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UK macroalgae aquaculture: What are the key environmental and licensing considerations?

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ABSTRACT

Macroalgae has numerous commercial uses and the potential to create large carbon sinks. The study reviewed the legal context, including environmental and social aspects, for the setting up of a seaweed farm in the UK. A lease is required to use the seabed and a Marine Licence is required from the national regulator. There is no need for new legislation, however, the existing guidance should be updated. There is a major need to clarify what level of assessment is required as part of the marine licensing process. The environmental and social considerations to licensing were also reviewed. Changes to the hydrodynamics and sediment transport are expected in and around the farm. These may lead to changes in seabed siltation and light levels. The addition of hard substrate (from the anchors) and a macroalgae canopy lead to attraction of benthic animals, fish, marine mammals and birds. These, in addition to potential changes in organic matter and nutrients reaching the seabed from exudate and detritus, could create changes in existing benthic communities on the seafloor. No reason for major population-level impacts were seen. However, numerous knowledge gaps where identified. Scale appears to be an important consideration. A small farm on its own is unlikely to have a large effect on the marine environment. However, a very large farm, or multiple small farms next to each other could have a more notable effect. Knowledge gaps were identified and recommendations were provided that can assist the development of the UK macroalgae farming industry.

1. Introduction

Macroalgae aquaculture – the farming of seaweeds and kelps, shows potential to provide a valuable source of algal biomass for a wide variety of products. These range from food products [59] cosmetics, medicines and pharmaceuticals [116], new materials such as biopolymers for use in solar panels [8] and particularly biofuels [43]. A large market for macroalgae already exists in several parts of the world, with production in 2013 reaching almost 26.9 million tonnes wet weight farmed, with an estimated value of $6.6 billion [42]. Asian countries are the biggest seaweed producers, with China being the largest producer, harvesting 13.4 million tonnes wet weight (50.1%) and Indonesia the second largest with 9.3 million tonnes (34.6%) [42]. In the UK, macroalgae have traditionally been wild-harvested in coastal communities for hundreds of years, and used for food, feed and as fertiliser. However, harvesting of wild populations is not a feasible long-term option and is nearing its sustainable limit [113]. It is estimated that 2000 – 3000 dry tonnes (equivalent to 25,000–40,000 t wet weight) of macroalgae are harvested per year in the UK to produce food and feed products as well as speciality chemicals and fertilisers [113]. To date there have been no economic studies published on macroalgae aquaculture for the UK. However, studies from Ireland [14] and the wider North Sea [126] suggest that there is still a notable gap to be overcome before offshore farming becomes viable. Despite the economic challenges interest in commercial macroalgae farming continues to grow.

Along with the economic uses of macroalgae, farming would have social benefits such as creating jobs in coastal areas and improved economic sustainability for coastal/island communities; it would also have environmental benefits regarding sequestration of carbon dioxide and the amelioration of pollutant loads of nutrients, in particular nitrogen. Marine primary producers act as carbon sinks ("Blue Carbon") and are responsible for 55% of the world carbon fixation [87]. In particular, marine macroalgae could represent a significant sink for anthropogenic CO_2. The cultivation and harvesting of seaweeds could play an important role in carbon sequestration and reduction of greenhouse gas emissions [27].

There are however, many challenges and hurdles to be overcome if

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Table 1
Overview of Marine Licence regulators by country within the UK. (Inshore waters are defined as 0–12 NM, offshore waters defined as 12 NM – edge of UK Economic Exclusive Zone or the UK continental shelf [85].

Country	*Regulator*	*Remit*	*Consultees*
England	Marine Management Organisation	Licensing of marine activities under the Marine and Coastal Access Act (2009). Responsibility for screening activities to determine if a licence is required.	Advice and consultation comes from scientific advisors, local/relevant bodies including heritage trusts, lighthouse authority, Maritime and Coastguard Agency and relevant statutory nature conservation bodies. Advice may be taken from organisations across the UK.
Northern Ireland	Department of Environment (inshore waters) Marine Management Organisation (offshore waters)	Provision of Marine licensing in adherence with the Marine and Coastal Access Act (2009) and the Marine Licensing (Civil Sanctions) Order (Northern Ireland) 2011.	
Scotland	Marine Scotland	The Marine Scotland Licensing Operations Team (MS-LOT) provide marine licensing services and enforcement under the Marine (Scotland) Act 2010 (within Scottish inshore waters and under the MCAA 2009 in offshore regional waters (12–200 NM). Macroalgae farms located in Shetland and certain parts of Orkney require an additional works licence from the relevant Harbour of Port Authority. Works Licences ensure that all relevant consultations have been carried out and that there are no adverse effects on the safety of navigation within the Harbour or Port area.	
Wales	National Resource Wales (NRW) (inshore waters) Marine Management Organisation (offshore waters)	NRW Marine Licensing Team (MLT) is responsible for the determination of marine licence applications, ensuring compliance with all relevant legislation in Welsh inshore waters.	

a sustainable macroalgae farming industry is to develop in the UK. Much of this relates to the process of licensing for macroalgae farming. The process of setting up a macroalgae farm in the UK is not clear. While legislation covering aquaculture exists, it has yet to be interpreted for macroalgae culture. This creates considerable uncertainty for potential developers and farmers. There are also a great number of unknowns of the environmental effects (both positive and negative) of macroalgae farming. In turn this further increases the uncertainty (and therefore the risk) for both farmers and regulators.

The purpose of this paper is threefold:

(1) Firstly, the legal and regulatory context of setting up a macroalgae farm was reviewed. Specifically, the following question was addressed: Does relevant legislation exist and is it clear to prospective farmers (and regulators)?
(2) Secondly, the existing evidence base was examined. The critical questions here are:

- Is the evidence base sufficient to allow regulators and their advisors to make informed decisions on applications?
- What are the environmental and social considerations when deploying a macroalgae farm off the UK coast that need to be considered when applying for a marine licence?

(3) Finally, the findings from (1) and (2) are drawn together to provide recommendations that will both assist the macroalgae farming industry in developing, while at the same time allowing regulators to assess applications in an effective manner.

2. Legal and regulatory requirements

The aquaculture consenting processes for England, Scotland and Wales, including algae, have recently been reviewed to varying degrees [2,24,92]. The process for Northern Ireland is essentially the same as in these other parts of the UK. There are two permissions that must be obtained before any development can be introduced to the marine environment in the UK. These are: a lease from The Crown Estate and; a marine licence from the relevant regulator.

2.1. Crown Estates lease

Prospective macroalgae farmers should initially contact the land owner to obtain permission to use proposed area of seabed. In nearly all areas of inshore waters around the UK this is The Crown Estate (custodians of the UK seabed out to the 12-nautical mile (NM) territorial sea limit). A lease must be obtained from The Crown Estate, incurring an annual fee for the lease duration [122]. When applying for a Crown Estate lease, applicants must specify the coordinates of the area proposed for development, along with a description of the cultivation equipment to be deployed and details of how the site would eventually be decommissioned. The Crown Estate also requires an outline of the business / production plan to verify that the prospective development is financially viable. If a marine licence has not yet been granted at the point of application, a lease-option can be obtained, which would remain in place until statutory consent is granted, but would lapse if the consent is not granted within the period specified in the option agreement. A lease-option does not permit development but provides the security of a time-limited exclusive interest in an area of seabed whilst regulatory licence applications and associated information are prepared and submitted.

While the process for applying for a lease appears straight forward, it is notable that all guidance currently refers to fin and shellfish aquaculture, with little or no mention of macroalgae culture. The Crown Estate rental rates are based on the value of the business undertaken and the nature of the development. Finfish farm lease rents are levied as a production-related tariff, while those for shellfish farm leases and macroalgae farm leases are levied on the type and amount of infrastructure installed (i.e. moorings, buoys, lines, platforms etc.). Applicants looking to develop macroalgae farms submit the generic ‘fish farm application form’. Upon receipt of an application, The Crown Estate advises whether the area is available for lease and also provides information on any neighbouring activities that might impact upon the proposed macroalgae farm. For example, the location of any nearby sewage outfalls would affect site suitability if the farmed product (or any waste/by-product) were destined for human consumption.

Table 2
Assessments of requirements that may be required in addition to a Marine Licence.

Assessment	Remit
Environmental Impact Assessment	Commercial macroalgae farms may be considered an Annex II project under the Environmental Impact Assessment Directive (97/11/EC) and so would require an environmental impact assessment (EIA).
Habitats Regulations Assessment	The licensing authority will require a Habitats Regulations Assessment (HRA) if the proposed farm has the potential to impact on designated sites such as Ramsar Sites and Natura 2000 sites, including Special Areas of Conservation (SACs) for the protection of certain habitats and species or Special Protection Areas (SPAs) for the protection of certain wild bird species.
Marine Conservation Zone / Marine Protected Area Assessment	A Marine Conservation Zone or Marine Protected Area Assessment will be required if the regulator deems that the proposed farm could potentially pose a significant risk to the conservation objectives of a Marine conservation zone (MCZ) or Marine Protected Area (under the Marine and Coastal Access Act 2009 or Marine (Scotland) Act 2010), or any ecological or geomorphological processes on which the protected features wholly or partly depend. If an identified risk cannot be avoided, the application would be rejected.
Water Frameworks Directive	An assessment under the Water Frameworks Directive (WFD) will be necessary where a farm located up to one nautical mile offshore has the potential to cause deterioration of the ecological or chemical status of a waterbody, or to compromise improvements that would otherwise lead to the waterbody meeting its WFD objectives.
Permitting farming of alien species.	In England, Wales and Scotland the farming of non-native macroalgae species is not permitted without a permit from the Fish Health Inspectorate. In Northern Ireland permissions must be sought from Department of Agriculture, Environment and Rural Affairs (DAERA). Before permission can be granted a risk assessment may be required under the European Non-native Species in Aquaculture Risk Assessment Scheme (ENSARS) in order to evaluate the risk of the species becoming introduced into the marine environment and to assess the potential damage that any such introduction would cause.
Navigational Marking of the Site	The submerged lines on of a macroalgae farm could pose a hazard to vessel navigation. Macroalgae farms must be marked on navigational charts and so the Admiralty must be informed of planned deployment works via The Hydrographic Office. Additionally, local mariners' and fishing organisations must be made aware of the activity. These steps are required to prevent accidental collision damage following deployment. When a marine licence is issued, it will include details of the number, position and character of navigational buoys required for the surrounding waters.

2.2. Marine environmental licensing

Currently, the introduction of macroalgae farms require a Marine Licence in all cases. There is however, a degree of uncertainty because, although the legislation for marine licensing exists, it has yet to be applied to macroalgae farming, with the exception of a handful of small farms, two of which are research facilities. The licensing process is broadly similar across the United Kingdom. However, the relevant regulator differs in each devolved territory (see Table 1) and there are minor policy differences between each. Applications are made to the regulatory body, who require details of the equipment to be deployed, number of moorings, the coordinates of the outermost moorings and a map of equipment and moorings. The regulator would likely consult various advisors and consultees depending on the size and location of the proposed farm (Table 1). The consultation process can be time consuming. Potential farmers may wish to engage with the advisors or consultees themselves in order to both discuss the farm and understand any concerns the advisory body might have.

Within the Marine Licence application process there may be additional licensing requirements (Table 2). Requirements vary depending on the scale, nature and location of the proposed development, and the risk it may pose to the local environment. In each case the regulator advises what is required to support an application. They can call upon the advice of statutory consultees and scientific advisors when necessary. Of particular note is the possible need for an Environmental Impact Assessment (under the EIA Directive (97/11/EC)). An EIA is an extensive information gathering process intended to identify potential environmental impacts of major development proposals and to ensure that decision makers consider the environmental impacts when deciding whether to proceed with a project.

There is a need to update the existing lease and licensing guidance to cover macroalgae farming. Guidance for marine aquaculture licensing is currently limited to the much more established finfish and shellfish farming. This is partly because most regulatory bodies and their advisors have not previously had to consider macroalgae farming due to the lack of applications for macroalgae farms. Shellfish aquaculture has been specified as exempt from marine licensing requirements under most circumstances [24]. This is not the case for macroalgae culture. However, it is not clear whether this is because it is not considered suitable for exemption, or because, given the relative youth of the industry, it has not been afforded a full review.

2.3. Strategic environmental assessment

Alongside the individual farm licensing requirements there may also be national requirements. If UK public authorities were to develop a national plan or programme to develop macroalgae farming, then a Strategic Environmental Assessment would likely be required under the Directive 2001/42/EC on the assessment of the effects of certain plans and programmes on the environment (SEA Directive). Scotland has begun this process with the release of the seaweed policy statement [78,79]. However, at the time of writing there were no such plans under development elsewhere in the UK.

3. Evidence base

In all Marine Licence applications, including EIAs and related assessments, it is important that the licensing authorities and their advisors have access to an evidence base of the known and potential environmental effects of the activities, including an indication of uncertainties. There are limited studies on the environmental effects of macroalgae farms. In addition, commercial macroalgae farming is almost non-existent in the UK. The result is a very small body of evidence on which to make direct comparisons. Instead, regulatory bodies will need to draw upon comparable activities on which to base decisions of licence applications.

A macroalgae farm is essentially a series of ropes, longlines or mats suspended in the water column [110,120]. Floats or buoys keep the lines off the seabed. Macroalgae are attached to the lines and allowed to grow until they reach a size suitable for harvesting. The lines themselves are anchored in place, typically using rock anchors, concrete weights, or other similar hard substrates. The combined structure shares similarities with structures used for shellfish aquaculture (e.g. [81]).

Farms of large brown macroalgae (e.g. sugar kelp) may be compared to natural kelp forests. However, caution should be taken before extrapolating studies made on natural kelp forests to a seaweed farm. Kelp forests are established over many years and decades with individual "plants" living for 5–25 years depending on the species and location [65]. The communities that are found in them have

Table 3
Summary of potential benefits and effects created by seaweed farming in the UK. For detailed explanation of each topic see individual section(s) below. Text in italics are option-based rather than evidence-based.

Effects On	Potential Benefits	Potential Effects	Potential for Scaling of Benefits/ Effects.
Hydrodynamics/sediment dynamics (Section 3.1)	• Reduction of water motion / wave action – coastal protection or reduced scour around offshore infrastructures; • Increased sedimentation resulting in increased water clarity;	Effect on sediment dynamics and suspended load resulting in changes in coastal erosion/accretion	Benefits/effects likely to scale up with size of farm(s). Potentially over a large area.
Nutrients (water quality) (Section 3.2)	• Uptake of nutrient in nutrient-enriched areas (phytoremediation); • Uptake of pollutants • Uptake of nutrients from fish/shellfish farms (IMTA)	• Competition for nutrients with wild, local, seaweed communities or other benthic plants • Uptake of pollutants complicating use of seaweeds in food products	Benefits/effects likely to scale up with size of farm(s).
Marine flora and fauna (Section 3.3)	• Refuge for animals (Section 3.3); • Increase in biodiversity (organisms living in/ around the kelp farms) (Section 3.3); • Nursery for fish (Section 3.3.1); • Creation of new substratum (e.g. with anchoring) (Section 3.3.2); • Fragments from seaweeds as additional food source for bottom organisms (Section 3.3.2); • Provision of food (Sections 3.3.2–3.3.5).	• Obstacles for fauna (Sections 3.3.4 and 3.3.5); • Shading / abrasion of the bottom – light limitation for bottom plants (Section 3.2; • Habitat change of sea floor with infrastructure e.g. anchoring (Section 3.3.2); • Attraction of grazers, disease or other pests (Section 3.3.2) • Excess deposition of seaweed fragments at the bottom (Section 3.3.2); • Changes in benthic community as result of the above (Section 3.3.2); • Stepping stone for spreading of existing non-native species (Section 3.3.2); • Displacement of native species (Section 3.2).	• Benefits/effects limited to the area of the farm and immediate surrounding area. • Habitat change due to anchoring minimal in comparison to seabed
Volatile gases (Section 3.4)	Sink for CO_2 emission (blue carbon).	Release of iodine compounds (nucleus for clouds formation) leading to alteration of local weather.	• Benefits would scale up with the size of the farm. • Effects thought to be highly unlikely in cultured macroalgae.
Social considerations (Section 3.5)	• Coastal area – benefits from reduced wave action (Section 3.1); • *Tourism – benefits from clearer water* (Section 3.1); • Aquaculture – offsetting nutrient production from fish/shellfish farms (Section 3.2); • New employment opportunities and business development for coastal communities; • *Seaweeds beach-cast may attract seabirds improving shoreline diversity and tourism*;	Beach-cast from farm can deter tourism or accumulate in ports;	• Hydrographic, sedimentation and nutrient benefits could scale up as farms get larger. • *Large scale beach-cast probably unlikely – would be mitigated against to avoid crop loss.*

developed alongside the kelp forest. In contrast, a seaweed farm is far less developed. If adopting a yearly cycle (with algae seeded and harvested within a year), a mature kelp forest will never develop. The differences could be likened to comparing a natural forest to hundreds of well-kept plant pots that are replanted each year.

The available information of the environmental effects and benefits of macroalgae culture are summarised in Table 3. The individual topics are examined in detail within the sections below.

3.1. Hydrodynamics and sediment dynamics

Water motion is highly important for macroalgae as it affects critical functions such as uptake of dissolved nutrients and gases, removes sediments and waste products, and can reduce settlement of epiphytes and grazers on algae (see reviews by [66,67] and references within). In fact, Kerrison et al. [66] suggested that for these reasons macroalgae culture should be carried out at sites with moderate to high water motion (flow > 0.1–0.25 m s^{-1}).

Just as hydrodynamics affect macroalgae, there is a feedback interaction between macroalgae and their physical environment. Aggregations of macroalgae act as a region of high drag and have been shown to affect water velocity and attenuate waves [48,60,67]. For example, kelp forests in California have a several-fold damping effect on alongshore water velocities and internal waves, as well as a reduction on across-shore velocities [48,60,108]. Furthermore, kelp forests create a region along the forest's outer boundary of accelerated flow compared with the incident water speed [108].

The effects of kelp aggregates dynamics on their physical environment are comparable to those observed from offshore aquaculture as they both have similar crop density and a suspended canopy [51,118]. However, in aquaculture, kelp canopies are generally suspended in the upper part of the water column while kelp forests are attached at the seabed, extending up through the water column [118]. There is evidence that suspended aquaculture reduces water flow, as shown by a model study of a bay in China. The model predicted a reduction of 54% in current within farms of kelp and scallops on suspended longlines [51]. Similar reductions in current (between 36% and 63% reduction) were measured by Plew et al. [103] for a large offshore longline shellfish farm in New Zealand. The authors also recorded wave energy attenuation across the farm (650 m), with waves at higher frequency (0.25 Hz) showing greatest loss (17%; [103]). Another important aspect observed in suspended aquaculture, was the presence of an undercurrent beneath the farm with higher velocities than within the longlines [103]; higher velocities are also predicted in the smaller secondary flow channels within the culture area [51]. It is expected that the drag of the farm and the current reduction will be dependent on the spatial arrangement of the farm, rope geometry, culture type, age of the culture and harvest status [51], although further work is required to understand this in the context of a macroalgae farm within the UK.

Changes in water flow associated with kelp forests can result in modification of sedimentation rates of suspended particles within kelp aggregates. Tracer particle experiments showed that kelp canopies reduced the penetration rate of suspended particles from the water column to the bottom [37]. However, beneath the canopy, the reduction of turbulent mixing and reduced shears, increased the residence time of the particles and their rates of deposition [37].

Although both shellfish and kelp culture have been shown to modify water flow and potentially particle deposition, it is unclear what the wider effects of macroalgae farming could be on coastal areas in terms of variations in particles budgets and dynamics or altered wave and current action. Suspended particle dynamics in coastal waters affect the light climate and therefore light availability for primary producers as well as the behaviour, predator/prey relationships and catchability of fish and crustacean (see review by Capuzzo et al. [22] and references within). To understand the effects of macroalgae farming on hydrodynamics, sediment budgets and light climate, a study of the area (including both modelling and in situ sampling) prior and during farming activities would be required. For example, the study should consider water velocity inside and outside the farm; sediment transport pathways; sedimentation rates within and outside farm (upstream and downstream); and identification of potential sediment deposition locations.

3.2. Nutrient levels and pollutants (water quality)

Macroalgae requires dissolved nutrients for growth and metabolic processes. Rates at which macroalgae uptake nutrients from water are affected by different factors including light availability, temperature, water movement, dissolved nutrient concentrations in water and their chemical form, plant age and nutritional past history [4,54].

As efficient absorbers of dissolved nutrients, macroalgae can act as biofilters, reducing nutrient concentrations released from fish and crustacean farms [4,13,15,26,75,111,125], as well as from other sources, helping to reduce the effects of anthropogenic nutrient-enrichment in coastal waters (e.g. [44,56]).

Integration of seaweed farms with fish/crustacean farms (Integrated Multi-Trophic Aquaculture or IMTA) has the dual effect of offsetting the waste nutrient produced by the fish farm while increasing growing rates and yields of macroalgae. For example, the red algae *Gracilaria* cultivated at 10 m from salmon cages in southern Chile showed a 40% higher growth rate than *Gracilaria* farmed further away. It was estimated that 1 ha of *Gracilaria* could remove 6.5% of dissolved nitrogen and 27% of dissolved phosphorous from the farm [124]. Similar experiments were also carried out in northwest Scotland with *Palmaria palmata* and *Saccharina latissima* [111]. As with the previous study, growth rates of algae increased near the salmon farm (48% for *P. palmata* and 61% for *S. latissima*), removing up to 12% and 5% of waste nitrogen from the farm for *P. palmata* and *S. latissima* respectively [111]. Neori et al., [89] showed that *Ulva lactuca* could remove 80% of the ammonium content of effluents from land-based fish tanks.

While the bioremediation potential of seaweed farms has been described in different studies, it is less clear what the effects of large-scale seaweed farms may be on phytoplankton and/or benthic plants, in terms of competition for dissolved nutrients. In a Chinese eutrophic bay [61], phytoplankton was not affected by kelp farming, and phytoplankton abundance was higher within the farm than outside. However, changes were observed in the phytoplankton community structure. Within the kelp farm, chain-forming diatoms dominated the phytoplankton community (possibly as result of reduced water velocity within the farm) and increased diversity of the phytoplankton community was observed [61].

Competition for dissolved nutrients between farmed seaweed and phytoplankton/benthic plants is more likely to occur in non-eutrophic water bodies as shown by Aldridge et al., [5] in a modelling study. Two model approaches (a kelp-phytoplankton compartment 1-D model and a 3-D coupled hydrodynamic-biogeochemistry model) were used to investigate the nutrient sink of a potential *S. latissima* farm (approximate 20 km^2) at different locations on the west coast of Scotland. The models predicted an effect on phytoplankton within the farm, as results of nutrient competition, compared with non-farmed reference sites; in particular, the decrease in phytoplankton (expressed as chlorophyll concentration) was predicted to be greater than 10% at distances in excess of 7.5 km from the edge of the seaweed farm [5]. However, in cases where competition for nutrients between microalgae and macroalgae does occur, due to the differences in their respective nutrient uptake rates, most seaweeds cannot compete with microalgae when nutrients are limiting [57] and will rely on stored nutrients to sustain growth.

A limited number of studies have investigated the potential competition between benthic plants and macroalgae farms, with the majority of studies focused on the effects of seaweed farming in shallow tropical lagoons, on seagrass beds [38,39,76,98]. These studies suggested that macroalgae farms caused a reduction in seagrass mainly due to shading and mechanical abrasion, rather than nutrient competition. In temperate waters, Stephens et al. [117] modelled (using GIS layers and a predictive model) the nutrient sink in a potential *S. latissima* farm compared to natural kelp beds, at different locations off the west coast of Scotland. The predictive models highlighted that, at location with high standing stock of 'natural' (as opposed to farmed) kelp, a farm of 20 km^2 could potentially compete with natural kelp for nutrients. How important this competition could be at an ecological level would require further study and should be considered at the site level.

Macroalgae are not only efficient in taking up dissolved nutrients but also heavy metals (e.g. cadmium, zinc, copper, lead, arsenic), which are absorbed by the components of the algae cell wall (alginic acid and fucoidan in brown algae; see review by Figueira et al. [45]) and radionuclides (see review by Burger [17]). Heavy metals reach the marine environments from different sources such as industrial and urbans wastes and effluents, excessive use of fertilizers in water runoff, boating marinas (see review by Evans and Edwards, [41] and reference within; Johnston et al. [62]); while presence of radionuclides could be natural, or caused by fallout from explosions, emissions from nuclear facilities, disposal of radioactive waste or accidents ([17] and reference within). The ability of seaweeds at accumulating heavy metals and radionuclides can have positive implications; for example, seaweeds can be employed as bioindicators [17,41,62] or for phytoremediation of water bodies [20,82]. Contrarily, contaminated seaweeds may introduce heavy metals or radionuclides into the human food chain (e.g. if used as food supplements, sea vegetables, animal feed, fertilizers (e.g. [94,107]).

To investigate further the potential effects of macroalgae aquaculture on dissolved nutrients, and other primary producers, it would be important to combine model outputs with in situ observations of nutrient budgets, nutrient uptake by macroalgae, phytoplankton concentration and composition, as well as growth and distribution of benthic plants. The presence of heavy metals or radionuclides in seaweeds can be detected from analysis of seaweed samples, and should be carried out at different algal growth stages and from different parts of the algae (e.g. holdfast, frond; [16,17]. The sources of potential contamination could be investigated with models, for example simulating tracer dispersion.

3.3. Marine flora and fauna

3.3.1. Zooplankton

There are limited studies on zooplankton within farmed macroalgae. However, they suggest that many species of zooplankton may benefit from the presence of a macroalgae farm in terms of shelter and food availability (e.g. [53,58,100]).

3.3.2. Benthos

In a kelp forest the combination of rocky substrate and a high level of shelter offered by the understory of the algae are attractive to a wide variety of benthic organisms such as lobster and crab [11,32], and herbivorous animals such as urchin and sea hares [63]. In a macroalgae farm the hard substrate is limited to the anchors (which are typically deployed on soft seabed). At Queen's University Belfast's pilot kelp farm in Strangford Lough, mesh bags filled with rocks are being trialled as anchors. The rocks and crevices of the anchor bags function as artificial substrate and provide additional habitat for a range of benthic organisms including seaweeds, tunicates, razor clams and crabs (K. Mooney observation). Elsewhere, direct observations are highly limited, although studies on other types of infrastructure (e.g. marinas, moorings, and particularly offshore wind farms) could provide an indication of what benthic species would likely colonise the anchoring of a macroalgae farm (e.g. [7,72,119,130,131]). Organisms already established on infrastructure foundations could use the anchors as the next “stepping stone” in their colonisation [3,83,102]. Evidence from the monitoring of offshore wind farms foundations suggest that the introduction of hard substrate does not affect the surrounding sediment infauna [10,12,31]. It should also be noted that the area occupied by the anchors will be minute compared to the natural seabed.

The macroalgae itself will provide habitat for a wide variety of benthic organisms. Macroalgae, and particularly kelp forests, are associated with high diversity of organisms [18,65,128]. In a study of subtidal environments around the UK, Burrows [18] noted that in particular *Laminaria hyperborea* appeared to be the main driver on patterns of species diversity in the UK subtidal environments. Whether a macroalgae farm would have similar positive benefits on species diversity is not known.

Natural kelp forests are grazed by a variety of benthic invertebrates including sea urchins, snails, abalone and small crustaceans. When cultivated, the kelp are suspended mid-water and so are not accessible to benthic invertebrates, however the planktonic larval stages can settle and develop into grazing juveniles. This process can lead to significant grazing and biomass loss during the early summer, as reported by Kerrison et al. [66], during cultivation of *S. latissima* grazed by 1–5 mm *Lacuna vincta* snails. Such grazing, or overgrowth by epiphytes such as bryozoans and mussels can affect the timing of the harvest [66,80]. Fish grazing is known to occur, but is considered to only have a minor influence on the overall yield [101].

Along with unwanted grazers, diseases are also important considerations. Disease outbreak in macroalgae farming can have major consequences for crop yield [29]. There is the potential that a disease could also be passed to nearby wild stocks of macroalgae – a risk that would be assessed during licensing in a similar way to other aquaculture.

The holdfasts of kelp are typically the most species-diverse part of the algae [123]. In a kelp farm, the holdfast habitat is not benthic, but suspended within the water column, therefore creating a different understorey area compared to a kelp forest. Walls et al., [128] examined the differences between benthic organisms on the holdfasts of kelp growing in natural forests and those of cultivated kelp. They noted that while similar numbers of individuals were found on the natural and cultivated holdfasts, a greater number of species where identified on the cultivated holdfasts. Further studies are needed to determine exactly why these differences might occur. Walls et al., [128] did, however, observe that the morphology of the holdfasts was quite different between cultivated and natural specimens, which could contribute to the differences.

Walls et al. [128] also observed that there are many differences between the hydrodynamic conditions experienced by natural kelp and farmed kelp including height, salinity, oxygen concentration, light levels and suspended sediment conditions. It is possible that the reduced light climate would affect other benthic primary producers, which could also compete with farmed macroalgae for nutrients. The shaded area below the algae may also provide refuge for specific sessile invertebrates [28,36]. A greater understanding of how macroalgae farming would affect light levels is required before assessments could be more confidently made.

Kelp forests can also affect benthic organisms through the detrital pathway as result of fragmentation and particulate organic carbon, POM [35,134]. In a kelp forest off Cape Town (South Africa), it was estimated that kelp detritus constituted > 65% of the POM in exposed and sheltered habitats, and represented an important food source for filter-feeders and grazers [19]. In addition to fragmentation and particulate organic carbon, kelp plants also produce organic exudate [1]. Within a natural kelp forest the organic material is utilized by animals living in the benthic layer beneath the algae [35]. The sedimentation of fragments from the canopy of a macroalgae kelp farm could lead to the formation of an organic-enriched sediment layer within and/or around the seaweed farm. Farmed macroalgae would be harvested regularly, therefore, the number of fragments (e.g. from senescent plants) would likely be less than a kelp forest. The most relevant comparisons can be drawn from the ecosystem interactions of kelp forests and the observed effects of shellfish farming. The degree and spatial extent of environmental effect is related to the system's ability to disperse bio-deposits from the farm [25,90]. Research on the effects of detrital output of mussel farms on the benthos have shown that, in low energy environments (similar to where kelp cultivation could take place), effects are localised and confined to < 50 m from the farm boundary [21,49].

Overall, there is a need to understand how both the presence of the macroalgae and the organic output of a macroalgae farm could alter benthic conditions. These include questions on how macroalgae farming could influence the wider ecosystem processes. They also include questions on how benthic grazers and indeed, other potential pests, epiphytes or diseases [29] could affect yields for the farmer.

3.3.3. Fish

The limited studies describing interactions between farms and fish populations typically report an increase in habitat for fish [9,133], particularly juvenile fish (e.g. [106]), although Bergman and Svensson, [9] also reported a decrease in fish numbers in certain cases. Studies have also focused on degradation of existing seagrass fish habitat caused by macroalgae farming (e.g. [39]). These are unlikely to be relevant to the UK however, as seagrass habitats are considered under the marine licensing process as a UK Biodiversity Action Plan priority habitat.

The high density of suspended algae means a macroalgae farm has similarities between an artificial kelp forest and a fish attraction device (FADs). It is well known that fish are attracted by floating objects of notable size [23,34]. Natural kelp forests are well documented as being highly diverse in fish species and also highly important to many fish species (e.g. [33,65,95,115]). The species of fish present vary depending on both the local area and also the species of kelp (see review in [65]). Studies elsewhere in Northern Europe suggest a number of species are likely to benefit. These include wrasse such as *Labrus bergylta* and *Ctenolabrus rupestris,* juvenile cod (*Gadus morhua*) and short spined scorpion fish (*Myoxocephalus scorpius*) [95]. Large macroalgae, and in particular kelp forests, provide shelter, refuge from predators and food, both for the kelp itself and fauna living on or around the kelp [55]. A large-scale commercial seaweed farm would have similarities to a kelp forest, although this would mainly be around the time of maximal growth and before harvest.

3.3.4. Marine mammals

Harbour porpoise (*Phocoena phocoena*), harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*) are regularly seen around the UK [105,114]. Harbour porpoise and seals are largely piscivorous and are not thought to eat macroalgae [112]. They should not to pose a nuisance issue to macroalgae farming in the same way as seals do to fish aquaculture (e.g. [88,96,97]). There appear to be no studies on the interactions of UK marine mammals with macroalgae farms, but it is conceivable that they may take advantage of increased aggregations of prey in a similar way to sea otters do in kelp forests (e.g. [40]) or seals do when foraging systematically around the foundations of offshore wind farms [109].

3.3.5. Birds

While there are few, if any studies on birds in macroalgae farms, birds are well known to use kelp forests around the world, particularly cormorants, eider ducks and egrets (e.g. [46,50]). Again, it is conceivable that many seabirds may benefit from the aggregated prey within the macroalgae farm. Conversely, changes to seabed habitat need to be considered in terms of prey availability, particularly in areas where seabird species depend on benthic fish such as sandeels for food (e.g. [121,129]). Finally, the surface floats and navigational markers offer some limited resting points and allow birds to extend foraging ranges (e.g. [74,127]).

3.4. Volatile gases

As well as taking up carbon, macroalgae also release volatile gases such as halogenated organic compounds and molecular iodine [69,70,93]. In particular, kelp accumulate high quantities of iodine which is used as an inorganic antioxidant [69]. When subjected to oxidative stress (e.g. if exposed during low tide), kelp plants release molecular iodine (I_2) into the surrounding water or air [69,93]. The iodine compounds, released by kelp during oxidative stress, can be measured in the lower atmosphere in the marine-terrestrial transition zone, particularly at sites with high density of kelp, at low tide (e.g. [73]). Atmospheric iodine plays an important role in the marine boundary layer as it forms hygroscopic iodine oxides turning into particles, which can develop into cloud condensation nuclei [69,93]. The latter could affect local and regional climate and radiative forcing [70].

In aquaculture, kelp is farmed suspended in the water column and not exposed during low tide. The amount of volatile gases released by farmed macroalgae would depend on the size of the farm and it would likely peak during the harvesting of the seaweed (i.e. when macroalgae are exposed to oxidative stress), if the algae is not sealed in containers immediately after harvesting.

3.5. Social considerations

The effects on seascape, or visual impact can be a major barrier for offshore developments. Objections based on the visual impact have often been cited as one of the main objections against offshore wind farms in particular [71] but also aquaculture sites [91]. For a seaweed farm only buoys and navigational markers would be visible. Visual disturbance should be much less than that traditionally associated with finfish aquaculture, but similar to that of mussel aquaculture.

Effects on tourism may be considered as part of the marine licensing process. Macroalgae produce detritus as results of blade erosion, fragmentation of blade, dislodgment of plants; the detritus may sediment underneath the plant or may be exported to other locations, including beaches [68]. Beach cast wracks (i.e. beach cast phytodetritus) are a major food source and/or habitat for invertebrates, which in turn attract birds; ([52] and references therein; [65,99]). However, large quantities of seaweed detritus washing up on tourist beaches may be unwanted due to the appearance and smell. This is probably highly unlikely for a macroalgae farm, considering that the macroalgae would be harvested before blade erosion has occurred (to obtain the highest algal biomass).

4. Discussion and recommendations

4.1. Legal context

The process of obtaining a lease from The Crown Estate is straightforward. However, the majority of guidance for this process refers only to finfish and shellfish aquaculture, rather than macroalgae culture. The present review has also highlighted the lack of an established procedure for obtaining a Marine Licence for macroalgae farming. Although the necessary legislation is already in place, it has not been clarified how this will be interpreted in practical terms. Currently, there is great uncertainty over the depth of information required for licence applications. The lack of guidance on the circumstances under which a full EIA would be required is particularly notable. Given the considerable cost associated with carrying out an EIA, the ambiguity over whether this process would be expected prevents confident prediction of start-up costs and may therefore deter prospective investors. There is a need to clarify whether macroalgae farming activities would be classified as exempt from marine licensing requirements, as is the case for UK shellfish aquaculture. Such an exemption would be associated with significant savings in farm set up and subsequent running costs, and would therefore be beneficial to growth of the industry.

It is recommend that the guidance on leasing and licensing is updated to include macroalgae culture. It is also recommend that these clarifications are made by the regulators, following consultation with their advisors, academics and the macroalgae industry. In addition, learning from regulators and scientists in countries where macroalgae farming is well establish is likely to be very beneficial.

4.2. Environmental and social evidence base

4.2.1. Effects not impacts

There is a need to use the appropriate terminology in order to support the emerging seaweed industry. Throughout this study it became apparent that while the available information on the environmental effects of seaweed farm is limited, there is nothing to suggest that population level “impacts” may be caused by seaweed farming. Macroalgae farming for example does not produce the highly publicised pressures such as loud impulsive noise or collision risks that have been of concern to the renewables industry (e.g. [47,64,86,104,132]). It is suggested that the term “impact” (i.e. marked influence of farming on the environment, particularly leading to population-level changes) is not used unless evidence shows this is a realistic possibility. Instead it is suggested that the term environmental “effect” (i.e. a change in the environment, resulting from farming activities) is used.

It may be helpful to consider the effects of macroalgae farming in terms of significance. The Environmental Impact Assessment (EIA) Directive 2011/92/EU requires developers to classify impacts in terms of their likely significant effects on the environment. This is determined by considering: geographical extent of impact; magnitude and complexity; probability; duration, frequency and reversibility; and trans-frontier nature of impact(s). In addition, the European Union's (2008/56/EC) Marine Strategy Framework Directive (MSFD), aiming to achieve Good Environmental Status (GES) by 2020 across European marine environment, requires Member States to take actions if there is a “significant risk” to the State's marine waters. Consequently the description of effects of seaweed farming in terms of significance would maintain consistency with language already in use in environmental legislation and provide defined and widely understood terminology for both positive and negative effects.

4.2.2. Define scale

It is not felt that the current evidence base supports concern for population level impacts. However, when the current knowledge base is examined, it is clear that there are many gaps in our understanding.

Some effects such as alteration of local weather are likely to be negligible. Other effects are far less understood and do have the potential for wider scale effects. Scale therefore, is a very important factor when assessing seaweed farms.

The environmental effects from a small isolated farm may be minimal. In contrast, very large farms would have an increased likelihood of environmental effects on a greater number of receptors. In the same manner, multiple small farms in close proximity to each other could create cumulative effects, and may need to be viewed as a single entity. Quantifying size, and possibly usage categories (i.e. food, biofuel, chemical etc.), is necessary for regulatory bodies to determine the appropriate level of assessment required.

4.2.3. Define research and monitoring priorities

In reviewing the existing evidence base, it becomes apparent that there are many unknowns surrounding the environmental assessment of macroalgae farming. Within this study three main groups of evidence requirements have appeared.

Firstly, there is a need to understand how seaweed farms might affect the physical environment. Large farms in particularly, could have notable effects on current speed, suspended sediment loads, light penetration and wave energy. Understanding these effects through modelling and in-situ measurements is needed before the potential for effects on the wider marine environment can be really determined.

Secondly, there is a need to understand dissolved nutrient dynamics in and around the farm. There are two considerations here: the first being competition with natural populations of algae (both micro and macro), and the second being competition between and within adjacent farms. This second point of “nutrient shadowing” would be of particular interest to the Industry. In order to maximise yield, farmers will want to avoid nutrient competition, both between adjacent farms or even within large farms.

Finally, there is a real lack of data and evidence to understand the effects of macroalgae culture on the marine life, within and around the farm. A large-scale macroalgae farm is likely to provide habitat for many species of marine organism ranging from plankton, benthos and fish, and in turn will attract likely marine mammals and seabirds, although further studies are required to determine which species might be affected in specific sites. How physical changes to current flow, suspended sediment and light levels within the farm affect marine organisms will require a much greater understanding than is currently possessed. Changes to wider population numbers (biomass) and community structures require investigation, and again require additional data. The effect of the reduction or complete removal of the algae canopy due to harvesting on marine life also needs to be investigated and understood.

Inevitably these gaps in our understanding will lead to calls for monitoring requirements to be placed upon new and early farms. With so many unknowns and gaps in the existing data and evidence, there is the risk of adopting an overly conservative approach. Requirements for excessive levels of surveying and monitoring could place an unnecessary burden on prospective farmers and deter investment. On the other hand, farmers could offer to carry out monitoring in collaboration with researchers to tackle a specific consideration of their farm. Doing so, in consultation with interested parties, could reassure local stakeholders that environmental factors are being suitably considered. In Scotland a “Survey, deploy and monitor” policy has been used in licensing wave and tidal energy device developments [77]. The survey, deploy and monitor approach provides a framework on which to base decisions on the appropriate levels of monitoring for a particular development based on factors such as size of the development, environmental sensitivity of the deployment area and the type of development. Adopting a similar approach could also be beneficial to the macroalgae farming sector.

To avoid duplication of monitoring and research effort it is recommend that a coordinated approach is taken both within individual countries and across the UK as a whole. In turn, this approach needs to flow seamlessly into the approaches of neighbouring states, wherever possible. Examples of such coordinated approaches include the COWRIE fund [30] for offshore wind and the ALSF used within the aggregates industry [6] and the NERC renewables programme. Such large-scale programmes may be difficult to fund in the current economic climate. Ensuring that any research or monitoring is question-led and avoids the criticisms of previous monitoring of UK offshore wind farms (see discussion in MMO [84]) through coordination and dialogue between researchers and regulators, can overcome many of the financial challenges. Such approaches require the continuous input and dialogue of all parties including the regulators, their advisors, including academic researchers and critically, input from the industry. Workshops were held as part of the development of a UK Roadmap for Algal Technologies [113]. It is recommended that the dialoge from these initial worshops is continued through forums and specific events at conference/symposiums to bring the relevant groups together so that the current knowledge gaps may be filled.

Overall, macroalgae farming in the UK has the potential to benefit communities and economies both in the immediate coastal areas of the farms and further afield, through further processing into various higher value products. To promote and ensure that the development of the industry is sustainable, both for the industry but also crucially for the marine environment, investment, research and dialogue is needed from all sides involved.

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