'organic rain' in the form of large particulates is enhanced directly underneath a seaweed aquaculture site, direct evidence of sediment contribution is still limited and will depend upon specific hydrodynamics and sediment characteristics of individual sites.

Next steps

A better understanding of the potential of sediment to store carbon lost from a macroalgae farm needs to be developed, which will likely relate to the position of the site and the hydrodynamic forces in the region. Suggestions such as a forensics approach which utilize multiple biomarkers can help form tools which will show the impacts of aquaculture from a carbon perspective (Hurd et al., 2022).

Farm site location will be an important part of decision-making. The location of the farm will have a unique a) sediment type, b) hydrology and energy in the region, and c) nutrient content in the water, which will all govern the potential of sediment carbon storage.

What are the barriers to seaweed becoming a net-zero aquaculture sector?

In the recent review of the Scottish macroalgal industry, it was noted that the primary challenges it faced were poor logistics and product chains, lowering start-up costs, uncertainty around markets for currently cultivated species and achieving the scale required to achieve economic viability (Scottish Government, 2022). Studies have shown that increasing the surface area available for MA will increase uptake of CO_2 (Sondak et al., 2017) but the fate of the produced biomass is again key to mitigation of atmospheric CO_2 (Chung et al., 2017). Caution must be advised when upscaling seaweed aquaculture to the scale necessary to meet/ contribute to net-zero market demands so that it does not become environmentally damaging (see section 4.1, Campbell et al., 2019). There are practical considerations including the competition for space and other industries at sea as well as possible collaboration between industries (such as offshore wind) that could benefit from MA integration into their practices (Banach et al., 2020; Tullberg et al., 2022; van den Burg et al., 2020).

As discussed, some aspects of carbon accounting are straightforward when it comes to MA (Section 2). It is often useful to look into existing schemes which are in place, even if the ecosystem is quite different in its function. For example, the Peatland Code is an established method for the quantification of GHG benefits derived from the restoration of degraded peatland areas (IUCN, 2022). Table 2 outlines the main requirements for a hypothetical 'Blue Carbon Code' to establish effective marine equivalents to the peatland Code. There is currently more demand for peatland code credits than supply can meet. And work is ongoing on a saltmarsh code and early discussions surrounding seagrass codes following various restoration schemes that are in place. Lessons can be learnt from other schemes that have faced significant challenges. For example, the Reduced Emissions from Deforestation and Degradation (REDD) has been drawn into debate for the efficacy and value of the scheme (Angelsen et al., 2017; R. Fletcher et al., 2016).

Upscaling

Upscaling production of seaweed biomass to make a significant difference to atmospheric CO_2 levels was the main challenge identified across all the aspects covered by the working group. While upscaling has been successfully achieved in other parts of the world, it remains a challenge in the Northeast Atlantic where the industry is currently small-scale. Upscaling will need to be streamlined effectively only if/once demand exists. The principal issues with upscaling relate to infrastructure and innovative designs and practices will need to be researched and developed.

Table 2.
An outline of the established requirements and PC methods for meeting these requirements as well as the hypothetical Blue Carbon Code requirements that will be necessary to establish a marine equivalent. Hypotheticals are in inverted commas.

REQUIREMENT	PEATLAND CODE TASKS	'BLUE CARBON CODE'
Project developers	Document completion, find buyers	Same
Brokers	Contact development, find buyers, proof of transfer	Same
Accreditation	UKAS against ISO 14065 (General principles and requirements to validate & verify environmental information)	Same
Updated & improved	Yearly	Same
Duration	30 Years minimum	Likely same, dependant on LCA, ownership status, Crown Estate
Legal ownership or land tenure	Duration of project	Crown estate permission/ lease of seabed for duration, other stakeholders, and rights of access
Accounting security	UK Land Carbon registry ensures credits are not double sold.	'UK Blue Carbon Registry'
Measurement	Peatland Carbon Unit (PCU) One tonne of CO_2e emissions savings from certified peatland restoration, and Pending Issuance Units (PIU) a promise to deliver certain units	'Blue Carbon Units (BCU)' 'Aquaculture Carbon Units (ACU)' PIU is the same
Emission factors	See Smyth et al., (2015) for full details of Peatland Code condition categories and emission factors	Descriptive statistics need to be developed for both Blue Carbon habitats and MA, large amounts of uncertainty are the main drawback here
Additional tests	Applicants must demonstrate the following: 1) legal compliance, 2) financial feasibility of the scheme, 3) economic alternatives, 4) barriers to overcome	Applicants would need to demonstrate the same, with additional thought to seafloor, access and ownership rights

Barriers continued...

The CO_2 emissions released by the United Kingdom were estimated at 365.7 Mt in 2018 (approximately 1.5 t C per person per year; UK Office of National Statistics, 2018), Scotland's annual emissions are a small portion of that amount and sit in the region of 9.8-10.2 Mt CO_2 (Scottish Budget, 2020-21; 2021-22). Kerrison et al., (2015) estimated it is possible to draw down 6.1 tonnes of C (dry weight) per hectare of seaweed farm, (the equivalent of 23.4 t CO_2). To place the space needed to draw down carbon to that scale these figures can be visualised.

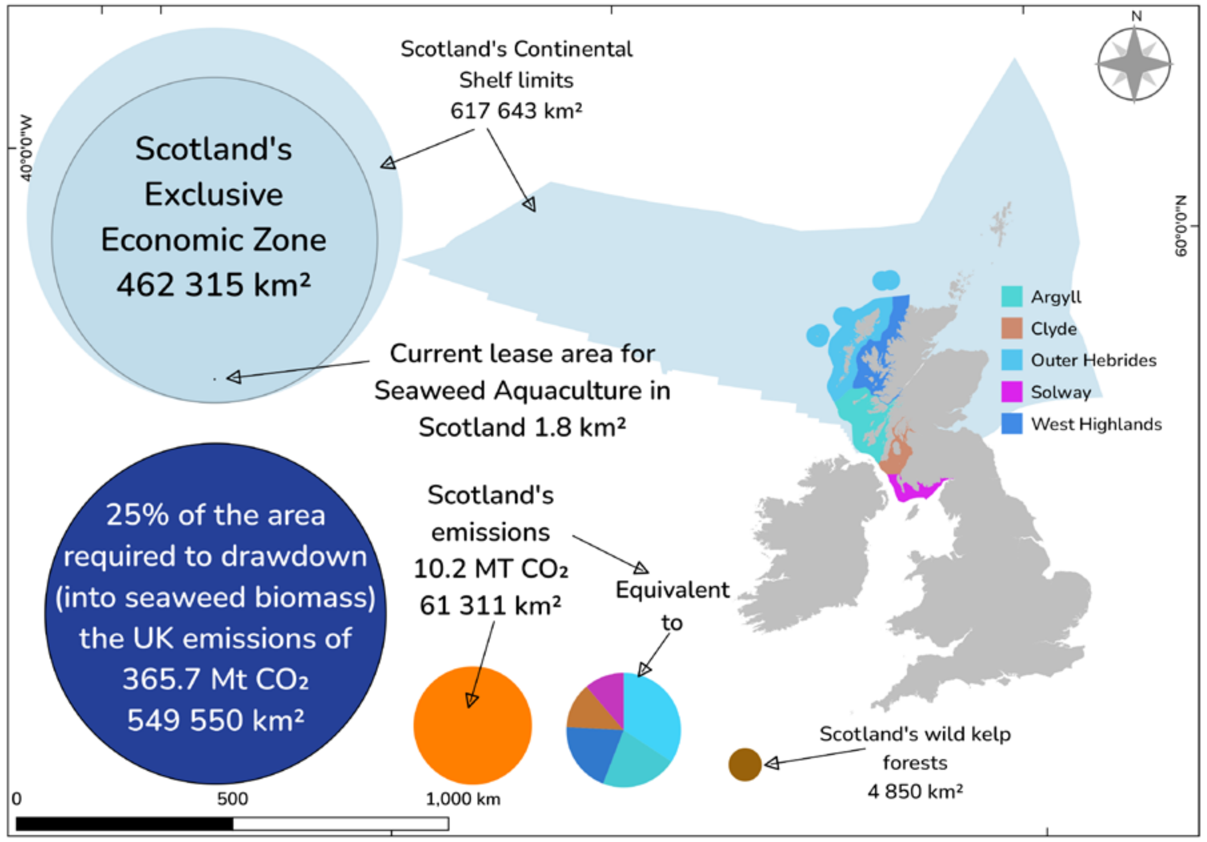


Figure 3.
Scotland's EEZ and continental shelf limit with circles to scale to demonstrate the size and potential productivity (i.e., growth of seaweed annually in Mt CO_2 yr^{-1} equivalent) drawn down by macroalgal aquaculture in the region. All figures are based on 6.1 tonnes of C per hectare of seaweed (Laminariales) farm (see Kerrison et al., 2015). Note that figures stated represent the addition of biomass to aquaculture over the growth period and do not state carbon sequestered. Carbon sequestered will depend upon the fate of farmed biomass as discussed and is likely to be a smaller percentage of that total. To put these amounts into perspective, 31 311 km² of seaweed aquaculture will therefore drawdown 10.2 Mt CO_2 into seaweed biomass annually, this area is practically the size of the Argyll, Clyde, Outer Hebrides, Solway Firth and West Highlands Marine Areas (pie chart with colours that match the specific areas).

Existing literature on large-scale farming seems to suggest that environmental concerns are minimal, and mostly shows that increasing the area available for seaweed aquaculture will enhance carbon drawdown, nutrient remediation and other benefits similar to those of natural macroalgal ecosystems (Chopin, 2012; Chung et al., 2017; Fei, 2004; Sondak et al., 2017; X. Zhang et al., 2022; Y. Zhang et al., 2017). The environmental impacts of upscaling in temperate areas such as Scotland include: disease facilitation and spreading, transport of non-native invasive species, population genetics being altered and wider physiochemical alterations to the environment (Campbell et al., 2019), but a more complete understanding of the risks is needed. There is also a need to understand the wider impacts on ecosystems and ecology of local regions as well as conflicts with other users.

There are concerns about reducing the nutrient concentration in surface waters with MA to the extent that it might limit the available nutrients for other important processes including ocean chemistry and altered ecology and physiology of microbes (Boyd et al., 2022). For example, nitrate and phosphate availability during key growth periods of kelps has been modelled showing a reduction in phytoplankton because of macroalgal uptake. This competition not only had a negative impact on phytoplankton primary production but could influence food webs and result in a net reduction in oceanic carbon sinks (Berger et al., 2023). Other models agree, showing that moderate kelp farming will have little impacts on phytoplankton but intensive farming over large areas again will reduce phytoplankton as well as mussel (if farmed in adjacent areas) biomass (Aldridge et al., 2021; Wu et al., 2023). It is important to develop methods for assessing carbon uptake and the permanence of carbon sequestration in deep water systems associated with MA, which include competitive interactions for nutrients in deepwater systems (Rose & Hemery, 2023).

Barriers continued...

Legislation

Legislative processes that will streamline licensing for seaweed farming need improvement. Multiple aspects of the above discussed concepts will require legislative input. For example, to sink large quantities of biomass requires legislation surrounding the ownership of that biomass, and the longevity of the ownership and responsibilities will also remain for sinking biomass outside of countries EEZs. Legislation will also be important when designating the ownership of carbon credits and the allocation of such credits. For example, do offset credits apply to seaweed farmers (producers), or the users of the product (i.e., in farmers using methane reducing products in their cattle feeds), or with the manufacturers of the feed?

Streamlining the licencing process might mirror existing legislation such as the renewables consenting process (UK Government, 2013) particularly when considering offshore locations (beyond 12 nm) and permissions from Crown Estate to occupy sea area or use the seafloor for depositing large amounts of seaweed.

The complex, costly and time-consuming lease and permitting process is not unique to the United Kingdom (Camarena-Gómez et al., 2022). The United States has achieved systems designed to support seaweed cultivation in Maine and Alaska which reduce the time taken to gain permission from between 3.5-10 years to 10 months to a year (Silverman-Roati et al., 2022). The process is streamlined largely by denoting responsibility for the issuance of a permit to one agency, while other agencies are very much involved, time limits are set to review applications and request responses (see Alaska Aquatic Farm Program Joint Agency Application – Part I). Streamlining the processes in Scotland requires collaborative Crown Estate Scotland, NatureScot and Marine Scotland work to potentially find a streamlined approach suitable to MA from The Crofters Act, The Environmental Assessment Act and the Marine (Scotland) Act (Scottish Parliament, 2005, 2010; UK Government, 1993). The Scottish Government is already considering MA in its aquaculture regulatory review process, so work in this field is underway.

Socio-economic aspects

Increased production and upscaling of existing infrastructure in the ocean will have a profound effect on the perception of seaweed aquaculture. Public perception of small-scale seaweed production is favourable where the environmental impact is low, local populations lifestyles are respected and the relationships with developers are considered truthful (Rostan et al., 2022). The effects on local communities are key and a degree of influence is exerted by the granting or withholding of social licence to operate (SLO, see Billing et al., 2021). Social considerations including the suitable places to grow to support estimated increased yield, marine planning, competition with other users such as fishermen, competition for space with recreational users and other industries such as marine transport are all factors that require consideration when attempting to gain SLO.

Conclusions & recommendations

The following potential routes for reducing atmospheric CO_2 were discussed during the workshop:

1. growing and sinking seaweed biomass
2. replacing/supplementing human food products with seaweed based products
3. replacing/supplementing agricultural food and fertiliser with seaweed based products
4. the potential for bioenergy produced by seaweed biomass
5. replacing other products such as plastics with seaweed based polymers
6. the direct contribution to sediment C stores and protection offered to sediments by MA infrastructure

The working group recognises that there is potential to offset atmospheric CO_2 through seaweed aquaculture likely through the replacement of carbon intensive products and practices (for example food, animal feeds, bioplastics) with seaweed biomass that is produced via either neutral or low carbon producing practices.

The routes to establishing a carbon offset accreditation programme are currently hindered by several factors many of which, are similar to those that are carefully being considered for the MA industry in general. Once a clear scientific knowledge base surrounding the Life Cycle Assessment LCAs of MA is established, logistics need to be considered. For example, upscaling MA sites and establishing effective supply chains to meet demand is important, upscaling is also coupled with concerns around social perspectives of MA expansion and occupation of coastline space. The lack of or need to streamline regulatory/licencing processes around all the discussed potential strategies was apparent as well as the need for robust scientific evidence of carbon offset.

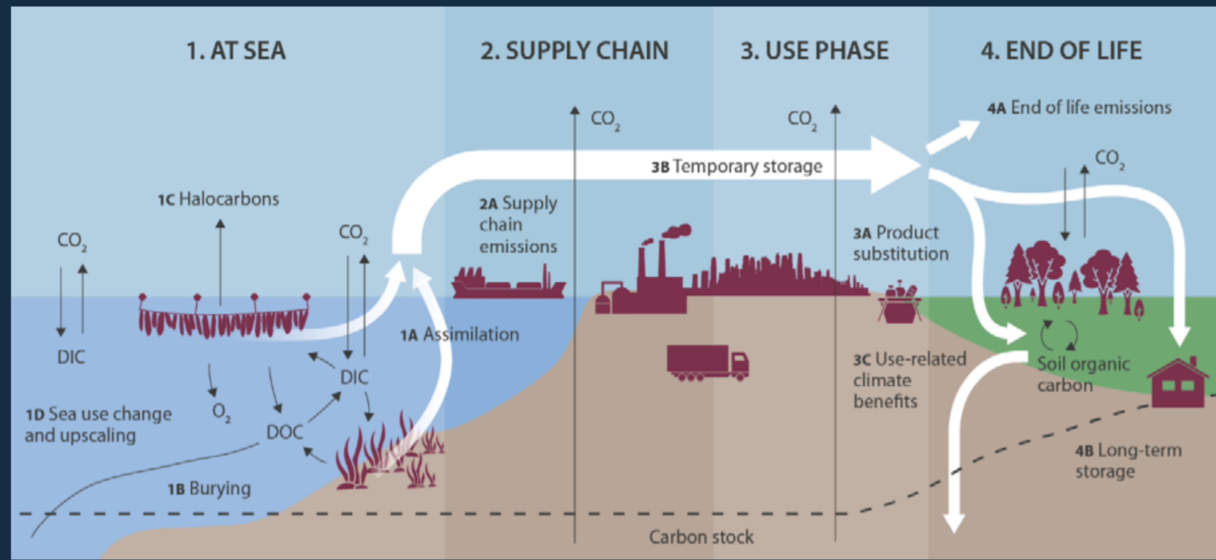


Figure 4.
Figure re-drawn from Hasselström & Thomas, (2022), showing the aspects of seaweed aquaculture that should be included in life cycle analysis (LCA) assessments.

There was much discussion around the 'grow and sink' concept and it was determined that until further research is conducted on the degradation processes, turnover rates, benthic impacts, broader ecosystem effects including those in the pelagic zone, moral issues, legal responsibilities for the ownership of sunk material, legislative frameworks and the duration of such schemes, farming seaweed biomass for sinking into deep water could not be advised. Uncertainty around this concept is particularly applicable to Scottish MA, where much of the coastal shelf is not deep enough to lock carbon away for significant time periods.

It was agreed that Life Cycle Assessment (LCA) analysis should be coupled with any offset scheme, particularly from the nursery stage of seaweed propagation to the packaged, end-product and use of the farmed seaweed (so called 'cradle-to-grave' or 'seed to shelf'). LCA analysis will help streamline this process and form effective C budgets which can be used to calculate offset potential. There is a unique opportunity to partner academia, research, industry and regulators in developing environmentally sustainable practices and legislation around this burgeoning industry.

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