Seaweed aquaculture and mechanical harvesting: an evidence review to support sustainable management

First published December 2021

Natural England Research Report NECR378

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Published September 2021

Project details

This report should be cited as:

Wilding, C. Tillin, H. Corrigan, S. E. Stuart, E. Ashton I. A. Felstead, P. Lubelski, A. Burrows, M. Smale D. 2021. Seaweed aquaculture and mechanical harvesting: an evidence review to support sustainable management. *Natural England Commissioned Reports. Natural England Report NECR378.*

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Keywords

Seaweed, harvesting, aquaculture, cultivation

Further information

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Executive Summary

Seaweed production in England and Wales is an emerging industry. The aim of this contract was to increase understanding of the methods used for mechanised harvesting and seaweed aquaculture, potential environmental effects or impacts, potential management measures, and to develop recommendations for best practices.

Aquaculture of seaweed

At present, most cultivation sites in England and Wales are small scale. Several pilot scale research farms exist, with a handful of commercial farms operational in England, and more proposed for both England and Wales.

Seaweed farming is generally considered to be relatively environmentally benign, with either limited or positive impacts on marine ecosystems, even when modelled at a large scale. Limited evidence was found on impacts in UK waters, however inferences can be drawn from Europe and globally.

The positive impacts of kelp farming include socio–economic benefits through provision of jobs and enhanced coastal protection. Farms may provide habitat (e.g. for fish) and support environmental quality through bioremediation (absorption of nutrients and pollutants) and carbon fixation (in seaweed tissues) mitigating climate change.

The potential negative impacts/risks of seaweed farming on ecosystems include direct impacts from activity and infrastructure including disturbance from noise and vessel traffic, entanglement risks for larger mobile species and effects on seabed habitats from shading and sediment and organic matter settlement resulting from water flow reduction. Seaweed farms (including non-natural materials such as plastic ropes) and the crop itself may also introduce and spread non-native species, parasites and disease. Non-native species that are likely to be associated with cultivated seaweeds and infrastructure and that have significant ecosystem impacts tend to be attached, epiphytic algae and biofouling tunicates, bryozoans and hydroids. For a number of these species, particularly invasive tunicates, natural dispersal is limited and the main vector for spread is movement of fouled floating structures, e.g. ship hulls and potential rafting on detached seaweeds.

Indirect ecological effects on ecosystems include potential changes in nutrient cycling pathways and rates, due to uptake of nutrients and trace elements; release of particulate and dissolved organic and inorganic matter; through to the effects of uptake of carbon at local, regional and potentially global scales. Farms may also impact wild kelp populations through harvesting reproductive tissue (for cultivation),

Impacts are likely to be scale dependent, with smaller farms unlikely to negatively impact the environment, but a very large farm or several small farms next to each other could have a larger or cumulative impact. Invasive non-native species that are likely to be associated with seaweed cultivation operations are epiphytic algae, tunicates, bryozoans and hydroids.

Knowledge gaps include technological and operational optimisation issues and understanding of the ecological effects of seaweeds farms on the surrounding environment. At ecosystem scales the consequences of indirect ecological effects such as uptake of nutrients and release of dissolved organic material have only really been addressed using modelling studies.

Cultivation best practice guidance recommend appropriate sourcing of fertile material, monitoring for pests, diseases and non-native species, maintenance of infrastructure in

good working order, monitoring of environmental impacts, reporting of entanglement incidents and production volumes, appropriate site selection to inform marine spatial planning, and community engagement to facilitate granting of social licence.

Mechanical harvesting

Large seaweeds such as kelps and wracks are the only species suitable for mechanised harvest in England and Wales. Trawling is generally used to harvest species that inhabit greater depths, such as kelp (i.e. *Laminaria hyperborea*). Mechanical cutting boats or mowers are used in a number of countries to harvest wracks, such as *A. nodosum* (i.e. Scotland, Iceland, Norway and Maine, USA). Generally it is not possible to harvest kelp with this method, as in the UK kelp inhabit greater depths and lack floating air bladders, so are inaccessible.

Canopy removal will impact reduce primary production and alter habitat provision and secondary production rates of associated species. Phase shifts, with harvested populations replaced by different species altering habitats, has been observed in Norway. Harvesting may alter and homogenise genetic composition in harvested populations with potential reduction in resilience to impacts. Studies on fish show that harvesting impacts vary although there could be potential effects on commercial fisheries. There is currently limited understanding of the extent to which marine mammals rely on or utilise kelp forests in the UK and wider Europe and hence how these may be impacted by canopy removal.

The impacts of mechanical harvesting will depend on geographic location, algal regenerative ability and harvesting pressure (technique, volume, frequency, intensity). The magnitude of impacts can be reduced through management actions such as implementing quotas, seasonal closures, spatial zoning (e.g. rotation, no take zones, fallow areas), gear restrictions and community co-management.

Several studies in Europe have found that new kelp forests are able to establish after mechanical harvesting or artificial removal. Recovery is more rapid if the harvest area is in close proximity to an untrawled area and the rock surface is not scraped entirely clean of small kelp recruits. Generally, fast growing opportunistic algae tend to colonise the rocks immediately after *L. hyperborea* is removed, but through the process of natural succession *L. hyperborea* becomes the dominant species 2-3 years after harvesting. However, the rate of recolonization and recovery is highly variable and seemingly affected by multiple physical and biological factors. As such, repeated harvesting e very 3 years or less will notallow *L. hyperborea* to re-establish as the dominant species.

Management tools are available and approaches should be tailored to meet the individual species, region and proposed harvesting regime in question. These include se asonal closures, mandated fallow periods, closed areas, selective and partial harvesting, and total allowable harvest (reviewed regularly).

Generalisations from other countries can provide insights into management procedures but for a sustainable commercial harvest for UK kelp populations, the monitoring of standing stock biomass before and after harvest should be implemented into management procedures so to correctly monitor recovery rates. Effective monitoring will capture changesin population structure through time, allow for natural and anthropogenic pressures to be disentangled and provide opportunities to alter management approaches to achieve sustainability. Research and monitoring programmes that have been developed in collaboration between harvesters, researchers and government agencies have generally been more successful.

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1. Introduction

1.1 Background

There is growing interest in the production of seaweed, driven by high market demand for a range of applications. Expansion of seaweed cultivation has been identified as a priority for blue growth (Daniels and others, 2020; Doumeizel and others, 2020; MMO 2019) and has the potential to contribute to ensuring global food security (Kerrison and others, 2020).

Seaweed has been intensively cultivated for food in Asia for centuries, but global seaweed farming has rapidly intensified in recent years and has expanded to regions in South America, Europe and North America. In addition, seaweed cultivation is now see n as an important component of integrated multitrophic aquaculture (IMTA) in many countries around the world. Approximately 30 million tonnes of seaweed were farmed globally in 2016 (Grebe and others, 2019), of which around 27% was derived from kelp species (ca. 30 genera of the order Laminariales) (Grebe and others, 2019). America and Europe's production of farmed kelp was only equivalent to 1.5% of global gross production in 2014, but is considered a 'speciality product' that fetches higher prices than kelp farmed in Asia (Grebe and others, 2019).

To date, seaweed production in the UK has focussed on wild harvesting (Capuzzo and others, 2018), although there is a consensus that growth of sustainable cultivation is necessary in order to meet the increasing demand for biomass while simultan eously protecting wild seaweed stocks (Buck and Grote, 2018; Capuzzo and McKie, 2016; Barbier and others, 2019; MMO 2019).

In England, development of seaweed aquaculture has been identified as a key area with substantial potential for national blue growth (MMO, 2019), both in a recent policy brief (Daniels and others, 2020) and 'Seafood 2040 - A strategic framework for England'[1]. Further, the UN Seaweed Manifesto (Doumeizel and others, 2020) outlines how responsible expansion of seaweed aquaculture can support several sustainable development goals including: economic growth and resilience in coastal communities; responsible consumption and production; facilitating climate action; benefiting marine life; and contributing to global health and wellbeing. To achieve these, seaweed aquaculture development must proceed in an environmentally conscious and beneficial way (Doumeizel and others, 2020).

Most of the evidence available relates to the cultivation of kelp species as this represents the majority of commercial activity and research in the UK and across Europe. While no large-scale commercial kelp farming has taken place in UK waters to date, several enterprises have recently been proposed. British and Irish researchers have been trialling methods of growing seaweeds since the 1980s and seaweed farming is seen as an 'emerging industry', which has yet to reach its full potential (Jansen and others, 2019; Rolin and others, 2016).

1.2 Aims

Natural England currently advise on a range of seaweed gathering and aquaculture enquiries and advice is given by specialists on the specific enquiry / application using the best available evidence and knowledge, using the precautionary principle.

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[1] http://www.seafish.org/about-seafish/news-and-events/news/seafood-2040-industry-plans-forfuture-of- the-english-seafood-sector

The aim of this contract was to increase understanding of the methods used for mechanised harvesting and seaweed aquaculture, potential environmental effects or impacts, potential management measures, and to develop recommendations for best practices. A key part of this project was to highlight evidence gaps and identify how these can be addressed.

Note: This project does not consider hand-gathering of seaweeds as this is considered in a separate project managed by Natural Resources Wales.

1.3 Project outputs

This project was a desk-based exercise which collated existing available evidence. The project outputs consist of this report.

1.4 Report structure

This report includes the introductory section and methods and two main evidence sections: Section 3 aquaculture of seaweeds and Section 4, mechanical harvesting of seaweeds. The report concludes with a final summary section on knowledge gaps, recommendations and conclusions. A list of invasive non-native seaweeds (INNS) that may be present in the UK and that might be considered for aquaculture is presented in Appendix 1. Further assessment information for INNS is provided in Appendix 2 (habitat and UK distribution) and Appendix 3 (ecosystem and socio-economic impacts).

2. Methods

The evidence review by the MBA team was undertaken in two stages as outlined below.

Stage 1: Collate available data from previous in-house projects undertaken by the team and researchers reference collections. This includes an extensive body of work collated by academics and research students.

Stage 2: Conduct a rapid evidence assessment. The evidence review adopted a strategic approach to maximise efficiency and provide the best returns within the project resource allocation. The review encompassed a wide range of literature, including government reports and peer-reviewed scientific literature.

2.1 Invasive non-native species (INNS) review

A high level screening exercise was undertaken with INNS experts at the MBA to determine which non-natives are likely to be associated with harvested seaweed and/or their habitats. Species considered to have low risk of ecological impacts were not considered and species associated only with sedimentary habitats or the water column were not included in the review.

A list of approximately 90 INNS species was generated that are associated with intertidal and subtidal habitats. From this initial full list, INNS algae were identified and are listed in Appendix 1 so that they may be recognised if proposed for cultivation.

To prioritise algae and invertebrates for further assessment, an assessment was made of whether the species was likely to lead to significant ecological impacts on other species and habitats. Evidence for impacts was based on expert judgement and high level review from a number of sources, including the GB non-native species secretariat (GBNNS[2]) online CABI invasive species compendium[3], CABI, Smithsonian Environmental Research Center's National Estuarine and Marine Exotic Species Information System (NEMESIS[4]) and a previous report for NRW by Tillin and others (2020). This resulted in a reduced list of 63 species.

For the list of 63 species that are potentially of concern a rapid review was undertaken to identify the likely habitats of each INNS to assess if these may occur either associated with seaweeds or artificial structures. These searches identified INNS that are potentially associated with seaweed and seaweed habitats. INNS were categorised into three classes, invasive algae, attached/fouling species and sheltering mobile species. Supporting information on current distribution, more detailed information and key references are provided in Appendix 2.

2.2 Assessment of INNS ecosystem impacts

The impact assessment criteria (impact pathways) and impact categories were adopted from the Environmental Impact Classification of Alien Taxa (EICAT) project (IUCN 2020), as these are well established, peer-reviewed and supported internationally by experts. The EICAT methodology identifies twelve impact mechanisms (impact pathways) by which alien taxa may cause deleterious impacts in areas to which they have been introduced (Table 1

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[2] http://www.nonnativespecies.org/home/index.cfm
[3] https://www.cabi.org/ISC
[4] https://invasions.si.edu/nemesis/

below). These are based on previous work and aligned with those identified in the International Union for Conservation of Nature (IUCN) Global Invasive Species Database (GISD).

For each pathway, there are five guidance criteria against which INNS are evaluated, to assign the level of impact caused under that mechanism (Table 2). The project adopted these impact mechanisms to assess the level of current or potential impact these may have on the ecosystem.

Table 1 Ecological impact categories (pathways) developed by EICAT

Ecological Impact Categories
Species level impacts
Competition
Predation
Transmission of disease or parasites
Parasitism This impact mechanisms is restricted to species that are parasites
Poisoning/ toxicity
Bio-fouling or other direct physical disturbance
Grazing/ herbivory/ browsing
Indirect impacts through interaction with other species
Chemical impact on ecosystems
Physical impact on ecosystems.
Structural impact on ecosystems

Table 2 Impact categories and definitions adopted from the EICAT risk assessment methodology. Habitat impact qualifiers (in italics) are based on a previous project by Tillin and others (2020).

Impact category	Definition for impact on Marine Protected Area habitat feature
Massive	Irreversible local, or global extinction of a native taxon (i.e. change in community structure) *and/or irreversible change to habitat character, e.g. loss of biogenic habitat or substratum type change, e.g. sediment to biogenic habitat structured by INNS*.
Major	Native taxon local extinction (i.e. change in community structure), *and/or change to habitat character, e.g. loss of biogenic habitat or substratum type change, e.g. sediment to biogenic habitat structured by INNS which is reversible.*
Moderate	Native taxon population decline *and/or alteration to key habitat features but habitat is still recognisable.*
Minor	Performance of individuals reduced, but no decrease in population size *and/or some alteration to habitat but not to degree that would impact key characterising species or habitat categorisation, structure or functioning.*
Minimal Concern	Negligible impacts, and no reduction in performance of native taxas' individuals, *negligible impacts on habitat.*
Data deficient	No evidence to assess.

2.3 Assessment of INNS socio-economic impacts

The socio-economic impact classification of alien taxa (SEICAT) approach to assess the socio-economic impacts of non-native species on human welfare was proposed by Bacher and others (2018). This approach assesses the impact on human capabilities. INNS can impact people's opportunities through changes in environmental factors, economic settings or social context. For the current project assessments of socio-economic impact focused on cultivation of seaweeds, which largely map to the category of material and immaterial assets (see Table 3). Other impacts on human capabilities associated with these activities were assessed under Health and Safety. The impact categories shown in Table 4 were used to indicate the level of impact.

Table 3. Socio-economic impact categories (pathways) through, health, safety, and assets developed for the SEICAT assessment methodology

Constituents of human well-being	Examples
Safety (combined with health for the SEICAT assessment)	Personal safety e.g. safe handling of by-catch, impacts on safe access or safe operations.
Material and immaterial assets	Impacts on infrastructure and operations. Impacts on farmed species.
Health (combined with safety for the SEICAT assessment)	Impacts on health.
Social, spiritual and cultural relations	Recreational fishing and hand gathering.

Table 4 Social and economic impact on activities through, health, safety, assets and social and relations.

Impact Category	Description
Minimal Concern	No deleterious impacts reported with regard to its impact on human well-being.
Minor	Negative effect on peoples' well-being, such that the alien taxon makes it difficult for people to participate in their normal activities. Individual people in an activity suffer in at least one constituent of well-being (i.e. health, safety; assets; and social and cultural relations). Reductions of well- being can be detected through e.g. incomeloss, health problems, higher effort or expenses to participate in activities, increased difficulty in accessing goods, disruption of social activities, induction of fear, but no change in activity size is reported.
Moderate	Negative effects on well-being leading to changes in activity size, fewer people participating in an activity, but the activity is still carried out. Reductions in activity size can be due to various reasons, e.g. moving the activity to regions without the alien taxon or to other parts of the area less invaded by the alien taxon; partial abandonment of an activity without replacement by other activities; or switch to other activities.
Major	Local disappearance of an activity from all or part of the area invaded by the alien taxon. Collapse of the specific social activity, switch to other activities, or abandonment of activity without replacement, or emigration from region. Change is likely to be reversible within a decade after removal or control of the alien taxon. "Local disappearance" does not necessarily imply the disappearance of activities from the entire region assessed,.
Massive	Local disappearance of an activity from all or part of the area invaded by the alien taxon. Change is likely to be permanent and irreversible for at least a decade after removal of the alien taxon, due to fundamental structural changes of socio-economic community or environmental conditions ("regime shift").

3. Aquaculture of Seaweed

3.1 Background and cultivated seaweed applications

A detailed review of the uses of seaweed is beyond the remit of this report. However, Barbier and others (2019), Capuzzo and others (2019), Stanley and others (2019), and West and others (2016) have all included recent reviews.

Historically, seaweed has been utilised in the UK as food, fertiliser, and animal feed. For the past 20 years, European seaweed cultivation has been driven largely by low value, high volume applications, such as biofuel and bioremediation of aquaculture operations, however more recent focus has been on higher value uses including food, cosmetics, nutraceuticals and pharmaceuticals (Barbier and others, 2019; Stanley and others, 2019). These low volume, high quality applications have been made possible by technical developments in biomass processing, such as biorefinary, which maximises the value of the biomass by allowing for extraction of valuable chemicals first, before secondary, lower value bulk products such as fertilizer.

The range of applications now also includes novel chemicals, bioactives, probiotics, cosmetics, functional food / livestock feed ingredients, phycocolloids (e.g. carrageenan, alginate, agar), and bioplastics (Adams, 2016; Edwards and Dring, 2011; MMO, 2019; Forbord and others, 2018 and references therein). There is continued interest in the bioremediation capability of seaweeds, for inclusion in circular economy IMTA systems where they absorb some of the excess nutrients produced by other forms of aquaculture (Barbier and others, 2019; Cappuzzo and others, 2019; West and others, 2016). Seaweed cultivation has also been the focus of carbon capture and climate resilience research (Duarte and others, 2017) with the potential for farmers to generate additional income through carbon credit schemes (Daniels and others, 2020)

With regard to scale, the terminology used in the Scottish government seaweed cultivation policy statement is applied (Marine Scotland, 2017). Small-medium refers to farms of 0-50 x 200 m lines of a similar scale to a typical mussel farm; large scale refers to >50 x 200 m lines, which is expected to require specialised equipment.

3.2 Review of producers and scale of industry in the UK

The number of businesses cultivating seaweed is rapidly increasing. Organisations involved with the European algae sector have recently been mapped (Araújo and others, 2021), and databases of European seaweed producers and processors have been compiled (www.phyconomy.net and www.emodnet-humanactivities.eu/search-results.php?dataname=Macroalgae+%28seaweeds%29)

In the UK, the majority of cultivation sites are still research or pilot scale, although some scaling-up is imminent. Established research farms exist in Scotland (SAMS), Shetland (University of the Highlands and Islands), Northern Ireland (Queens University Belfast), Rep. Ireland (Bantry Bay Research Station), Wales (Swansea and Aberystwyth Universities) and England (Marine Biological Association and University of Exeter).

Recent / ongoing seaweed farming projects with UK partners, updated from Capuzzo and McKie (2016), include:
- PEGASUS;
- IMPAQT (IMTA);
- MACROSEA;
- Bindweed (binder seeding);
- Genialg;
- EnAlgae;
- SeaGas project (biofuel);
- MacroFuels (biofuel);
- BioMara (biofuel);
- At-Sea; and
- NetAlgae.

Commercially, there are still a small number of growers in the UK, most established in Scotland, Ireland and Northern Ireland, with newer or proposed enterprises in England and Wales. Current or proposed farmers include in England: Biome Algae (Devon), Cornish Seaweed Company (in partnership with Westcountry Mussels), Jurassic Sea Farms Ltd, Green Ocean Farming (Devon and Dorset), SeaGrown (Scarbourgh), Sustainable seaweed (Norfolk); in Wales: Seaweedology (Tenby), GreenSeas (Pembrokeshire); In Scotland GreenSea solutions (Dumfrieshire), Shore (Wick), Caledonian Seaweeds (Dumbarton), KelpCrofting (Skye); in Northern Islander Kelp (Rathlin Ireland), Irish seaweeds (Strangford Lough), and Rep. Ireland: Bord Iascaigh Mhara (various), Roaring Water Bay Seaweed Cooperative (Co. Cork), Dingle Bay Seaweed Ltd (Co. Kerry), and Bere Island Aquaculture Group (Co. Cork).

This list should not be considered exhaustive as the situation is fast evolving, and was comprehensively reviewed by Capuzzo and McKie (2016). Seaweed industry organisations now exist including, Seaweed Forum Wales, Scottish Seaweed Industry Association (SSIA), and the Irish Seaweed Consultancy.

3.3 Review of species used (or potentially used) in aquaculture in England and Wales

3.3.1 Cultivation of native species

Table 5 below presents seaweed species known to be cultivated in the UK. However, no formal records for seaweed production, wild or farmed, exist for the UK (although see review by Capuzzo and McKie 2016). Table 5 outlines by species the Latin and common names, key applications, methods, producing nations and state of commercial readiness of cultivation activities (technological readiness level TRL).

The most commonly cultivated seaweed species in the UK at present are kelps including: *Saccharina latissima*, *Laminaria digitata*, *Saccorhiza polyschides*, *Alaria esculenta*, and *Laminaria hyperborea* (Arbona and Molla, 2006; Edwards and Watson, 2011; Redmond and others, 2014). Cultivation of *Saccharina* and *Laminaria* is the most established as these are the most reliably productive species (Capuzzo and others, 2019; Stanley and others, 2019), with *S. latissima* particularly popular due to its ease of cultivation and the range of market end uses.

The cultivation of *A. esculenta* in England and Wales is likely to be limited due to high summer sea surface temperatures which exceed the optimum growth range for this species (MMO, 2019). *L. hyperborea* is less attractive for cultivation due to its slow growth rate, and large volumes are produced from wild harvest in Norway which will limit the demand for cultivated biomass. However, its cultivation has been trialled (Capuzzo and others, 2019;

Stanley and others, 2019).

The red seaweed *Palmaria palmata* is also grown (Capuzzo and others, 2019; Stanley and others, 2019), and Mac Monagail and Morrisson (2020) list *Mastocarpus stellatus* and *Chondrus crispus* as grown on longlines in Ireland. Small red and green seaweeds for which there is market demand, but which require further research and development, include *Osmundea spp, Porphyra spp,* and *Ulva spp,* with tank cultivation identified as the most likely method for these relatively delicate species (Kerrison and others, 2016; Barbier and others, 2019, Stanley and others, 2019).

3.3.2 Cultivation of invasive non-native species

Non-native species listed on Schedule 9 of the Wildlife and Countryside Act 1981 are illegal to cultivate for sale without a licence and are unlikely to be approved for cultivation in England and Wales in the near future, due to their non-native status (see Appendix 1)

Commercial exploitation in adjacent countries may facilitate spread INNS in UK waters. *Asparagopsis armata* was commercially grown in County Galway in Ireland from 1996 but cultivation has since ceased (Mac Monagail and Morrison, 2020). It is used to improve the water quality of fish farms and also has antibiotic and cosmetic applications (Kraan and Barrington 2005; Santos, 2006; Schuenhoff and others, 2006). The INNS Asian Kelp "Wakame", *Undaria pinnatifida*, is commercially cultivated for food purposes in France and Spain (Peteiro and others, 2016). Another potentially invasive genus, *Gracilaria spp.* is also cultivated in Italy and Spain (Capuzzo and others, 2018).

Appendix 1 provides a list of INNS algae in addition to the Schedule 9 species that are present in the UK or likely to reach the UK soon and that might be proposed for cultivation. For each species, literature searches were undertaken to identify if it was cultivated in parts of its range or if it had been investigated for potential uses.

Table 5. Farmed seaweed species in the UK; current applications, key cultivation producers / and state of commercial readiness of cultivation activities (technological readiness level TRL).

Species name	Main applications	Method/equipment	European Producers	TRL	Comments
Saccharina latissima; Sugar kelp, Sweet Kombu, Royal Kombu	Food, Biofuel, Potentially chemical extraction/conversion	Longlines, adapted mussel droppers, Offshore ring	Denmark, Norway, Netherlands, France, Germany, Portugal, Spain, Ireland, Scotland and the Faroes Islands	Well developed TRL ~4-5	Fast growing, harvest within 9 months of deployment
Alaria esculenta; Atlantic Wakame, Dabberlocks, Winged kelp	Food	Longlines, adapted mussel droppers, Offshore ring	Ireland, Scotland, Norway and the Faroe Islands	Well developed TRL ~4-5	Predicted northward range shift; limited aquaculture potential in England and Wales
Laminaria digitata; Kombu, Oarweed, Tangle	Food (high Iodine content requires blanching), Alginate, Printer ink and biodegradable polymer film.	Longlines, adapted mussel droppers, Offshore ring	Northern Ireland; previously wild harvested in Scotland	Well developed TRL ~4-5	Slower growing than *S. latissima;* lower demand can be met by wild harvest
Laminaria hyperborea Curvie, Forest kelp	Alginate, Printer ink and biodegradable polymer film.	Non-commercial. Potentially longlines, adapted mussel droppers, Offshore ring	Unknown	Unknown	Slow growing*;* demand could potentially be met by wild harvest
Palmaria palmata Dulse, Dilisk	Food, Fodder	Nets and Tank cultivation	Ireland, Scotland, Faroes	Requires some R&D TRL ~3-4	Complex life cycle
Mastocarpus stellatus Grape pip weed	Food, Carrageenan extraction	Longlines	Ireland	Unknown	Limited information available
Chondrus crispus Irish moss	Food, Carrageenan extraction	Longlines	Ireland	Unknown	Limited information available
Porphyra spp.	Food	Tank cultivation /	Trials in Norway, Ireland,	Requires R&D	Complex life cycle

Species name	Main applications	Method/equipment	European Producers	TRL	Comments
Nori, Laver		Extended hatchery phase / Nets or frames of lines at sea	Portugal and Scotland		
Ulva spp. Sea lettuce	Food	Possible to line culture but more suited to tank cultivation	Southern Europe and Israel	Requires R&D	Delicate structure fragments easily
Osmundea spp Pepper dulse	Food, Pharmaceutical, Nutraceutical	Tank cultivation, Line culture under development	Scotland	Requires R&D	Focus of current PhD
Himanthalia elongata Sea spaghetti	Food	Potentially longlines, adapted mussel droppers.	Ireland, England	Requires R&D	Harvestable in second year of growth; Focus of current PhD

Compiled from: Capuzzo and others, 2018; FAO, 2018; Mac Monagail and Morrison, 2020; MMO, 2019; Sanderson, 2006; Schiener and others, 2015; Stanley and others, 2019).

3.3.3 Species suitability and site selection

The choice of species and farm site location are critical factors that will determine the reliability or feasibility of farming as well as the potential quality and yield of biomass. When deciding which species to cultivate, whether or not the environmental conditions of the site will deliver an optimal environment for successful growth must be considered. For example, requirements for temperature, light, water motion, nutrients and salinity differ considerably between the kelps *Laminaria digitata*, *Saccharina latissima* and *Saccorhiza polyschides*, so the location of any farm would need to be species-specific and may not be viable for multi-species cultures (Kerrison and others, 2015). The optimal conditions for cultivation of kelp and *Palmaria palmata* cultivation were reviewed by Kerrison and others (2015) and Capuzzo and others (2018). Water depth will also influence farm design, with sites in the UK generally located in 2 – 25m waters, while commercial production in the Faroes takes place in areas 50-70m (van der Molen and others, 2018; Buck and Grote, 2018).

In addition to the conditions required for optimal growth, other factors which will influence site suitability include socio-economic considerations, such as the interests of other stakeholders or protected designations, and operational considerations, such as accessibility from shore or access to processing facilities.

GIS modelling approaches can provide a broad level, strategic indication of sites which may be suitable for seaweed cultivation, from which high resolution local environmental data (for example on water depth and seabed substrate type) can be combined with marine activities distribution and intensity to identify sites which could optimise farm yield while reducing conflict with other users (MMO, 2019; van der Molen and others, 2018; Thomas and others, 2019).

Modelling data suggests that large scale farms in the North Sea could produce high, annually stable yields of kelp (van der Molen and others, 2018). 58% of English coastal waters (equivalent to approximately 29,000km^2) may be suitable for cultivation of the kelps *Laminaria digitata* and *Saccharina latissima*, while suitable areas for *Alaria esculenta* are more restricted due to its requirement for lower (<16°C) maximum water temperature (MMO, 2019). The red algae *Palmaria palmata* appears to be suitable for cultivation in 31.2% of English coastal waters (equivalent to 15,600km^2), with limitations due both reduced salinity and thermal regime (MMO, 2019).

Biofouling by invertebrates and other algae presents a major issue for seaweed farming, as it can substantially reduce crop quality and value, sometimes to a devastating extent (Handå and others, 2013; Marinho and others, 2015; Mols-Mortensen and others, 2017; Peteiro & Freire, 2013a,b; Stévant and others, 2017). It is a critical factor in cultivation success, and if heavy can force early harvest, reducing potential yield (Bruhn and others, 2016). Sites can be selected to minimise biofouling. Higher fouling occurs in wave-sheltered locations with low water flow, particularly where wild source populations of biofouling organisms are well established, than at more wave-exposed sites with higher current flow (Bak and others, 2018; Bruhn and others, 2016; Matsson and others, 2019; Visch and others, 2020b). Onset of fouling also appears to begin earlier at lower latitudes (Forbord and others, 2020a).

Where synergies exist between seaweed cultivation and marine protected areas (where seaweed farms provide habitat and act as *de facto* no take zones by excluding fisheries), there may be future potential for co-location of the two. However careful consideration of potential impacts on designated features and a case by case assessment is recommended.

3.3.4 Licencing requirements

Due process should be undertaken in England and Wales for any required consents, authorisations, and assessments. Natural England or Natural Resources Wales advice should also be sought as statutory advisors if the proposal is in or may affect an MPA (Capuzzo and others, 2019).

3.4 Methods and equipment that are or can be used for seaweed aquaculture

3.4.1 Kelp cultivation process

Established cultivation guidelines and protocols exist for the kelps *Saccharina latissima*, *Laminaria digitata*, *Alaria esculenta* (Arbona and Molla, 2006, Barbier and others, 2019; Edwards and Watson 2011; Forbord and others, 2018; Mooney-McAuley and others, 2016; Grebe and others, 2019; Rolin and others, 2016; Redmond and others, 2014). *Palmaria palmata* cultivation follows similar methods to kelp (Stanley and others, 2019).

The cultivation system comprises two main components: the hatchery and the farm. Generally, wild fertile material is collected, spore release is induced, and seedlings produced in the hatchery. Seeding of cultivation substrates can be either direct, using a binder, or indirect, using traditional "twining" methods. Once seedlings are large enough they are deployed at sea, following which growth is monitored and the site maintained, before harvesting and processing of biomass. The process is detailed as follows:

Hatchery processes
Hatchery processes usually involve carefully controlled light, cleaning and temperature regimes, and addition of nutrient media to provide optimal conditions for seawee d growth. See Edwards & Watson (2011) and Flavin and others (2013) for more detail.

Collection of fertile material
Reproductive 'sorus' tissue is collected from mature kelp and cleaned. Spore release is induced, usually by exposure to air overnight in cool (~4°C), dark conditions, followed by rehydration in sterile seawater. The resultant spore solution can then be allowed to settle immediately onto spools of cultivation twine, or used to initiate gametophyte cultures.

The quantity of fertile material collected from the wild for cultivation activities is not currently known for most species, nor is the required amount for successful cultivation (Stanley and others, 2019). However with application of best practice (see Section 3.8) only small amounts of material from 10-30 plants are needed to initiate a gametophyte culture or for storage in seed banks. Sourcing wild fertile material is seasonally dependent and varies by species, for example *S latissima* is fertile in the UK between autumn and early spring, whereas *L. digitata* reproduction peaks in summer and autumn. Fertility can also be induced in lab cultivated *S. latissima* by manipulation of lighting rhythm (Forbord and others, 2012). Natural settlement may also be exploited for both kelps and *P. palmata*. In the case of kelps, unseeded lines are deployed at a cultivation site allowing wild spores to settle, resulting in a harvestable crop of *S. latissima*. *P. palmata* settlement was achieved by placing cultivation substrates in dense wild beds during their reproductive season (Rolin and others, 2016).

Gametophyte cultures
Under natural conditions, kelp spores will develop into microscopic, filamentous gametophytes, which settle onto the substrate, produce eggs or sperm and following fertilisation grow into juvenile kelp sporophytes. It is possible to maintain gametophyte cultures (Figure 1) in a state of vegetative production in the lab by keeping them in aerated

nutrient media under red light; sexual reproduction resulting in development of sporophytes is induced by moving cultures into blue/white light (tom Dieck, 1993). This "seed stock" can be maintained for several years, available for use year-round without the need to collect fresh fertile material from the wild.

Figure 1 A gametophyte culture in the hatchery. © Benoît Quéguineur. Reproduced with permission.

Seedbanks
Stanley and others (2019) propose that future, long-term storage of cultivated strains from different regions will be biologically banked (biobanked) and cryopreserved, to supply commercial seed to farms and conserve wild genetic diversity over long time periods. At SAMS a seedbank has been established for European *S. latissima* strains as part of the Genialg project (Stanley and others, 2019).

Seeding
The hatchery phase improves survival of microscopic kelp by growing them in optimal conditions. There are two approaches to seeding production:

Twining
'Seed lines' of 1-2 mm twine are prepared by wrapping around spools of plastic tubing (Figure 2 and 3). These are either sprayed with or dipped into a solution of microscopic seaweed (usually spores), then immersed in tanks of seawater, allowing the seaweed to settle onto the twine and develop. Seedlings are usually grown on for 6-8 weeks until the young seaweeds reach specific size for transplant at sea (e.g. <10 mm for kelp). Twine seeding is the most reliable method of cultivation (Stanley and others, 2019), as seedlings are grown through their most vulnerable life stages free from grazer damage or competition from other algae.

Figure 2 Spools of twine being seeded in a hatchery tank. © Benoît Quéguineur. Reproduced with permission.

Figure 3 Close up detail of *S. latissima* kelp germlings growing on twine. © KelpCrofting Ltd. Reproduced with permission.

Direct seeding

A more recently developed method allows for seeding almost immediately prior to deployment at sea, so is attractive due to reduced hatchery costs. Direct seeding may use meiospores, gametophytes, or juvenile sporophyte life stages (compared by Kerrison and others, 2019) which have been cultured in suspension media (i.e. unattached to a vessel of twine, sometimes referred to as tumble culture) in the hatchery. These seaweeds are mixed with a hydrocolloid "bio-binder" glue (Figure 4) and applied directly onto cultivation

substrates (Figure 5). Direct seeding has been demonstrated to be effective in sheltered locations, but requires further validation for dynamic environments (Kerrison and others, 2018; Stanley and others, 2019).

Figure 4 Binder solution being mixed for use in direct seeding. © Cat Wilding. Reproduced with permission.

Figure 5 *S. latissima* juveniles ~2 months old, growing directly on cultivation rope. © Cat Wilding.

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Farm processes

Deployment at Sea

On cultivation substrates at sea, kelps continue to grow rapidly through late winter-spring, utilising natural sunlight and available nutrients. The most common method in Europe following twining seeding, is for the seeded twine to be unwound from the spool, wrapping helically around larger longline ropes (for example see Mooney-McAuley and others, 2016). Alternatively, short (~10cm) sections of twine may be inserted (lazy spliced) at 30cm intervals into dropper ropes, or individual juvenile kelps (5 -10cm long) are inserted directly into lines. The latter methods are more labour intensive so unlikely to be economically feasible in Europe (Stanley and others, 2019). Direct seeding allows for use of a wider range of cultivation substrates, expanding from ropes to include ribbons, nets or textile sheets, which will require different deployment techniques.

Cultivation ropes (Figure 6) are typically submerged 1.5 – 2.5m below the water surface which protect them from wave action, boat traffic and high irradiance. Once deployed at sea, seaweeds do not require artificial fertilizers or pesticides, however as the crop grows additional buoyancy may be necessary.

The optimal deployment time will vary between species and site locations. Even so, for kelps the deployment period is generally October to January, although may vary between sites and regions. Stanley and others (2019) suggest that *P. palmata* timings are expected to be similar, while *Porphyra* spp. may be possible to deploy between January and April. The earlier young seaweeds are deployed, the longer the growing season. However, if put out to sea too early then phytoplankton may compete for nutrients, and larvae of fouling epiphytes may be abundant in the water (Mooney-McAuley and others, 2016; Rolin and others, 2016).

Following deployment, cultivation should be monitored and maintained to prevent damage to infrastructure or loss of biomass due to entanglement of lines. Environmental conditions and growth rates should be monitored with regular (monthly, more frequently approaching as harvest) biomass estimates recommended (Mooney-McAuley and others, 2016; Stanley and others, 2019)

Figure 6 A spool of twine being deployed around a cultivation long line at sea. © Benoît Quéguineur. Reproduced with permission.

Harvest

Growth rates of most kelp species peak in spring but growth can continue through to midsummer, after which growth is limited by nutrient availability, and portions of the blade

are lost from the tip due to natural erosion or drag forces from heavy biofouling. Optimal harvest timing is therefore a trade-off between maximising kelp biomass and minimising biofouling. Timing will also be informed by the intended market. For example, human consumption requires high quality biomass with very little fouling, while biofouling is less critical for uses such as biofuel, bioremediation or carbon capture. The chemical composition of seaweeds also varies seasonally (Marinho and others, 2015; Mols-Mortensen and others, 2017; Schiener and others, 2015), so the desired proportion of bioactives, protein, carbohydrate or flavour required for the end use will also influence harvest timing.

Optimal harvesting time will also vary geographically, particularly with latitude, as harvesting may be delayed in more northerly sites compared with southerly sites (Forbord and others, 2020a). Harvesting time will vary inter-annually due to changes in environmental conditions that affect growth rate, and also by species (Bruhn and others, 2016; Mooney-McAuley and others, 2016; Stanley and others, 2019). For example *S. latissima* should be harvested in May/June before heavy biofouling and senescence, *A. esculenta* before May when it begins to degrade, whereas *Palmaria palmata* and *Porphyra* spp may be harvestable throughout summer (Stanley and others, 2019).

For commercial scale operations, cultivation lines heavy with seaweed (Figure 7) can be lifted out the water workboats with winches, before cutting seaweed from the lines. Depending on processing capacity, logistics and weather windows, the harvest may be staggered or conducted all at once. Currently the majority of seaweed farms in the UK harvest by hand, although use of mechanisation is likely to expand if farms increase in scale. Basic mechanisation is possible by using a winch to pull the line through a shackle. Stanley and others (2019) describe a Dutch company that harvests seaweed longlines by pulling the rope through a circular cutter or knife. Mechanisation of harvest is the focus of recent research but reporting may also be commercially in confidence.

Figure 7 Images of harvest. Left: a 6m *S. latissima* "dropper" rope. © Cat Wilding. Reproduced with permission. Right: *S. latissima* cultivated on a non-woven textile belt. © AtSeaNova. Reproduced with permission.

Multiple partial harvest

For kelps, multiple partial harvests may be possible from one seeding event if the blade is cut above the meristem. This may be referred to as coppicing (Campbell and others, 2019), and has the potential to substantially improve the cost efficiency of production (van den Burg and others, 2016). In the Shetland Islands, Rolin and others (2017) harvested twice in one season, finding that *S. latissima* showed greater potential for application of this technique than *L. digitata*. The approach may be more suitable for offshore sites, as Bak and others (2018) successfully partially harvested *S. latissima* and *A. esculenta* four times in 16 months without the need for re-seeding from an offshore cultivation rig in the Faroes.

Biomass yield

The biomass that can be obtained from seaweed farms will depend on species selection, farm design, timing of deployment and harvest, and environmental conditions. Actual growth rates of cultivated seaweeds are extremely variable and will be influenced by many factors including: environmental conditions, seeding technique, grow-out density, harvesting strategy, timings of seeding, grow-out and harvesting, effects of grazers and biofouling organisms. No studies to date have explicitly compared growth rates of cultivated kelps with rates exhibited by nearby natural populations. Despite being highly productive, biomass yields of farmed seaweeds remain seasonally, regionally, and annually unpredictable (Forbord and others, 2018). Production of *Saccharina latissima* in Scotland ranges between 10-15kg per metre of linear rope (Stanley and others, 2019) or an estimated 75-170 tonnes per hectare in Norway (Forbord and others, 2018).

3.4.2 Farm Design, Equipment and Infrastructure

Seeding materials

Generally, seeding twine is 1-2mm in diameter and may be either twisted or braided (Forbord and others, 2018), although braided twine has been found to perform better (Kerrison and others, 2019). Initial Scottish trials from 2004 used Kuralon twine sourced from China as a seeding substrate (Stanley and others, 2019). Seeding substrates now include string, ropes and fabric sheets made from materials including nylon, polypropylene, polyester, and polyester silk (Forbord and others, 2018). Kerrison and others, (2016; 2019) tested a range of different seeding textiles, surface pre-treatments, identifying synthetic twines as the most suitable for hatchery processes.

Binder seeding methods in combination with ribbon textiles have been found to result in high seaweed density or biomass yield when deployed at sea, although binder seeding has only achieved comparable biomass yield to traditional twine in Scotland and the Faroes (Bak, 2019; Kerrison and others, 2020), with a Norwegian study finding binder yields lower than twine (Forbord and others, 2020b). Environmental context is likely to be important, with wave exposure and turbidity implicated as important factors (Boderskov and others, 2021; Mols-Mortensen and others, 2017).

Farm design and Cultivation materials at sea

At sea, the goal of seaweed cultivation is to maintain the crop at a fixed water depth to generate maximum yield while avoiding damage from high irradiance. This is achieved by mounting cultivation substrates from mooring systems, with buoys used to add floatation, so that the growing seaweed remains at a depth of 1 – 2.5m below the surface. In areas of exceptional water clarity such as the Faroes, growing depths of 20m have been proposed (Bak and others, 2018), but a maximum of 5-6m is more likely in England and Wales (Wilding 2021, personal observation).

Cultivation substrates include ropes, nets and textiles such as canvas or non-woven fabric belts and ribbons, which can be made from various synthetic materials. Ropes (typically 10-12mm but ranging from 5-14mm diameter) are currently most extensively used, either specially designed for seaweed farming (e.g. Algaerope by AtSeaNova), or more widely

accessible materials such as polymer ropes or weighted lines (e.g. polypropylene and SEASTEEL 3 strand rope by GaelForce Marine) (for examples see Kerrison and others, 2020; Rolin and others, 2016; Campbell and others, 2019). Flattened substrates such as nets and ribbons are used in the southern parts of the North Sea (Lona and others, 2020), and nets are likely to be the most suitable substrate for *Palmaria* and *Porphyra*. If binder seeding methods are validated for a wider range of conditions, the use ribbons and textiles may become more widespread. However, it has been suggested that ribbons may attract more fouling than ropes (Boderskov and others, 2021), which could limit uptake.

Cultivation infrastructure is secured to the seabed with concrete block moorings, helical screw pile anchors, or rock anchors, attached to trestle, pole, or chain systems. Floatation and markers for navigation are usually provided with plastic buoys (MMO, 2019; Stanley and others, 2019). Growing substrates can be mounted in various designs: as horizontal long lines, head-lines supporting vertical or 'V' shaped "dropper" systems, as zig-zag or 'U' shape, or a grid system.

Farm designs are detailed by Stanley and others (2019). Coastal systems include adapted mussel longlines, individual longlines, and grid-based systems, the suitability of which will be influenced by the target species, scale of the site, environmental conditions and intended methods (i.e. mechanised or by hand).

Adapted mussel lines can reduce start-up costs by utilising existing infrastructure. They usually consist of headlines on or just below the surface from which growing lines are attached as droppers. Droppers may be made from weighted line or attached to a weight at the bottom. Moorings are tensioned drag embedment anchors, and the resultant tension on the headline can make access to monitor the growing crop difficult without a winch.

In longline systems, the growing lines are suspended horizontally from moorings every 100m, which may be stone or concrete block. The growing lines are loose, with the advantage that they can be easily pulled to the surface to monitor growth, but a resultant need for a wide (10m) spacing between rows to prevent entanglement.

Stanley and others (2019) identified adapted mussel systems as ideal for production of small volumes, and longlines as the suitable scale for the majority of existing farms in the UK. Longlines are unsuitable for very large sites, as the need for a large number of anchors becomes economically unfeasible.

Grid based systems are best suited for large scale sites. A rope grid is suspended below the surface at a fixed depth, held in place by pilings or embedment anchors around all sides and floatation at the surface. Growing lines are attached to the grid as parallel rows. The gird is tensioned, making access to the crop more difficult than in flexible longline systems.

Vessel

To date, seaweed farmers in the UK have used vessels such as mussel harvesting platforms, only slightly adapted to accommodate seaweed. The recent Seaweed Cultivation Vessel 2020 project in Norway sought to develop a specialised vessel for use with industrial seaweed cultivation. The vessel will ser ve all stages of the process from installation to harvest, but feature modular technology allowing for alternative uses out of season. The design incorporates extensive mechanisation and automation to improve efficiency and safety (https://taredyrkingsfartoy2020.no/; Lona and others, 2020).

Integrated Multi-Trophic Aquaculture (IMTA)

Seaweeds can be a key component in IMTA, which is the co-culture of species which require food inputs, such as fish, with "extractive" species, such as algae or filter feeders. The system is circular in that the wastes or by-products of one species are recycled as the inputs for another. These systems are beneficial because they have additional marketable products to monospecific culture, business continuity generated by cr op diversification, improved environmental performance resulting from the bioremediation activity of the extractive species, and potentially access to premium markets through ecolab eling schemes.

Theoretically, the balance between component species (i.e. fed species with shellfish which extract particulate organic material and seaweeds which extract dissolved inorganic nutrients) in the IMTA system should be driven by ecological function as well as commercial value (Chopin and others, 2006 cited from Tew and others, 2019) to increase production throughout the whole system. IMTA systems could also be pivotal in the monetarisation of ecosystem services, such as nutrient trading credits (NTCs) for recovers of nitrogen and phosphorous from marine environments (Buck and Langan, 2017)

In the UK, IMTA is still nascent, although it has gained public attention and research interest, due to the opportunity for more productive and environmentally friendly sensitive production. In the case of mussel and seaweed cultivation, the two species can even be farmed using the same infrastructure, which presents many commercial opportunities for diversification with minimal investment costs.

When grown alongside salmon farms seaweed growth can be enhanced by utilising excess nitrogen in the water (that is released from salmon farming process). In a trial in Norway, *Saccharina latissima* was cultivated various distances from a salmon farm, and results found that IMTA could enhance kelp growth by 60%, and a 25ha kelp farm could remove 12% of the ammonia released from salmon farming and yield a 1125 tonnes fresh weight of kelp (Fossberg and others, 2018). Model estimates suggest that an area of approximately 220 ha−1 would be needed to cultivate enough kelp to fix an equivalent of the nitrogen released by the salmon (Fossberg and others, 2018).

In Bantry Bay, Ireland, seaweed is integrated with salmon and shellfish farming. Cultivated seaweed is used to feed abalone, and abalone enriched water is used to grow *Porphyra* sp. By utilising the seaweeds as internalised food sources as well as for bioremediation, the sustainability of the system in maximised (FAO, 2009 cited from Tew and others, 2019)

IMTA is also the focus of current research interest, for example the IMPAQT project at SAMs, and "kelp ring" trials where kelp is grown inside fish pens in order to increase survival of the cleaner wrasse (added to remove lice from the farmed salmon) by giving them a more natural habitat (KelpRing – A natural habitat for cleaner fish (FS016) - Seafood Innovation Fund)

Certain areas of the UK, for example Dorset, have been identified as "high potential for aquaculture" status for the development of IMTA aquaculture investment, with kelps, *Palmaria* and *Ulva* spp identified as candidate seaweed species (Tew and others, 2019)

3.4.3 Offshore and co-location

Ultimately, expansion towards large scale seaweed cultivation is likely to be more feasible in offshore, rather than coastal waters. This is due to more stable temperatures, greater water mixing, higher light and nutrient availability, and reduced spatial constraints and conflicts with other uses including potential Marine Protected Area (MPA) constraints (Buck and Grote 2018; Broch and others, 2019; Kim and others, 2017, in Capuzzo and others,

2019). Open sea conditions also appear to contribute towards contaminant-free biomass and reduced biofouling, with implications for target applications (Bak and others, 2018; Bruhn and others, 2016; Mac Monagail and Morrisson, 2020).

Offshore sites are defined by high wave exposure, water depth and tidal currents, rather than areas extending beyond the 12 nm limit of territorial waters (Tew and others, 2019). Typically, they are remote, high energy environments, which presents additional logistical, technical, operational, legal, regulatory, political, economic and ecological challenges (Jansen and others, 2016; Benetti and others, 2010; Langan, 2009; Stevant and others, 2017). Indeed, studies from the North Sea and Chile respectively concluded that the activity would result in economic losses due to the cost of investment and operation outweighing the value of the cultivated biomass (van de Burg and others, 2016; Zuniga-Jara and others, 2016). However, the Macroalgae Cultivation Rig (MACR) used in the Faroes Islands has been deemed to be profitable and economically low risk (Bak and others, 2018), and site selection, quantity and quality of the seaweed produced, both have a positive effect on generated revenues (Capuzzo and others, 2019). Further, multi-use sites which combine seaweed aquaculture with other sectors can optimise use of space resulting in cost reductions (Jansen and others, 2016).

Further details on offshore cultivation are available from recent reviews, including Buck and Grote (2018) and Tew and others (2019). Commercial scale offshore cultivation currently takes place in the German North Sea (CRM 2001), Norway (SES 2015a,b), the Netherlands (Hortimare), and the Faroes (Ocean Rainforest). Kelp species are the most suitable for offshore conditions, followed by *Palmaria* sp. And *Ulva* sp. As with nearshore systems, the Sugar kelp *Saccharina latissima* is the key species cultivated in Europe over the past 20 years (Buck and Grote, 2018).

Candidate seaweed species must not only be tolerant of the high energy conditions but also be sufficiently valuable to justify the high costs associated with offshore cultivation (Buck and Grote, 2018). Kelps exhibit high morphological plasticity, and are able to invest more energy into holdfast growth in order to withstand high wave energy conditions if deployed as young individuals (Buck and Buchholz, 2004a, 2005, cited from Buck and Grote, 2018; Sjøtun and Fredriksen, 1995). Indeed, *S. latissima* has been demonstrated to withstand a maximum current velocity of 1.52m/s and wave height of 7-8m (Buck and Buchholz, 2005; Buck and Grote, 2018). As such, the technical capability of the infrastructure to withstand the conditions, rather than the tolerance of the kelps themselves, is the key driver of offshore system design.

Farm designs tested to withstand substantial wave action and current speeds have included longlines, ladder, grid systems, ring devises and sea-floor mounted fixed longline constructions. Novel designs commonly feature single point mooring systems, which allow some flexibility to withstand stormy conditions. These technologies can be floating, submerged, or a combination (Luning and Buchhols, 1996; CRM 2001, cited from Buck and Grote 2018). Infrastructure includes anchors, wires, ropes, chains, couplings, buoys, floats, and pipes, with the mooring system particularly important in withstanding harsh offshore conditions. Mooring systems include concrete blocks (for use on hard sea bed types), metal tension, screw thread, and drill anchors.

The Alfred Wegener Institute have developed and patented a ring construction following trials in the North Sea (Buck and Grote, 2018 and references therein), which can produce approximately one tonne of seaweed biomass (wet weight) from a 20m^2 ring platform (Buck and Buchholz, 2004a,b; Buck and Grote, 2018). The seeded cultivation ropes are either coiled around thicker backbone rope, or hang down from it as single or looped droppers. Cultivation ropes may be made from 6-10mm polypropylene, while thicker "backbone" lines are 15-35mm polypropylene or polyethylene. Buoys are lashed or shackled to the backbone for floatation, with additional marker / corner buoys attached with a single

chain/mooring. Pencil, rather than ball-like floats reduce wave-stress on the systems below.

Seaweed Energy Solutions (SES), Norway, have patented the Seaweed Carrier (SES 2015a,b see Buck and Grote, 2018). This 2D sheet-like structure mimics the form of a giant seaweed thallus, connected to the seabed by a single point mooring which allows the rig to move with the prevailing water flow direction. It is designed to withstand dynamic offshore conditions, has been tested on a small scale, and has the potential to produce industrial-scale volumes of kelp, but is not yet used commercially (Lona and others, 2020).

The Norwegian Proaqua rig system also features a single point anchor, from which four mooring lines, each with a buoy, support a large plastic ring which holds horizontal cultivation mats. The system moves freely vertically, and is close to neutrally buoyant allowing for ease of inspection (Lona and others, 2020).

Offshore cultivation requires a greater degree of flexibility that those in coastal waters, in order to reduce the hydrodynamic forcing loads on infrastructure during stormy weather. In the Faroes, Ocean Rainforest cultivate commercially using growing ropes that are attached vertically to a horizontal rig system anchored in deep (50-200m) water. A small buoy attached to the top of each growing line provides floatation, but will submerge in large waves which reduces the total loading on the rig (see Figure 8). The system has been successfully tested in wave heights of up to 7-8 m and in currents up to 3 knots (Bak, 2019; Buck and Grote, 2018). However, due to the flexibility, relatively large spaces are necessary between horizontal lines to prevent entanglement, so it is less suitable for small areas.
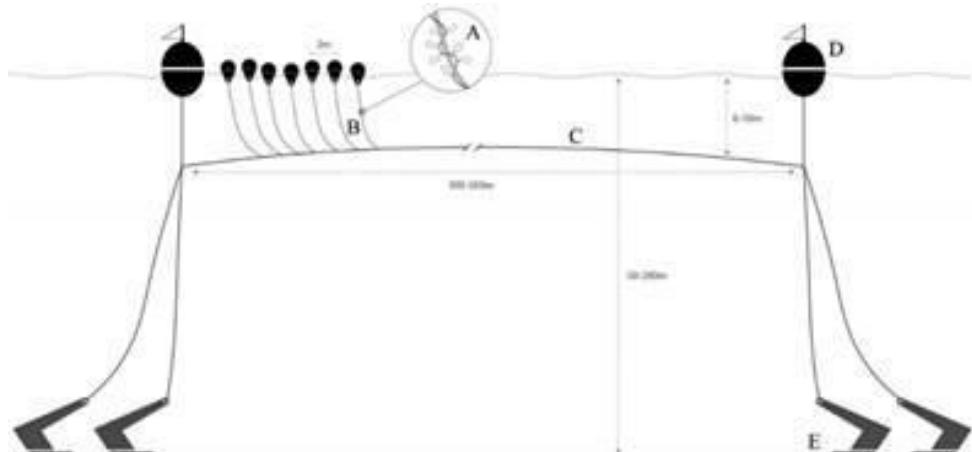
Figure 8. Macroalgal cultivation rig. Source: Bak and others, 2018. © 2018 Elsevier B.V. Reproduced with permission.

It should be noted that offshore cultivation will influence the morphology of seaweed produced, which may impact of market applications. For example, *S. latissima* grown in sheltered sites exhibits a wide blade with ruffles margins, while offshore adapted specimens are characterised by a streamlined, flat, narrow blade (Buck and Buchholtz, 2005).

Co-location and IMTA offshore
Co-location with other sectors at offshore sites, particularly wind farms, is attractive as the high costs and risk of operating offshore can be shared bringing economic and environmental benefits. In offshore environments during prolonged calm weather, seaweed growth could be impaired by nutrient limitation, which is overcome in IMTA systems (Troell and others, 2009; Bucholz and others, 2012 cited from Buck and Grote, 2018). The bioremediation capacity of seaweed can also mitigate the environmental impact of wastes produced by other, co-cultivated species (Buck and Langan, 2017).

The North Sea has been proposed to hold suitable sites (Jansen and others, 2016), and a modelling study proposed that, if conducted in combination with wind energy, salmon and mussel farming, cultivated seaweed production the volumes of 160-180,000 tonnes, valued at 160-210 million EUR are achievable from an area in the southern North Sea (He and others, 2014).

Despite being the focus of several studies, the lack of appropriate technology which can connect aquaculture systems to the foundations of offshore wind turbines appears to limit progress (Buck and Krause, 2012 cited from Buck and Grote, 2018). Infrastructure for co-use trials of cultivation at a Dutch offshore wide site in 2012 utilised steel cables suspended 2m below the water's surface with a system of anchors and buoys, from which 100m^2 horizontal nets were suspended as a kelp cultivation substrate (Hortimare).

3.4.4 Emerging technologies

The rapidly developing sector, wide range of market end uses and highly variable conditions in UK waters are driving innovation in technological approaches to cultivation. Advances in systems that improve reliability in more exposed locations and reduce costs through optimising of infrastructure are commercially sensitive and companies are not motivated to publish, although there are exceptions (Buck & Buckholz, 2004).

Modifications which reduce labour costs (i.e. reduced hatchery period by binder seeding) and increase efficiency and safety of operations are the focus of current research and development (Edwards and Watson, 2011; Kerrison and others, 2015). These are likely to include increased mechanisation of seeding and harvesting, species diversification and co-culturing, year-round production and stabilisation of yield, and economies of scale (Campbell and others, 2019). For example during seeding the process of winding twine around spools can be done manually, or be mechanised (Stanley and others, 2019).

Emerging mechanised harvesting technologies are utilised in Norway (Alver and others, 2018; Efstathiou and Myskja, 2019; Lona and others, 2020; Stevant and others, 2017), and China (Yang and others, 2017). Once developed, specialised equipment will require adaptation to local conditions (Forbord and others, 2018).

In Norway, scaling up of existing seaweed farm concepts has been proposed to require an automated, cost-efficient and robust method for connecting and disconnecting the cultivation ropes to standardised mooring grids units (Alver and others, 2018; Lona and others, 2020). The MACROSEA project included theoretical development of an area-efficient production system for seaweed cultivation, featuring a high degree of automation. The SPOKe (Standardized Production of Kelp) concept utilises standardised production units with a harvesting robot that can be moved between different seaweed farms (Bale, 2017; Lona and others, 2020).

Further development of specialised cultivation vessels which can harvest large volumes at low operating costs are anticipated to be key to the future development of the seaweed industry (Nilsen, 2018; Lona and others, 2020).

Finally, both SAMS (IMPAQT and ASTRAL projects) and the 5G Rural Dorset project are developing cloud based monitoring systems which will autonomously collect real time data from sensor arrays deployed at farm sites. These remotely managed monitoring systems will improve management and have the potential to substantially streamline costs.

3.5 Impacts of seaweed aquaculture on the marine environment

Seaweed farming can have positive and negative effects depending on many factors including site selection, scale of the farm(s), site design and choice of species (Kerrison and others, 2015; Peteiro and others, 2016). Benefits are loosely grouped below into socio-economic and environmental but there are overlaps as environmental remediation would increase the flow of goods and benefits and/or enhance human well-being. Risks from seaweed farming on species, habitats and the wider ecosystem are classified as direct resulting from infrastructure and ancillary activities (e.g. vessel traffic, shading and introduction of INNS) and indirect such as changes in water flow enhancing sedimentation on benthic habitats. Impacts may occur within the footprint of the farm or locally or regionally (although there is little evidence to support effects on that scale).

The potential positive impacts of seaweed farming can be summarised as follows:
- Socio-economic benefits directly through income generation and employment and indirectly by coastal protection that benefits other assets valued by people;
- Positive ecological enhancements, through:
  - provision of novel habitat (discussed in risks as these can also be negative);
  - mitigation of climate change;
  - water remediation;
- Protection of habitats and species through the exclusion of more damaging activities (de facto marine reserves); and
- Indirect socio-economic and ecological benefits resulting from seaweed use.

The potential negative impacts are summarised as follows:
- Direct and indirect impacts from infrastructure and ancillary activities
  - Impact of harvesting fertile material
  - Seabed scour from mooring chains
  - Noise and visual disturbance
  - Entanglement of marine mammals and birds
  - Wave energy attenuation and changes in coastal hydrology
  - Artificial habitat creation (cumulative with cultivated seaweeds also contributing)
  - Conflict with other users of marine space
- Direct and indirect impacts resulting from crops
  - Crop-to-wild gene flow
  - Changes to nutrient cycling and carbon storage
  - Absorption of nutrients
  - Release of dissolved or particulate organic matter
  - Spread of parasites and disease
  - Habitat for non-target nuisance species
  - Artificial habitat creation
  - Introduction and movement of INNS

3.5.1 Benefits derived from seaweed farming

Seaweed farming has the potential to create new jobs and income str eams for coastal communities (Rolin and others, 2016; Wood and others, 2017), although there is limited information available on the cost of establishing a full-scale commercial farm and potential revenues that could be derived. Kelp suspended in the water column can absorb wave energy and alter water flow and sedimentation patterns, therefore they could theoretically be used to reduce erosion of the coastline (Wood and others, 2017), although this is remains to be tested.

Kelp farms are an attractive habitat for fish and small mobile species (albeit temporary, see Section 3.6), which may in turn attract other marine predators such mammals and birds (Hasselström and others, 2018) (although this is linked to a potential risk of entanglement –

see section 3.5.6). However, there is little understanding of how harvesting at the end of the season, which removes the seaweed 'canopy', influences the marine life aggregatedaround the farms (Wood and others, 2017).

Seaweeds grow by removing carbon from the water column, and can in theory sequester carbon if particulate organic matter sinks to the deep sea, or is buried in sediments, or if faecal pellets of associated fauna grazers sink to deeper waters or storage habitats (Krause-Jensen and Duarte 2016; Krause-Jensen and others, 2018). Seaweeds also leach dissolved organic carbon (DOC) into the sea, some of which is non-reactive (recalcitrant DOC) that is stored in the oceanic carbon pool for thousands of years (Hansell and others, 2009; Hansell 2013). Therefore, cultivation of seaweed could potentially be used to enhance long-term carbon storage in the ocean and help mitigate climate change (Duarte and others, 2017). However, seaweed farming would need to be substantially up-scaled to have potential as a natural carbon sequestration mechanism.

Cultivation on very large scales can also absorb enough CO_2 to cause local increases in pH, potentially mitigating the effects of ocean acidification (reviewed in Campbell and others, 2019). The end use of the biomass produced will dictate the extent of actual sequestration, as much of the captured carbon will later be released (as CO_2) when the kelp biomass is processed into other products (Hasselström and others, 2018).

Kelp farms may be used to absorb nutrients and pollution in nutrient-enriched areas (e.g. due to agricultural/urban runoff), and as part of IMTA, thereby reducing the negative impacts of aquaculture (Sanderson 2006; Marinho and others, 2015; Fossberg and others, 2018). However, uptake of pollutants complicates the use of seaweed as a food product (Wood and others, 2017).

Seaweed farms can also create positive effects in addition to those outlined above, such as exclusion of mobile fishing gear, potentially creating no-take-areas (Hughes and others, 2013).

Applications such as biofuel, animal feed supplements with reduce methane production, and replacement of synthetic fertilizers can have additional sustainability and carbon emission reduction benefits. Although CO_2 may be released if fossil fuels are relied on to run/operate the kelp farm (e.g. to operate harvesting equipment and aquaria).

3.5.2 Direct and indirect impacts from infrastructure, ancillary activities and crops

Intuitively any large-scale structure would have an environmental footprint and alter physical and biological conditions to some extent. Wood and others (2017) suggest that a small farm on its own is likely to have negligible impact on the environment, but a very large farm or multiple small farms next to each other could have an increased impact (Wood and others, 2017). In addition, one of the only ecological impact studies conducted in the British Isles to date found that a kelp farm in Ireland had little impact on benthic community structure and eelgrass (*Zostera marina*) underneath the farm, and that impacts of seaweed farming are relatively benign compared to other aquaculture industries (Walls and others, 2017b). It should be noted that the stocking density of the farm is likely to be an important variable influencing benthic impacts.

Several reviews of kelp farming impacts from outside of the UK can be drawn upon for highlighting potential risks. For example, Grebe and others (2019) reviewed the potential impacts of kelp aquaculture in Maine, USA. Moreover, the impacts of seaweed cultivation on ecosystem services were studied in Sweden by Hasselstrom and others, (2018). The potential negative impacts associated with kelp farming are summarised from a number of publications (Buschmann and others, 2017; Hasselström and others, 2018; Hughes and

others, 2013; Grebe and others, 2019; Reith and others, 2012; Wood and others, 2017).

Key environmental risks associated with seaweed aquaculture are reviewed in more detail below under additional sub-headings (Section 3.5.3 to 3.7). Other potential impacts that were considered to be of less significance or for which there was little information are summarised briefly below. The impact categories are similar to those laid out in Buschmann and others (2017) and Hughes and others (2013). Unforeseen ecosystem effects are possible during rapid expansion of the emerging seaweed industry (Cottier-Cook and others, 2016).

3.5.3 Impact of harvesting fertile material

In order to cultivate seaweeds, reproductive tissue (called sorus in kelps) must first be harvested from wild populations. The possible risk of this practice is that over -harvesting reproductive tissue may impact the reproductive output, life cycle and longevity of wild seaweeds. However the amounts harvested are mall and therefore impacts are considered unlikely 9see Section

3.5.4 Seabed scour from mooring chains

Mooring chain scour can cause a small loss of physical habitat, however the tension through the longline system keeps the mooring chain and line from rotating. Impacts from mooring chain movements are relatively generic and were reviewed by Griffiths and others, 2017)

3.5.5 Noise and visual disturbance

Disturbance effects, particularly on mobile species from the presence of cultivation vessels, visual impacts of the farm infrastructure, and potential displacement of marine mammals are considered as generic impacts likely to arise from any large marine development, so are not considered in detail. However these additional impacts would require further consideration on a project specif ic basis. While raised as an issue, the impacts review (Campbell and others, 2019) considered the effects noise from ve ssel engines as likely to be small given the magnitude of traffic associated with farms, but nonetheless suggested that farm sites should be sited away from features sensitive to noise.

3.5.6 Entanglement of marine mammals and birds

Entanglement often refers to snagging or encircling the animal (e.g. Johnson and others, 2005; Benjamins and others, 2012), which requires a net structure or slack lines. There are reports of entanglement from fishing and aquaculture gear across a range of bird and mammal species in net structures and discarded gear (Lloyd, 2003). Many reports also relate to interactions with human intervention, such as dolphins becoming entangled whilst stealing bait in crab fisheries (Noke and Odell, 2002), or seals attempting to gain access to fin fish installations (Pemberton and others, 1991). However, there are a lack of data that scientifically reports negative entanglements (i.e. entanglements are only reported when they happen, not when they do not). Price and others (2017) identified that reported entanglement with existing aquaculture incidents are rare, incidents that have been reported are discussed here.

Interaction and entanglement risk can be separated between the species who use echolocation to identify and avoid structures, such as dolphins, and those which do not, such as whales (Lloyd, 2003). For species who use echolocation, the presence of taut lines is of limited danger and risks are limited to aforementioned deliberate interactions. However, for species that do not echolocate, reports of collisions with aquaculture are thought to be accidental (Pemberton and others, 1991) and in these cases, accidental interactions become a risk to consider in site design (Price and others, 2017). Lloyd (2003) reviews some of entanglement reports with a focus on long line mussel aquaculture in New

Zealand, where the structures and changes to local ecology are most similar to proposed seaweed cultivation. Lloyd (2003) reports on the deaths of two Bryde's whales in loose mussel spat-catching lines and concludes that although reported entanglement risk is currently deemed inconsequential, expanding aquaculture sites prompt concern and further study. Risks of entanglement are associated with loose lines and net structures, which can be limited through mooring design. Wood and Carter (2008) attributed a reduction in whale entanglement with underwater cables to improvements in design and deployment that reduced slack of those cables. Accordingly, Price and others (2017) highlight that slacker grow out lines, spat collecting lines and surface marker buoy lines are those of primary concern at mussel farms (Clement, 2013). Similarly, the bending radius of cables is not sufficient to pose the same risks as slack mooring lines. Harnois and others (2015) used tension and the curvature of mooring lines as indicators of the likelihood of entanglement in mooring lines.

Entanglement risk in seaweed farms will be increased where an intense accumulation of wild species, or co-culturing with intense fin-fish aquaculture are expected. There are a range of solutions to mitigate entanglement risk in development for seaweed aquaculture. As previously mentioned, long-line systems originally designed for mussels have a primary risk in the 'free' dropper lines, while those serving marker buoys can be designed to minimise slack and curvature, by increasing rope weight and thickness, and thus reduce associated risks. Alongside these systems, 'mesh' systems, with inter-crossing lines on a horizontal plane have also been trialled (Buck and Buchholz, 2004). These systems will include rectangular near-surface mesh, but with mesh sizes of 10 m^2, the entanglement is not comparable to by-catch from fishing gear. As such, seaweed farms that using net structures for growing seaweed may have a higher entanglement risk than seaweed farms that use taut, longline structures (Clement, 2013), however by increasing mesh size, this risk can be mitigated.

Marine renewable energy

In this review, the term marine renewable energy (MRE) is used to describe devices to convert wind, tidal currents and wave energy into electricity. These structures are designed for large-scale deployments, offering a useful comparator when considering offshore aquaculture. The primary similarity with seaweed aquaculture will be the mooring ropes. As such, the comparison is limited to floating devices, not those fixed to the seabed (the majority of offshore wind and tidal energy devices are currently fixed to the seabed). These devices will also have cables in the water column, used to carry power to an export cable located on the seabed. The potential for entanglement in mooring lines and cables has been raised by stakeholders within MRE and has been the subject of recent research. In particular, a wide-ranging review (OES-Environmental 2020).

Due to the scale of MRE moorings, the focus has predominantly been around larger marine mammals. However, no direct interaction with MRE moorings has been reported. As such, reviews have focussed on evidence from reported entanglements with fishing gear or submarine cables. Mooring systems for MRE do not typically contain enough slack to form a loop around an animal and with no net structure, do not create the factors observed to be prevalent in reported incidents. Similarly, the bending radius of cables is not sufficient to pose the same risks as slack mooring lines. Harnois and others (2015) introduced an attempt at prediction of entanglement, focussed on MRE, but applicable to moorings for aquaculture. Notably, they found an overall low risk, due to the tension in the lines, but highlighted that these factors can be managed through mooring design. Presumably, by extension, suitable monitoring and repair plans for damaged moorings is also important.

The MRE review offers a method for mitigation through design, by limiting loose or slack lines and through implementation of a monitoring and rapid repair plan to limit the length of time damaged lines are left in the water.

3.5.7 Wave energy attenuation and changes in coastal hydrology from cultivation infrastructure

The presence of seaweed in the water column will absorb energy from waves and currents and act as an obstruction to the flow. As such, it will reduce water motion within a seaweed canopy and also has the potential to alter flow conditions outside of the canopy, as flow is preferentially diverted around the obstruction. This review considers published evidence for understanding the impacts on currents and waves separately. Specific evidence for the associated impacts on sediment movements are not included, but techniques for predicting changes through the use of hydrodynamic models are reviewed as these represent the greatest potential for predicting sediment changes for specific locations.

The review finds that the structures in use are diverse and the stock density varies significantly in published studies. These factors will control the impact cultivated seaweed has on the waves and currents, but there is limited empirical data from the deployments to date. As such, this review also considers literature from both natural seaweed populations and other floating structures, including shellfish aquacultu re. It would seem pertinent to assume that the industry will converge to floating structures which are optimised for st ock density and cost, using established mooring components. However, any attempts to predict impacts on waves and currents should be continually reviewed against current practice and would benefit from ongoing empirical evidence from existing sites.

Review of likely density and structures for seaweed cultivation

The infrastructure used and the density of the seaweed cultivated will contr ol the impact of seaweed cultivation on hydrodynamic conditions. There is strong incentive to maximise density as this will increase obtainable yield from the farm, optimising the economic viability.

For this review, we identified the values for yield from a range of cultivation trials of *S. latissima* in the northern hemisphere (Table 6). The majority of the studies have been at a relatively small scale compared to projected commercial scale and therefore have been normalised in order to gain an understanding of the yields per unit area that could be expected from a full-scale farm. In some instances this estimate was provided in the literature as tonnes per hectare (t/h), although extrapolations to this unit of measure were seen to vary depending on the cultivation method used and are not directly comparable. For example, Broch and others (2019) extrapolate the yields of Sharma and others (2018), given in kilograms per meter squared, directly to tonnes per hectare by multiplying by ten thousand (square meters in a hectare). This is potentially unrealistic as it does not seem to consider access to frames, potential shading effects and reduced nutrient availability.

To allow consistent comparison between studies, we have estimated the potential density for all studies using a representative farm layout and calculating the length of seeded line that could be achieved per hectare. This layout is used to convert from kilograms per meter of seeded line to tonnes per hectare. We used longline method, with separati on of 8-10m between parallel lines and droppers at 4m intervals. This layout is based on Marinho (2015) and whilst it is achievable for a large-scale farm, it is used here to enable consistent comparisons between published studies (Table 6), not to give accurate values for likely stock intensity in commercial farms.

The outcomes demonstrate significant variability in published growth rates between studies of 0.5-23kg/m, and farm yields between 2 and 70tonnes/hectare. Variability between approaches has a high influence on stock intensity (Kerrison and others, 2015), and by extension, the potential disruption to wave and cur rent regimes. The high range of estimates results from the different infrastructure, growing schedules, species and other

factors in the published studies. This serves as further demonstration that seaweed cultivation in the northern hemisphere has not converged on a specific methodology and highlights a limitation in the current potential to accurately predict impacts on waves and currents for future seaweed farms. This should be continually reviewed as there remains significant potential for increasing density and implementation of novel cultivation methods.

Table 6 Biomass yields from cultivation trials of *S. latissima* in the literature (various sources).

Source	Cultivation Type	Crop Cycle (days)	Yield (kg/m)	t/h (Stated)	t/h (scaled)
Buck and Buchholz, 2004	Ring	180	4.0	N/A	14
Peteiro and others, 2014	Longlines	104	7.8	45.6	27
Druehl and others, 1988	?	240	8.0	N/A	28
Sanderson and others, 2012	Longlines + Droppers	141	4.0[1]	220	14
Holt, 1984	Longlines	365	23.0[2]	N/A	70
Marinho and others, 2015	Longlines + Droppers	471	1.4		5
Marinho and others, 2015	Longlines + Droppers	229	1.3		5
Bruhn and other, 2016	Longlines and Droppers	122	0.5	N/A	2
Sharma and others, 2018	Frames at two Depths	134	6.4[3]	383	22
Peteiro and Freire, 2013a	Longlines with Interconnecting Ropes	121	16.1	40.2	57
Rolin and others, 2016	Longlines	218	4.0	N/A	14
Forbord and others, 2020b	Longlines + Droppers	120	7.2	N/A	25
Chopin and others, 2004	Longlines	252	12.0		42
Peteiro and others, 2006	Longlines	119	6.0	N/A	21
Authors data with Cornish Seaweed Company, 2020	Longlines + Droppers	202	3.6	7.4	13

Potential changes to waves and currents due to floating aquaculture

Wild populations of seaweed

Natural kelp beds have been studied for the absorption of kinetic energy, showing 70-85% absorption of wave energy (e.g. Mork, 1996) and a reduction in tidal currents within the canopy compared to those outside (Jackson and Winnant, 1983). Umanzor and others (2018) linked this reduction to canopy density, while Jackson and Winnant (1983) provided an equation for the 'transition zone' for currents entering a kelp stand and beyond which the effect of kelp on the current will be consistent. This distance was generally below 100m, but is dependent on the drag co-efficient of the kelp, CD. This again will be a factor of the density of seaweed within the farm. Further analysis could estimate this for cultivated sites, allowing this equation to be re-purposed if necessary, but the established diversity in current practice means estimates should consider infrastructure proposed.

The effect of the kelp on currents will also depend on the wider geography of the area and

the potential for flows to divert. Diversion effects were highlighted by Zeng and others (2015) who used measurements to identify that flow within cultivated seaweed was reduced by up to 70%, dependent on growth-stage of the seaweed. The field observations suggest that the reduction in flow at the surface was balanced by an increase in flow beneath the cultivated kelp (change of 140% at time of harvest). Gibbs and others (1991) also measured diversion below floating aquaculture (in this case mussels), with the increase greatest immediately below the canopy. Fan and others (2009) identified similar changes to the velocity profile through the water column, again linked to cultivation intensity.

Whilst these changes may have connotations for associated ecological and physical assessments for the benthos in that location, it will be highly site -specific, depending on location and surrounding geography. It does, however, highlight that impact assessments should take into account flow diversion beneath or around cultivation. This will have increasing importance the greater the proportion of tidal flow is disrupted and should be prioritised for larger scale projects or those in areas important for water exchange, such as restricted channels between larger bodies of water.

Impact on the wave field

Damping from seaweed can be expected to result in reduction in wave conditions. Mork (1996) quantified this reduction at 70-85% over 250m for a natural kelp stand, with the greatest reduction in higher frequency waves. The level of reduction will be related to distance into the kelp stand or farm, until an energy balance is achieved between wind input and the energy dissipation by the seaweed. Where this energy balance is found will depend on the energy dissipation of the seaweed, which can be expected to vary with species, growth stage and density (Zeng and others, 2015). However, species will alter their physiology in response to wave conditions (Bekkby and others, 2014), a factor that is also reviewed in Kregting and others (2016) in the context of growth rates in seaweed species. Vettori, and Nikora (2019) found that *Saccharina latissima* blades adjust to high energy flows with flexible blades that reduce the drag forces as currents increase, altering the response to hydrodynamic conditions. The complexity here suggests that empirical evidence for specific, or similar locations and cultivation methods, will be highly valuable in assessment of expected changes to kinetic energy.

Price and others (1968) examined the impact of seaweed on wave field including a simple hydrodynamic model. Although simulated seaweed was 'planted' rather than floating, results showed the orbital motions of waves were altered to promote along-wave transport where the seaweed was vertical in the water column. This was linked to sediment accretion on the down-wave side of the seaweed. However, this was directly related to the seaweed attached to the seabed and given the expected position in the water column, the relevance to floating seaweed cultivation may be limited.

Natural compared to floating structures

Some of the discussion here relies on data from natural kelp beds. There are some obvious differences between natural populations and cultivated kelp that will change how they alter waves and currents. Perhaps most importantly, the geographical extent of the kelp beds in the reviewed literature varies. In addition, kelp stands only grow naturally within a range of hydrodynamic conditions (Bekkby and others, 2019), meaning that results from natural populations may not cover the full range of wave and current conditions considered for seaweed farming. A natural kelp stand will be fixed to the seabed and plants will be more mature, often larger than those actively cultivated and with different morphology. As such, information derived from other floating systems has been included, including other aquaculture species. However, in many cases, empirical evidence for seaweed cultivation is required to improve understanding.

Modelling for prediction

As described above, Jackson and Winnant (1983) provide an equation for estimating drag from a natural kelp stand, which can account for the density of plants. This allows calculation of the 'transition zone' beyond which currents reach a steady (slowed) rate. More recently, hydrodynamic modelling has been explored to represent aquaculture installations. Grant & Bacher (2001) used the same approach as Jackson and Winnant (1983), implemented within a regional finite element model (FEM), to model the flows through a combination of kelp and bivalve aquaculture, which they note are based on limited empirical studies. Wu and others (2014) take this form of modelling one step further, investigating alterations in cage location and depth to adjust tidal flow and associated erosion within the farm.

Uncertainties discussed in previous sections will continue to affect modelling effort. How different species respond to hydrodynamic conditions has the potential to alter drag forces between cultivation projects using the same species but in different conditions. Furthermore, different stock densities and infrastructure used also add variability to the overall impact of cultivation projects. Whilst initial modelling efforts are possible now, they must either be highly site and structure specific, or generic with high uncertainty. Continued collection of empirical data and the convergence of seaweed aquaculture implementation will continue to improve ability to accurately model the impacts.

Experience from modelling impacts of tidal energy extraction also suggest that cumulative effects from the wider area should also be considered (Fairley and others, 2015). This will account for any associated changes to hydrodynamic regime in local or linked areas. However, for many developers, particularly small scale, the implementation of a full-scale hydrodynamic model for the farm and local area is perhaps not realistic. In many cases, regional initiatives can develop regional or national-scale models that can support impact assessments. It will be critical that these initiatives have the opportunity to gather and/or benefit from empirical evidence at any installations to continue to refine modelling techniques to better reflect the species and conditions in which seaweed aquaculture is being cultivated. This in turn will further improve understanding and prediction of the effect of cultivated seaweed on hydrodynamic conditions, inform optimum cultivation practice and predict downstream impacts on the marine environment.

3.5.8 Conflict with other users of marine space

Establishment of new seaweed farms, particularly in coastal waters, may result in conflict with other sea users, such as shipping, fisheries, recreation, marine reserves and the military.

3.5.9 Crop-to-wild gene flow

Propagation of kelp 'seed' (or spores) from a limited number of individuals can artificially increase the reproductive fitness of a small number of individuals. Subsequent 'out-planting' may lead to genetic modification/variation of wild populations. Further, seaweed strains may be locally adapted, so out planting to wider geographic areas may reduce the genetic diversity or local adaptation. While not yet studied in seaweeds, the consequences on genetic structuring and evolution could be profound (Loureiro and others, 2015).

3.5.10 Changes to nutrient cycling and carbon storage

Here we review the evidence for potential impacts of seaweed cultivation due to environmental changes: from uptake of nutrients, release of particulate and dissolved organic and inorganic matter, through to the effects of uptake of carbon at local, regional and potentially global scales. We also infer effects of adding seaweed biomass to an area from understanding of the contributions of natural seaweed populations at a range of spatial scales. At ecosystem scales the consequences many of these environmental

changes are tightly interwoven, such as the effects of uptake of nutrients and release of dissolved organic material, and have only really been addressed using modelling studies.

Beside the capacity for seaweed farms to mitigate coastal eutrophication, there has been much recent interest in the potential for seaweed aquaculture to play a role in greenhouse gas (GHG) reduction and mitigation (Chung and others, 2013, 2017; Raven, 2017), through absorption of CO_2 during carbon fixation by plants. Large scale seaweed farming has been proposed as a potential geoengineering solution to reducing atmospheric carbon dioxide (Froehlich and others, 2019), using open ocean seaweed farming as a carbon offsetting activity rather than the economical generation of seaweed products. Froehlich and others (2019) considered this to be feasible for offsetting the carbon produced by the aquaculture industry. Even commercial seaweed farming may play a positive role in GHG mitigation. Life cycle analysis of farmed kelp (Thomas and others, 2021) shows more CO_2 and phosphate are absorbed than emitted during supply chain, albeit dependent on the choice of low-energy processing methods (ensilage or air drying) versus high-energy ones (freezing or air cabinet drying).

The effect of added seaweed biomass and habitat associated with seaweed aquaculture, especially in areas with relatively little natural seaweed, can be inferred from the contribution of macroalgae to the marine environment. Natural seaweed populations are seen as an important component of the "blue carbon" system (Duarte and others, 2013, 2021), the production and storage of carbon in coastal vegetated habitats and their associated sediments. Production from coastal macroalgae is becoming recognised as a major source of organic carbon in the ocean (Krause-Jensen & Duarte, 2016). While the magnitude of seaweed farming in Europe and the UK is tiny compared to the growth of natural stocks, there is potential for the additional organic carbon to affect the local environment. Seaweed farms differ from natural stocks, with a much greater proportion of biomass removed from the ocean to the supply chain in farmed weed than is lost as particulate detritus from natural seaweed beds. However small, such farms may potentially enhance production of organic detritus in the immediate vicinity.

Experimental studies of the effects of seaweed farms on the local environment are rare in Europe, likely due to the lack of commercial scale operations so far, but two recent detailed reports in Ireland and Sweden using rigorous Before-After-Control-Impact designs showed very limited effects. A seaweed farm in Dingle Bay, Ireland (Walls and others, 2017 b) had no impact on benthic macrofauna beneath the farm and a small reduction of total organic material in the sediment after accounting for particle size differences, with a decrease in particle size under the farm possibly as a result of reduced water velocity.

On the west coast of Sweden, a sugar kelp (*Saccharina latissima*) farm produced some shading of the seabed, and positive effects with increased numbers of species of mobile macrofauna and other macroalgae growing on the crop itself (Visch and others, 2020b). The study found no effects on oxygen flux, nutrient concentrations and mobile seabed fauna, and importantly showed an improvement of the ecological status of the seabed at the site from "poor/moderate" to "good" through increases in species abundance and species richness after the installation of the farm, as well as an increase in "Benthic Quality Index" (a weighted metric of the relative abundance of disturbance-sensitive species and species richness (Rosenberg and others, 2004). This study followed a quantitative review and synthesis of effects of seaweed farming for kelp on ecosystem services using the likely effects of the same farm on those services as an example (Hasselström and others, 2018). Expected effects on ecosystem services in this study were seen as generally positive, with only space use, recreation and aesthetics seen as potentially negatively affected (Hasselström and others, 2018) by the small farm.

3.5.11 Absorption of nutrients

Large scale seaweed farming reduces coastal nutrients, potentially mitigating excessive inputs to coastal waters and reduce hypoxia (Duarte & Krause -Jensen, 2018), thereby helping to restore degraded coastal marine ecosystems (Duarte and others, 2020). Seaweed aquaculture in coastal waters of China removes 75kt of nitrogen and 9.5kt phosphorous annually (Xiao and others, 2017) with the potential to remove all inputs of phosphorous to coastal waters by 2016, thereby playing a major role in mitigating coastal eutrophication. The present, and even proposed, scale of seaweed cultivation in the UK (Daniels and others, 2020) is unlikely to achieve this coastal-scale effect but may have a significant impact locally in semi-enclosed water bodies such as sea lochs in Scotland.

Effects of seaweed aquaculture on larger areas have rarely been measured, and more often addressed using ecosystem models out of necessity. An ecosystem model of ke lp farming in N Ireland (Aldridge and others, 2021) showed that shading and nutrient competition between growing kelp and phytoplankton produced predicted decreases in phytoplankton chlorophyll a of 23% for kelp farming that used 22% of the area of a semi-enclosed marine water body (Strangford Lough). Competition for dissolved inorganic nitrogen was also seen in a model of bivalve and kelp aquaculture in a bay off the Yellow Sea in China (Shi and others, 2011). The same model also showed a reduction in curr ent flow in the area, an effect seen in the experimental study of a kelp farm in the west of Ireland (Walls and others, 2017b).

3.5.12 Release of Dissolved or Particulate Organic Matter (DOM and POM)

Macroalgae can be significant contributors to the pool of dissolved organic matter (DOM) in coastal waters, with up to 20% of DOM coming from kelp (Wada & Hama, 2013). Living plants exude carbohydrates during photosynthesis, with 35% of carbon fixed that may be lost as exudates (Hatcher and others, 1977). While some of this contribution may be exported to the deep ocean (Krause-Jensen and Duarte, 2016), much may be locally remineralised and released back as CO_2 and converted to particulate material by heterotrophic bacteria. Many studies have sought to trace the organic carbon released by kelp through the food web using stable isotopes, for example showing that suspension feeding invertebrates in kelp beds derive much of their energy from kelp detritus (Norderhaug and Christie, 2011). Similar methods have also shown that kelp-derived material contributes significantly to organic carbon in surface sediments (Queirós and others, 2019). Other studies, however, have found that seasonal changes in isotopic and lipid biomarkers (Dethier and others, 2013) can make conclusions about carbon sources difficult to make using such approaches. A promising avenue for such work is the development of understanding patterns of environmental DNA in sediments (Ortega and others, 2020). The fate of detritus and contribution of seaweed to coastal ecosystems and their food webs derived is an area of active research, particularly in improving understanding of kelp forests and other macroalgae habitats as sources of blue carbon.

The effects of adding farmed kelp biomass on the ecosystem has been explored using trophic modelling of food webs (Ecosim) (Wu and others, 2016). Removal of kelp farms promoted the biomass of exploited fishes that rely on pelagic prey, ultimately using phytoplankton as a food resource. This suggests that reduced phytoplankton production by large scale kelp farming may have a negative effect on some fishery species. The model also suggested that added organic detritus from kelp farming enhanced benthic production.

3.5.13 Spread of parasites and diseases

Depending on the strictness of protocols, there is a risk that parasites attached to wild seaweeds may be introduced to the hatchery / aquaria when they are harvested for reproductive tissue and spore release. These may unknowingly be introduced to new

locations when cultivation are deployed at sea.

Intensive seaweed cultivation can result in increased spread of disease, which can in turn spread to the wild populations. Examples of diseases that have infected the kelp *Saccharina japonica* in Asia include 'rot disease', 'twisting disease', 'blister disease', 'stipe blotch' and 'dark spot' disease, although it remains uncertain whether these diseases pose a threat in Europe. The reduction in genetic diversity associated with domestication and selective breeding can further increase susceptibility to diseases (Valero and others, 2017).

3.5.14 Habitat for non-target nuisance species

An unexpected effect of extensive seaweed farming has been the initiation of nuisance blooms. A green tide in the Yellow Sea (Liu and others, 2009) emerged as a result of growth of an unwanted macroalga (*Enteromorpha prolifera*) associated with the expansion of the aquaculture of a red alga *Porphyra yezoensis*. The large bloom was thought to have originated by growth of *Enteromorpha* on the rafts used for *Porphyra* culture, with growth and expansion during subsequent drifting towards the coastal city of Qingdao and disrupting sailing events for the 2008 Olympics (Wang and others, 2015a).

3.6. Artificial habitat creation

Currently, there is relatively limited evidence on which marine species utilise UK farm sites. Wild kelp populations provide important habitat for a diverse range of organisms, including numerous species of conservation and commercial importance (Christie and others, 2009; Norderhaug and Christie, 2011; Smale and others, 2013; Teagle and others, 2017; 2018; Bué and others, 2020). Seaweed aquaculture creates new, suspended habitats that may support comparable biodiversity to wild populations, despite differences in age of the habitat, species composition (mixed wild stands vs monoculture), kelp morphology and benthic or pelagic positioning (Walls and others, 2016; 2017a; Visch and others, 2020b). Like their wild counterparts, cultivated seaweeds create three distinct microhabitats: the holdfast, stipe and blade. The supporting infrastructure also represents a substrate which supports biodiversity. This section will detail the current understanding of the habitat value provided by seaweed aquaculture for a range of different species compared to wild kelp populations and other aquaculture types commonly used in the UK.

Microorganisms and epibionts

Some of the smallest but most important biodiversity associated with seaweed cultivation are also often overlooked in biodiversity assessments. Microorganisms, including bacteria, viruses and fungi play important roles in maintaining ecosystem health and functioning through improving water quality, nutrient cycling and decomposing organic matter (Hyde and others, 1998; Arrigo, 2005). The importance of maintaining "good" microorganism biodiversity in seaweed cultivation is critical, as most microorganisms improve ecosystem health and some can even help prevent harmful diseases (Bentzon-Tilia and others, 2016). In macroalgal cultivation, the settlement of algicidal bacteria can also contribute towards the mitigation of harmful algal blooms (HABs) (Imai and others, 2006). Therefore, a greater understanding of algal microbiome ecology is urgently needed (Langton and others, 2019). Algal microbiomes are morphologically difficult to identify, which makes assessing their biodiversity using current microbial methods challenging (Gachon and others, 2010; Loureiro and others, 2015; Barbier and others, 2019; Capuzzo and others, 2019). In other forms of aquaculture, environmental DNA (eDNA) is often used to successfully identify pathogen or parasite presence e.g. in crayfish populations (Witter and others, 2018) and finfish farms (Gomes and others, 2017) and should be explored further in the context of seaweed cultivation.

Most research on habitat creation through aquaculture is heavily focussed on the epibionts or fouling organisms that settle on cultivated species or infrastructure, due to their impacts on crop quality and production (Radulovich and others, 2015; Bannister and others, 2019). Biofouling species such as bryozoans and amphipods can impact seaweed cultivation by eating, degrading, contaminating or breaking off biomass and inhibiting productivity and photosynthesis (Førde and others, 2016; Rolin and others, 2017; Walls and others, 2017a; Gutow and others, 2020). Aquaculture may also facilitate settlement of INNS, which can threaten biodiversity and cause economic damage (Airoldi and others, 2015; Firth and others, 2016) (see Section 3.7 for further information). However, primary colonising species also enhance the biodiversity value of farms and act as food sources for higher trophic level species (Radulovich and others, 2015). Biofouling organisms may also improve water quality, benefit shellfish growth (Dalby and Young, 1993), enhance phytoplankton productivity (Lodeiros and others, 2002; Ross and others, 2002; Le Blanc and others, 2003), encourage settlement of commercially farmed shellfish (Hickman and Sause , 1984; Fitridge, 2011) and mitigate for disease risks (Paclibare and others, 1994).

Previous preliminary studies in Europe have found similar or higher levels of epibiont biodiversity associated with cultivated macroalgae compared to wild populations (Walls and others, 2017a, 2018; Visch and others, 2020a). This suggests that macroalgal farms create novel suspended habitats for epibionts including non-target and other algal species, crustaceans, bivalves, gastropods, bryozoans, colonial ascidians, brittle stars, nudibranchs and tunicates (Walls and others, 2017a, 2018; Visch and others, 2020a). These farms supported similar but distinct epibiont populations to wild kelps, likely due to the pelagic positioning and ecological priming of seeded ropes (Walls and others, 2018). However, they may support lower diversities of algal species if the ropes are seeded compared with unseeded lines (Walls and others, 2018). Epibiont communities may differ between the holdfast, stipe and blade of the cultivated seaweed due to morphological differences such as the interstitial spaces between haptera of the holdfast, creating a more sheltered area for organisms to settle and detrital matter to accumulate as a food source (Walls and others, 2018). The blades of cultivated seaweeds are usually the parts of commercial interest and value for farmers, and offer a more wave-exposed environment for epibiont settlement (Visch and others, 2020b). Therefore, cultivated blades are expected to have lower biodiversity value than holdfasts (Walls and others, 2017, 2018). However, blades are still likely to be colonised by amphipods, bryozoans, algae and tunicates (Førde and others, 2016; Rolin and others, 2017). Seeding density, site positioning of farms, and harvesting or regrowth techniques also affect the epibiont co mmunities which can settle (Førde and others, 2016; Rolin and others, 2017; Walls and others, 2017a, 2018; Visch and others, 2020a).

Increased knowledge of how epibiont communities develop over growing seasons, between cultivated species and in relation to environmental variables such as temperature and hydrodynamic activity is needed. This will aid in understanding the potential habitat value of farms, as well as informing farmers of how to maximise their crop quality and yield and farm more efficiently with an ecosystem based approach. The creation of novel macroalgal habitat could aid in restoration of macroalgal communities in areas that have been degraded, by encouraging primary settling species that may act as prey to attract higher trophic level species back to the area (Marzinelli and others, 2009; Walls and others, 2018).

Benthic species and habitats

Benthic habitats support a range of flora and fauna associated with the seabed, and their monitoring can provide important insights into the health and functioning of an ecosystem (Wilding and others, 2017). Several key indicators of benthic habitat health can be measured below aquaculture sites, including the biodiversity, composition and abundance of benthic infauna and epifauna. Infauna refers to organisms living in the sediment, and are

comprised primarily of detritivores, grazers and filter feeders such as polychaetes, flatworms, gastropods and bivalves. These species are important for recycling nutrients, filtering water and providing prey to benthic fish species or macroinvertebrates (Callier and others, 2006; Clynick and others, 2008; Weisberg and others, 2008). The presence and diversity of infaunal communities are used as bioindicators of contamination, eutrophication, and hypoxia, due to the varying tolerances of species in the community (Weisberg and others, 2008; Borja and others, 2009). Epifauna refers to organisms living on the seabed, such as echinoderms, crustaceans or demersal fish species like plaice or flounder, many of which are of commercial importance. It is therefore important to assess how macroalgal farms influence benthic community structure, to monitor the health of the cultivation site and of the wider habitat.

The impacts of seaweed aquaculture on benthic habitats are poorly understood, but have so far been considered negligible compared to other aquaculture types (Zhang and others, 2009; Zhou, 2012). Some finfish aquaculture, particularly intensive salmon farming, has contributed to benthic habitat degradation through smothe ring, creation of hypoxic and anoxic environments, and consequently substantial biodiversity loss (as discussed in Taranger and others, 2014). However, other finfish aquaculture has been found to stimulate benthic community productivity and enhance biodiversity (Tomassetti and others, 2016). Shellfish aquaculture is normally found to have minimal impact on benthic communities, with either no differences in diversity or community composition (Wilding and Nickell, 2013), or higher abundances and richness of benthic species (Kraufvelin and Díaz, 2015; Drouin and others, 2015). This increased diversity may further provide protection against hypoxia from farm drop-off that accumulates below shellfish farms (Kraufvelin and Díaz, 2015; Bergström and others, 2020). In cases where an increase in sulphidic and hypoxic sediments have been observed under mussel farms, these effects are generally within 50-100 m of the site, limiting the scale of their environmental impact (D'Amours and others, 2008; Froehlich and others, 2017). This can vary however with environmental conditions, and effects are site specific (Cranford and others, 2009). The impacts of all aquaculture types on benthic communities can be reduced by following straightforward farm design and positioning guidelines, such as ensuring water depths are twice that of mariculture infrastructure, and minimum water flow rates are >0.05m/s (Belle & Nash 2008; Froehlich and others, 2017).

Seaweed farms can be suspended over any benthic habitat type, including soft se diments where detritus can amass and enrich the benthos, unlike in natural kelp beds, which grow on rocky substrates. Like shellfish aquaculture, biomass drop-off from seaweed farms could provide food, refugia (Langton and others, 2019) and organic enrichment of sediments, which could affect benthic community health (Zhang and others, 2012; Kellogg and others, 2014; Walls and others, 2017a). Epibenthic macrofauna may be attracted to seaweed aquaculture sites due to this increase in food availability, and the creation of a more heterogeneous habitat from detritus accumulation or introduced infrastructure such as mooring systems (Morrisey and others, 2006; D'Amours and others, 2008; Langton and others, 2019). Ecosystem models of potential large-scale kelp cultivation sites have demonstrated they will cause minimal alterations to benthic foodwebs, and might instead strengthen them by provisioning habitat, food and detritus (Wu and others, 2016). In preliminary studies of European macroalgal farms, no alterations to the ecological status of benthic communities have been observed, although changes in sediment particle size and organic matter composition have been identified (Walls and others, 2017b; Visch and others, 2020a).

There is currently insufficient evidence to determine whether seaweed farms enhance the recruitment of juvenile benthic macrofauna through the provisioning of breeding and nursery grounds, or whether they simply aggregate individuals from adjacent populations. Due to the large sizes of wild species observed inhabiting other aquaculture systems, it appears farms attract adults from adjacent populations rather than directly enhan cing the

recruitment of juveniles (D'Amours and others, 2008). However, the larvae of some lobsters settle out of the water column into wild seaweed habitats (Acosta and Butler., 1999), so seaweed farms may offer similar benefits to recruitment of similar species. Future monitoring should include the aging of individuals to understand the habitat value of seaweed farms for different life stages of species that inhabit them (Langton and others, 2019). Benthic habitats within and around cultivation sites should also be surveyed multiple times throughout the year, as assemblages are strongly seasonal and will be influenced by the harvesting of farmed crops (D'Amours and others, 2008). A range of abiotic parameters, biotic indices and monitoring techniques should be used to assess clear objectives, thresholds and standardisation requirements provided by regulating bodies (Borja and others, 2009; Wilding and others, 2017).

Sampling and monitoring benthic habitats normally requires taking standardised sediment grabs or cores of the seabed and determining their associated infauna and biogeochemical properties (e.g. Xu and others, 2011; Kraufvelin and Díaz, 2015; Walls and others, 2017b; Visch and others, 2020a). Pre-surveys are often required by regulating or marine licencing bodies, such as The Crown Estate in the UK, to identify any vulnerable or protected habitats (Wood and others, 2017b). Benthic epifauna may be more challenging to monitor than infaunal communities, as these species tend to be more mobile, patch ily distributed and may also be camouflaged (Mabrouk and others, 2014). Epifauna can be surveyed using a variety of methods including diver surveys, benthic trawls, traps, or remote video surveys. Small beam trawls are routinely conducted to compare epibenthic assemblages (Eleftheriou and Moore, 2013), however they are relatively destructive and cumbersome to deploy around farm infrastructure. Static benthic traps are comparatively easier to deploy around cultivation sites for surveying selective macrofauna species such as crabs, lobsters and fish (e.g. Visch and others, 2020a), particularly those of commercial importance. However, selective trapping should be used concurrently with additional survey methods to derive a more holistic assessment of whole-site biodiversity and reduce survey bias. These may include diver or remotely operated camera surveys, the latter of which are increasingly common for monitoring long-term effects of human-induced impacts on the benthos including at shellfish (e.g. Mabrouk and others, 2014) and finfish cultivation sites (e.g. Tanner and Williams, 2015; Hamoutene and others, 2015).

Pelagic vertebrates

Pelagic organisms live in the water column, and comprise of a diverse range of invertebrate and vertebrate species. This section focuses on pelagic vertebrates, including fish, mammals and seabirds, due to the availability of research on these sp ecies and because they are of particular interest to conservation and other stakeholders, such as fisheries. More research is needed on the potential effects of aquaculture on pelagic invertebrates, such as jellyfish.

Fish

Wild kelp populations support diverse assemblages of bony and cartilaginous fish (Hartney, 1996; Norderhaug and others, 2005; Smale and others, 2013). Likewise, seaweed farms create novel suspended habitats, which may also provide important feeding, breeding, spawning and nursery grounds for many fish species and enhance or restore degraded areas (Bergman and others, 2001; Peteriro and Freire, 2012; Zhou and others, 2019; Tonk and others, 2019; Wu and others, 2019). Furthermore, the presence of mariculture infrastructure restricts fishing activities in an area, indirectly reducing pressures on local fish populations (Burta and others, 2013; Wang and others, 2015b), although fishing activities may be displaced to other nearby areas, increasing effort there. The attraction of fish species to shellfish and finfish farms (e.g. Davenport and others, 2003; Dempster and others, 2009, 2011; Morrisey and others, 2006; Tsuyuki and Umino, 2018; Sheehan and others, 2019), artificial reefs and marine renewable energy sites (Macura and others, 2019;

Hemery, 2020) has been well studied (Callier and others, 2018; Macura and others, 2019; Hemery, 2020). Limited research has been conducted on fish populations at seaweed farms, despite recent findings that at IMTA sites, fish were more abundant in macroalgal areas than mussel zones (Wang and others, 2015b). Increases in fish abundance including sardines, grunts, barracuda and shark species have also been observed in or around tropical macroalgal farms (Radulovich and others, 2015). In Sweden, a preliminary study identified 17 fish species around kelp farms during the growing season, highlighting the potential habitat value of seaweed aquaculture for fish in Europe (Visch and others, 2020). However, further study is needed to determine how fish populations are using seaweed cultivation sites, at which life stages and time of the year they are present, how they may be impacted by harvesting schedules, and how far reaching the effects are for the wider populations and ecosystems.

Fish have been monitored in marine habitats using a variety of methods, including diver surveys (e.g. Pondella and Stephens, 1994; Clynick, 2006; Wehkamp and Fischer, 2013), trapping (Wang and others, 2015), and remote video surveys (e.g. Tonk and others, 2019; Sheehan and others, 2020). Most previous studies around macroalgae farms have used extractive methods such as fishing, nets or traps (Wang and others, 2015b), which can enable effective comparisons of fish abundance, biomass, diversity, and age classes between aquaculture types and artificial reef systems (Wang and others, 2015b). Gut content analysis can also be conducted to determine diet and whether macroalgae from the farm supplies food webs through isotopic analysis. Video surveillance techniques may also be effective for quantifying pelagic fish biodiversity in macroalgal farms, and novel camera technologies have been designed specifically for suspended aquaculture monitoring (e.g. Tonk and others, 2019; Sheehan and others, 2020). Environmental DNA (eDNA) monitoring may also provide accurate, non-invasive methods to detect fish species in seaweed farms, particularly cryptic species which may be hidden within fronds, and has previously been used to effectively census wild kelp beds (Port and others, 2015; Stat and others, 2018). Nevertheless, quantifying pelagic fish populations is challenging due to their mobile, seasonal and transient nature, and fish assemblages can vary dramatically over a few months. In Ireland, juvenile mackerel and pollack were abundant at a seaweed farm in summer months, however they were completely absent by September, whereas wrasse, which are more associated with the benthos, remained abundant across the whole study period (Bicknell and others, 2019). This demonstrates that year-round monitoring of pelagic fish around seaweed farms is necessary to accurately assess their overall impact on fish populations.

Megafauna

Marine megafauna include mammal, elasmobranch and seabird species, which are often of conservation importance (e.g. Dulvy and others, 2014). It is therefore important to understand and implement the best management practices of marine aquaculture to minimise disturbance and maximise environmental protection for megafauna species (Pimiento and others, 2020). The likely increased abundances of prey species associated with seaweed aquaculture, including fish and macroinvertebrates, could provision novel foraging grounds for marine mammals and seabirds, which are frequently observed around finfish and shellfish aquaculture sites (Nemtzov and Olsvig-Whittaker, 2003; Roycroft and others, 2004; Zydelis and others, 2008; Northridge and others, 2013). Farm infrastructure, such as buoys, floats and lines, also provide resting platforms for seabirds (Nemtzov and Olsvig-Whittaker, 2003; Roycroft and others, 2004). However, compared to shellfish and finfish aquacultures, the attraction of carnivorous megafauna poses limited risks of reducing yield of cultivated seaweed crops. It may instead help to maintain trophic balance by controlling grazing species, as seen in wild populations (Estes and others, 2004).

Conversely, kelp farms could displace megafauna during construction, and displace echo locating mammals during operations as identified in papers from shellfish farms in New

Zealand (Markowitz and others, 2004; Watson-Capps and Mann, 2005). Kelp farms could also cause entanglement in the infrastructure, similarly to stationary fishing gear such as suspended gill nets or those with slack lines (Kirkwood and others, 1997; Read and others, 2006), although the risk is relatively low. Entanglement risk is discussed further in section 3.5.6, is well studied and can be largely mitigated by proper site maintenance (Campbell and others, 2019).

Further research is needed to assess the habitat value and other environmental impacts of seaweed farms on megafauna to enable better management and enhance potential benefits of cultivation sites. However, accurate monitoring of marine megafauna is challenging as they are highly mobile and have generally low population densities. Future census of megafauna at seaweed farms should use a variety of methods, including: visual land or boat-based surveys (e.g. Díaz López and others, 2005; Methion and Díaz López, 2017), genetic and eDNA techniques (Lieber and others, 2020), tagging or biologging (e.g. Cook and others, 2008; Clark and others, 2020), and citizen science reports and observations (Harvey and others, 2018; Hann and others, 2018; Sayer and others, 2019). Quantifying how habitat value scales with the size of different cultivation site sizes is also poorly understood, and it is unlikely that effects will scale linearly (Campbell and others, 2019).

3.7 Invasive non-native species

Table 7 identifies INNS seaweed species that occur in the UK and have been recorded in at least some part of their range (not necessarily in the UK) as growing epiphytically on cultivated seaweeds or colonising artificial structures. These biofouling seaweed species may have a range of effects on the ecosystem and on cultivation activities, as described in the following section. Table 8 identifies mobile species that may shelter within cultivated seaweeds or that may be associated with infrastructure. Some of these associations may only be temporary, for example use of artificial structures by *Rapana venosa* (Veined rapa whelk) for egg laying. Finally, Table 9 identifies attached species, often referred to as biofoulers that may colonise infrastructure and or cultivated seaweeds. More habitat detail and current UK distribution for each group of INNS are presented in the corresponding habitat tables for each group of species in Appendix 2.

The assessed species all occur associated with seaweeds and/or artificial habitats. Typically when introduced, INNS tend to be associated with artificial habitats such as harbours and marinas as these are the main sites of introduction. Over time they may then disperse to suitable natural habitats.

Table 7. Invasive non-native seaweed species that may occur epiphytically on cultivated seaweeds or that have been recorded on artificial structures.

Name	Habitat	Key references
Asparagopsis armata	Attaches to other seaweeds by its barbed branchlets. The Falkenbergia stage is epiphytic.	Sweet, 2011a
Bonnemaisonia hamifera	Grows predominantly epiphytically on using hooks to attach.	Sweet 2011b
Caulacanthus okamurae	Epiphyte and found on artificial structures	Wood 2019b
Codium fragile subsp. fragile	Epiphyte and found on artificial structures	Sweet, 2011f
Colpomenia peregrina	Usually epiphytic	Sweet, 2011c
Dasysiphonia japonica	Epiphyte and found on artificial structures	Wood, 2021c
Grateloupia subpectinata	Not an epiphyte: recorded on artificial structures	Sweet, 2011d, Guiry and Guiry, 2021.
Grateloupia turuturu	Not an epiphyte: recorded on artificial structures	Sweet, 2019a
Melanothamnus harveyi	Epiphyte and found on artificial structures	Maggs and Hommersand, 1993
Undaria pinnatifida	Epiphyte on other seaweeds and found on artificial structures	Sewell, 2019a

Table 8. Sheltering mobile species evidence for occurrence among aquaculture and/or algae.

Sheltering mobile species	Habitat	Key reference
Ammothea hilgendorfi	Seaweeds: Observed amongst sublittoral algae.	Sweet, 2011e
Caprella mutica	Infrastructure: seaweeds Often found on artificial structures. Preferred habitats include fine filamentous structures such as hydroids (Ashton, 2006; Cook and others, 2007 and references therein), foliose surfaces of macroalgae and bryozoans	Tillin and others, 2020 (impacts); Cook 2019-CABI datasheet; Ashton, 2006.
Rapana venosa	Infrastructure: May be found on artificial structures where it may lay eggs.	Tillin and others, 2020.

Table 9. Attached or biofouling species that may attach to seaweeds and/or infrastructure.

Attached/fouling species	Attachment/fouling substratum	References
Asterocarpa humilis	Infrastructure	Tillin and others, 2020 (impacts) Bishop J. 2017.
Botrylloides diegensis	Infrastructure: seaweeds	Bishop, 2011a
Botrylloides violaceus	Infrastructure: seaweeds	Bishop, 2012
Bugula neritina	Infrastructure: seaweeds	Bishop, 2011b
Ciona robusta	Infrastructure: seaweeds	Yunnie and Bishop, 2017
Corella eumyota	Infrastructure: seaweeds	Bishop, 2019a
Diadumene lineata	Infrastructure: seaweeds	Tillin and others 2020.
Didemnum vexillum	Infrastructure: seaweeds	Bishop 2010: Impacts Tillin and others, 2020
Hydroides ezoensis	Nuisance fouler on artificial substrates.	
Magallana gigas	Infrastructure	Tillin and others, 2020.
Schizoporella japonica	Infrastructure: seaweeds	Wood, 2017
Styela clava	Infrastructure: seaweeds	Bishop 2019b
Tricellaria inopinata	Infrastructure: seaweeds	Bishop 2019b
Watersipora subatra	Infrastructure: seaweeds	Bishop & Wood, 2021; impacts: Tillin and others, 2020

3.7.1 Impacts of INNS on ecosystems: EICAT Assessments

Appendix 3 provides supporting information for the EICAT assessment of potential impacts on ecosystems, the results of which are summarised below in Table 10. The predominant pathways through which the INNS impact ecosystems are through competition and biofouling and biofouling associated structural changes in habitats. There was no supporting information for hybridisation, transmission of disease or parasites, poisoning/toxicity or chemical impacts. The whelk *Rapana venosa* was the only predatory species considered, this species has not yet reached the UK and would only be associated with seaweed cultivation seasonally, during the spawning period as it may lay eggs on infrastructure. Species which are considered likely to lead to the most significant impacts on natural habitats are the invasive seaweeds: *A. armata* and *U. pinnatifida*, the tunicates, *Botrylloides diegenesis*, *B. violaceus* and *D. vexillum*. Although not currently present in the UK the whelk *R. venosa* may have major impacts on mussel and oyster beds and other bivalve dominated habitats.

Table 10 provides the summary scores for the EICAT impact assessment. Key to impact ranks: MC=Minimal Concern; Mr= Minor; Md=Moderate; Mj=Major; Ms=Massive; DD = Data Deficient.

INNS Algae	EICAT Impact	Score	Attached or biofouling Species	EICAT Impact	Score
Asparagopsis armata	Competition, Physical and Structural changes:	Mj	*Asterocarpa humilis*	Competition	MC
Bonnemaisonia hamifera	Competition	Md	*Botrylloides diegensis*	Competition: Biofouling	Mj
Caulacanthus ok amurae	Physical and structural changes	Md	*Botrylloides violaceus*	Competition: Biofouling	Mj
Codium fragile su bsp. fragile	Competition	Mr	*Bugula neritina*	Competition: Biofouling	Md
Colpomenia peregrina	Biofouling and Structural Impacts	MC	*Ciona robusta*	Potential Competition	Mr
Dasysiphonia japonica	Competition	Ms	*Corella eumyota*	Competition	Mr
Grateloupia subpectinata	Competition	MC	*Diadumene lineata*	Competition	MC
Grateloupia turuturu	Competition and physical impacts:	Mr	*Didemnum vexillum*	Competition, Biofouling and Physical and Structural changes	Mj
Melanothamnus harveyi	No evidence.	DD	*Hydroides ezoensis*	Competition, biofouling	Md
Undaria pinnatifida	Competition	Mj	*Magallana gigas*	Competition and Structural impacts:	Ms
Sheltering mobile species			*Schizoporella japonica*	Competition:	Mr
Ammothea hilgendorfi	No known impacts	MC	*Styela clava*	Competition:	Md
Boccardia proboscidea	No known impacts	DD	*Tricellaria inopinata*	Competition, Biofouling	Md
Caprella mutica	Biofouling	Mr	*Watersipora subatra*	Competition and Structural changes:	MC
Rapana venosa	Predation and Structural changes	Mj			

3.7.2 Impacts of INNS on seaweed cultivation: SEICAT Assessments

More detailed information for the SEICAT assessments, impact scores and key references are presented in Appendix 3 and are summarised below in Table 11. Key INNS organisms that are likely to cause more severe impacts are epiphytic algae and biofouling tunicates, bryozoans and hydroids. The ability of these species to attach to hard surfaces such as ship hulls or oyster shells has facilitated their spread globally and most of the assessed INNS are accidental introductions. Biofouling has been more extensively studied for shellfish and finfish cultivation (Fitridge and others, 2012) although a review by Bannister and others (2019) also considered seaweed cultivation.

Biofouling impacts infrastructure operations by fouling of longlines reducing settlement. It adds considerable weight to both stock and culture equipment and increases the costs associated with buoyancy and anchoring systems (see Fitridge and others, 2012 and references within). No evidence was found for biofouling costs or impacts on infrastructure for the assessed INNS species and information from others forms of aquaculture such as mussel longlines were used as a proxy.

Severe biofouling by INNS or native species reduces the value of seaweeds as they cannot be used for human consumption (Rolin and others, 2017). Species such as the bryozoan *Tricellaria inopinata* can cover the surfaces of kelp while tunicates may cover both the infrastructure and overgrow seaweeds.

Epiphytic and fouling species compete with cultured seaweed species for light, space and dissolved nutrients (Buschmann and Gomez 1993; Fletcher 1995). Studies on the red algae *Gracilaria chilensis* (Buschmann and Gomez, 1993) and *Kappaphycus alvarezii* (Marroig and Reis 2016) show that biofouling significantly reduces levels of solar irradiance reaching cultured stock, leading to lower photosynthetic rates and photosynthetic efficiency than unfouled stock (Borlongan and others, 2016).

The worst case assessments for impacts of INNS on seaweed cultivation were for moderate impact as it was not considered that impacts would meet the criteria for Major which refers to 'Local disappearance of an activity from all or part of the area invaded by the alien taxon'. Confidence in assessments is low due to the lack of specific information relevant to seaweed cultivation. Continuation of an activity in areas which are invaded by INNS may require investment and/or changes to activity or acceptance of lower yields and profits.

3.7.3 Impacts of INNS on workers

The only direct impact on safety was noted from the Pacific oyster, *Magallana gigas*, which has very sharp edges. Incidents were not recorded from aquaculture but it is noted that this potential fouling species has affected activities on shores as its sharp shells can cause injuries.

Although minor, it was noted that the red seaweed, *Asparagopsis armata* can cause nuisance by sticking to the clothing of people using its barbs. This could affect people handling gear and processing seaweed.

The main potential indirect pathway for impacts on workers, was associated with biofouling, leading to increases in the weight of gear that could result in lifting and handling injuries. This was mainly a concern resulting from attached fouling species, however, the whelk, *Rapana venosa* may climb onto longlines and other artificial structures in order to lay attached egg capsules. The additional weight from these may result in difficulties lifting lines. Attached fouling species that were considered likely to foul at high abundances and that would make handling more difficult were the tunicates *Botrylloides diegensis*, *B.*

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violaceus, *Didemnum vexillum* and the bryozoan *Schizoporella japonica*.

Table 11 Summary table of SEICAT Assessments. Key to impact ranks: MC=Minimal Concern; Mr= Minor; Md=Moderate; Mj=Major; Ms=Massive; DD = Data Deficient

IINNS	SEICAT Impact	Score	INNS	SEICAT Impact	Score
Algae			**Attached Species**		
Asparagopsis armata	Impacts on infrastructure and operations. Impacts on farmed species. Safety.	Md	*Asterocarpa humilis*	Impacts on infrastructure and operations. Safety	MC
Bonnemaisonia hamifera	Impacts on infrastructure and operations. Impacts on farmed species.	MC	*Botrylloides diegensis*	Impacts on infrastructure and operations and Safety	Md
Caulacanthus okamurae	No known impacts	MC	*Botrylloides violaceus*	Impacts on infrastructure and operations and Safety	Md
Codium fragile subsp. fragile	Impacts on infrastructure and operations and Impacts on farmed species:	Md	*Bugula neritina*	Impacts on infrastructure and operations.	Mr
Colpomenia peregrina	Impacts on farmed species	MC	*Ciona robusta*	Impacts on infrastructure and operations	Md
Dasysiphonia japonica	Impacts on farmed species:	Md	*Corella eumyota*	Impacts on infrastructure and operations and Safety:	Md
Grateloupia subpectinata	Impacts on infrastructure and operations.	Mr	*Diadumene lineata*	No direct impacts on aquaculture operations were found in the literature.	DD
Grateloupia turuturu	Impacts on infrastructure and operations.	Mr	*Didemnum vexillum*	Impacts on infrastructure and operations and Safety	Md
Melanothamnus harveyi	Impacts on farmed species	Mr	*Hydroides ezoensis*		
Undaria pinnatifida	Impacts on farmed species	Mr	*Magallana gigas*	Impacts on infrastructure and operations: Safety	Mr
Sheltering mobile species			*Schizoporella japonica*	Impacts on infrastructure and operations and Safety	Md
Ammothea hilgendorfi	No known impacts	MC	*Styela clava*	Impacts on infrastructure and operations	Md
Boccardia proboscidea	No known impacts	MC	*Tricellaria inopinata*	Impacts on farmed species	Md

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IINNS	SEICAT Impact	Score	INNS	SEICAT Impact	Score
Caprella mutica	Impacts on infrastructure and operations and farmed species	Md	*Watersipora subatra*	Impacts on infrastructure and operations and Safety	Md
Rapana venosa	Impacts on infrastructure and operations: Safety.	Md			

3.8 Cultivation best practice

Development of cultivation best practice requires a review of evidence of the associated benefits, risks and challenges. These have been recently reviewed by Campbell and others (2019), Wood and others (2017b), and Visch and others (2020a), and are outlined in Sections 3.5-3.7.

The goal of seaweed farming best practice should be to ensure long-term sustainable and profitable production by maximising productivity while minimising negative environmental impacts. Suggestions for best practice are expanded from the European management principles outlined in Campbell and others (2019) "siting that minimizes damage to sensitive environments; seed sources that maintain the genetic diversity of wild stocks; no cultivation of non-native species; biosecurity measures to control the spread of diseases, parasites and non-natives; no fertilization; and infrastructure which is well maintained" as follows:

Fertile material and genetic preservation

Best practice recommendation for kelps is to collect fertile material from only a restricted number of wild plants (i.e. 10-30 individuals) which can be biobanked and also used to initiate gametophyte cultures. Collections should be carried out in accordance with the Crown Estate harvesting licence. It would be prudent to source reproductive material from sites relatively near to the aquaculture site, however the exact distance is not defined. Potential risks of genetic introgression from farmed to wild populations (crop-to-wild gene flow) can be minimised by sourcing fertile material from multiple locations (still close to the cultivation site) in order to maximise the genetic diversity and tolerance to environmental variables (Stanley and others, 2019). Currently, collection of fertile material from farmed populations is not recommended unless part of a selective breeding programme. Further, harvesting crops prior to the onset of reproductive maturity will minimise farm-to-wild gene flow.

Recommendations are based on the following evidence:
- **Quantity of fertile material:** the potential impact of harvesting fertile material from the wild can be minimised by the use of seedbanks or gametophyte culturing, by which one collection event can supply seed for several subsequent years of cultivation. For kelps, collection of fertile material can involve harvesting only part of the frond, leaving the rest of the plant in place. Kelp species have very high fecundity, so relatively small amounts of sorus tissue can produce large volumes of seed. For example 5-10 sorus regions can seed 10-20 km of twine (Stanley and others, 2019). The quantity of fertile material necessary for other species is unknown, but appears to be greater for *Palmaria*, which requires 6.5-13.1 kg of fertile material per linear km (Werner & Dring 2011).
- **Farm-to-wild gene flow** the impacts of genetic introgression from farmed to wild populations are poorly understood, but can include maladaptation, homogenisation (genetic swamping from farm populations), and effective population size effects (see below).. Harvesting the crop prior to the onset of

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reproductive maturity could minimise this risk of these impacts.

- **Genetic population structure:** the genetic population structure of most seaweeds is poorly understood. In efforts to mitigate impacts to genetic diversity, Marine Licences can state that fertile material must be locally sourced, however the definition of 'local' is often arbitrary (e.g. up to 25 km), and should be underpinned by the genetic population structure for which baseline data is generally lacking (Barbier and others, 2019; Stanley and others, 2019). *Saccharina latissima* populations from the Irish Sea appear to show relatively limited differentiation at a scale of over 60km (Mooney and others, 2018). At a regional scale, there appear to be four distinct populations along the west coast of Scotland, separated by oceanographic features, although diversity can be observed at local (<35km) scales when physical hydrological boundaries exist (Thompson and others, 2021). The recommendation of fertile material sourced from at least 5-10 sorus regions will ensure mixed genetic diversity in the resultant crop (Stanley and others, 2019).
- **Effective population size** in selecting fertile material from a small number of individuals, which then artificially produce large volumes of offspring through cultivation, the effective population size is reduced. Collecting seed from a larger number of parent donors will increase diversity in the stock, with 30 adult plants considered reasonable (Thompson and others, 2021; Stanley and others, 2019).
- **Environmental distance**: for some seaweeds, clear genetic structuring and local adaptation leading to distinct ecotypes has been observed, whereas other seaweeds show less local adaptation (King and others, 2019, Augyte and others, 2018). Sourcing material from a greater number of donor plants, from multiple source populations, will effectively increase the genetic population size of the cultivated crop. This can reduce the potential detrimental impact of a small hatchery source population, by increasing diversity and tolerance to a wide range of environmental conditions (Laikre and others, 2010; Stanley and others, 2019)
- **Source stock**: Collection of fertile material from wild, rather than farmed stocks is currently recommended to reduce possible inbreeding (Stanley and others 2019). However, this may change as strains are developed to select for certain traits, such as fast growth, high yield, or desirable morphology (Loureiro and others, 2015).

3.8.1 Monitoring for disease, pests and parasites

Following best practice guidelines for hatchery processes (e.g. Mooney and others, 2018) which include use of sterile air and seawater, UV filtration systems, and germanium dioxide to remove diatom contamination (Kerrison and others, 2016) can minimise the change of spread through seedling production. Recommendations for best practice are difficult develop as there is limited knowledge about seaweed diseases in the UK (Campbell and others, 2019). Intensification of high density of monospecific cultivation may increase vulnerability to pests and disease, although the risk of transfer to wild populations is likely to be low (Marine Scotland 2017). Optimal cultivation density, which may impact the vulnerability to disease, is not yet known for the UK. Improvements to pest and disease prevention and detection have been identified as priorities in the development of the seaweed industry globally, and a precautionary approach is advised (Cottier-Cook and others, 2016)

3.8.2 Monitoring and management of INNS

Biosecurity planning (and cleaning processes) need to be put in place to prevent movement on non-native species. Improvements to biosecurity and detection on INNS have been identified as priorities in the development of the seaweed industry globally

(Cottier-Cook and others, 2016; Loureiro and others, 2015). The Scottish Seaweed Cultivation Policy Statement provides that "only species native to the area should be cultivated" (Marine Scotland 2017).

INNS that are likely to be associated with cultivated seaweeds and infrastructure and that have significant ecosystem impacts tend to be attached, epiphytic algae and biofouling tunicates, bryozoans and hydroids. For a number of these species, particularly invasive tunicates, natural dispersal is limited and the main vector for spread is movement of fouled floating structures, e.g. ship hulls and potential rafting on detached seaweeds. Invasive seaweeds may also spread through drifting of reproductive material and through movement of fouled objects.

Management to limit the INNS should take into account biosecurity measures that reduce the movement of fouled objects, including services vessels. Following recommendations to 'check, clean and dry' surfaces would also be beneficial to growers where these reduce colonisation and associated losses of seaweed biomass and reduce operational costs resulting from biofouling.

Siting and management may reduce impacts from INNS by considering levels of exposure and water movement, water temperature, cultivation period, timing of harvest, and through the choice of infrastructure materials, which all influence biofouling rates (Bannister and others, 2019).

Where species tolerances allow, farming at more exposed locations may limit biofouling. This is more suitable for robust species such as *Saccharina latissima* and *Laminaria digitata* (Andersen and others, 2011; Peteiro and Freire 2013a,b; Rolin and others, 2017). However, cultivating seaweeds at exposed sites may also present other environmental challenges as severe storms can damage seaweeds and displace aquaculture structures, leading to reductions in biomass and farm productivity (Rolin and others, 2016).

3.8.2 Monitoring and surveys

Monitoring of how seaweed farms interact with the surrounding environment is necessary to fill the knowledge gaps which currently impede development and licensing consent (Campbell and others, 2019; Wood and others, 2017b). Environmental impact assessments are required in most nascent industries to minimise ecological damage and ensure long-term sustainability and a Habitat Regulations Assessment will be required where seaweed farms are sited near European Marine Sites. The scale of the cultivation activity will inform the likely extent of impacts, and therefore monitoring requirements, and an ecosystem approach is recommended (Grebe and others, 2019). Cumulative effects must also be considered, as a small farm is unlikely to result in nutrient depletion, whereas several farms in close proximity may have a detectable local impact (Marine Scotland 2017).

3.8.3 Maintenance of infrastructure

Regular maintenance of all cultivation infrastructure is advised, in order to prevent losses into the marine environment (Marine Scotland, 2017). Mandatory reporting of material losses is recommended (Campbell and others, 2019).

3.8.4 Risk of entanglement

Entanglement risk of small farms using longlines is thought to be low (Marine Scotland, 2017), although the use of nets as a cultivation substrate could pose a greater risk (Stanley and others, 2019). Although entanglement risk can never be entirely ruled out (Campbell

and others, 2019), it is advised to maintain tension of anchor lines, select sites carefully (i.e. avoiding feeding, breeding and migration routes for the relevant marine species), with mandatory reporting / monitoring of entanglement incidents recommended, to minimise this risk (SIFT, 2021; Campbell and others, 2019).

3.8.5 Reporting of production

There are currently no available FAO estimates either cultivated or wild harvested seaweed production for the UK. The absence of this requirement impedes both management and licencing decisions, so a management system for reporting production volumes is recommended.

3.8.6 Spatial planning, site design and site selection

To assist with spatial planning studies and coastal management, site selection should be informed by optimal environmental conditions in combination with minimal socio-economic conflict. An example of this approach is provided by the MMO (2019) in a study that identified suitable areas in English waters for seaweed (and IMTA) cultivation using modelling approaches and then refined locations with more detailed surveys and stakeholder engagement.

Planning should incorporate the risk of catastrophic loss of infrastructure due to storm events (Capuzzo and others, 2014; Marine Scotland 2017), impacts on hydrodynamics, and the carrying capacity of the site in terms of cultivation density, however this curr ently represents a knowledge gap. Depending on the application of the biomass produced (i.e. bioremediation or human consumption), water quality at the proposed location should be determined (due to potential for sewage, effluent and heavy metal contamination). Location within designated shellfish waters is recommended for food production. Subject to additional, site specific impacts assessments and alignment with conservation objectives, it may in future be beneficial to locate seaweed farms within or just outside marine protected areas (SIFT 2021). For example a seaweed farm in Ireland was found to have no impact on a nearby seagrass bed (Walls and others, 2017b), and can be indirectly beneficial by serving as a *de facto* no take zone due to restricted fisheries access. However, siting a farm directly over seagrass or mearl is not recommended due to benthic shading and risk of scour from some mooring systems (Campbell and others, 2019). Co-location with offshore energy production and other forms of aquaculture (IMTA) is recommended, but may be subject to technical limitations or synergy of goals. Further, site design can incorporate additional sustainability features, such as the use of Eco moorings using local stone (Mooney-McAuley and others, 2016), or of helical screw type mooring systems with a lower seabed footprint.

3.8.7 Social-economic engagement

Engagement of the developing seaweed industry with the communities in which the activity is taking place will be key to the formation of local support and granting of "social licence" (see Billings and others, 2020 for details). One of the challenges to growth of the sector is the impact on cultural services (recreation and aesthetic values), posed by the visual disturbance of the infrastructure, or restriction of marine leisure activities within the farm (Hasselstrom and others, 2018; Cabral and others, 2016; Wood and others, 2017b). The visual impacts are considered to be minimal by comparison with fin fish aquaculture (Wood and others, 2017b), and the type of activity will determine whether interaction is possible (for example a kayaker could paddle overs submerged cultivation lines, whereas fishing gear would risk entanglement). A recent report by the Scottish Sustainable Inshore Fisheries Trust outlines community participation in seaweed farm proposals (SIFT 2021), and community ownership is included in Stanley and others (2019).

3.9 Aquaculture knowledge gaps

Seaweed cultivation remains at an early stage in the UK and producers have primarily drawn on a combination of established systems for floating shellfish aquaculture and seaweed cultivation in Asia. While cultivation protocols are established for several kelp species, they are lacking for potentially valuable species such as *Himanthalia elongata, Osmundea* spp and *Porphyra* spp. Even where methods are established, there is still research required to optimise techniques, for example stocking densities, seeding methods, and harvest strategies.

Areas requiring more research have been recently reviewed by Campbell and others (2019), Wood and others (2017b), and Capuzzo and McKie (2016). Evidence gaps and suggestions for improving knowledge are summarised below:

Diseases, pests and INNS
- Knowledge of seaweed diseases in UK and Europe
- Protocols to monitor for diseases and mitigate crop losses
- Extent of ecological impacts of diseases or parasites
- Biosecurity planning

Genetics and sourcing of fertile material
- Assessment of genetic population structure baselines for cultivation areas (with exceptions of Mooney and others, 2018; Thompson and others, 2021)
- Impact of farm-to-wild gene flow (i.e. maladaptation, homogenisation, and effective population size effects)
- Clarity in definition of "local" with regard to maintenance of genetic integrity when sourcing fertile material
- Biophysical models of spore dispersal
- Strategic assessment of breeding practices and their consequences for the environment

Habitat creation and wider biological impacts
- Carrying capacity of the site with regard to stocking density or cumulative effect of multiple farms
- Flora and fauna utilising the site
- Ecosystem function (i.e. food web modelling) consequences of cultivation
- Entanglement risk: reporting, monitoring and management
- Effect of benthic shading with varying cultivation density

Optimising production
- Improved reliability and stabilisation of biomass yield, for example through co-cultivation of species or multiple cropping
- Optimal seeding method and density
- Stocking density, proximity of cultivation structures to maximise yield
- Optimal harvest time and strategy (i.e. application of multiple partial harvesting to increase productivity and distribute production through the season)
- Approaches to minimise biofouling
- Diversification of seaweed species cultivated, including co-cultivation of multiple species
- IMTA species interactions

Physical and chemical impacts

- Modelling changes to hydrodynamics to determine the environmental footprint of the farm
- Uptake of anthropogenic nutrients by seaweed farms
- Sediment transport and siltation, light levels,
- Role of farmed algae in carbon capture and nutrient cycling
- Noise impacts of farms
- Fate and volume of farm produced POM and DOM (organic matter and detritus export)

Varying effect of scale

For all impacts above the extent of the effect will vary substantially with scale, and impacts may not scale-up linearly.

Operational, legislative and spatial planning

- Lack of specific regulation for seaweed farming in the UK (established licensing procedure for finfish and shellfish is not always be applicable)
- Unclear designation of implementation responsibility
- Insufficient evidence-base on environmental impacts to inform licencing decisions
- Lack of clarity on application requirements under (for example, under which circumstances an Environmental Impact Assessment would be required)

3.10 Aquaculture future directions

Future directions are likely to seek to reduce labour costs for example through development of reliable binder seeding techniques, mechanisation and automation of production. Minimising hatchery time from seeding to deployment, with maximised survivorship of seedlings may be achieved through, standardisation of seedling production, and increased quality control (for example by ascertaining optimal seeding density) will be essential (Forbord and others, 2020b; Kerrison and others, 2016; 2020).

While kelp species are highly productive, the biomass yield remains unpredictable even in commercial operations due to seasonal, regional, and site specific variation (Bak and others, 2018; Forbord and others, 2018). Improved environmental datasets will aid site designation and marine spatial planning.

Better understanding of site specific environmental conditions, along with species diversification, and where applicable, multiple partial harvesting techniques have the potential to stabilise production, and reduce production cost by increasing the yield per seeding (Bak and others, 2018; van den Burg and others, 2016).

Cutting edge technological developments may include cloud based monitoring of real time site data and remote farm management (see the IMPACT projects ASTRAL). Bespoke, specialised equipment including cultivation vessels and robotic harvester systems (e.g. the Standardized Production of Kelp system proposed by MACROSEA) will further reduce labour costs, while technological development for offshore cultivation at offshore wind sites can reduce capital investment and spatial constraints.

Cryopreservation and biobanking practices for a wider range of species will allow for preservation of genetic diversity and potential strain selection. Breeding programmes for traits such as disease resistance, rapid growth or site-specific physiological adaptation (e.g. tolerance to high wave energy/ current flow for offshore conditions) are under development.

Climate resilience may be improved by developing culture of warm adapted species (such

as *Laminaria ochroleuca*). Biosecurity protocols and horizon scanning for diseases, pests and INNS will also be important as the industry develops, and may be underpinned by improved knowledge of stocking density and site carrying capacity.

Further, while to date synthetic materials appear to be more suitable for cultivation at sea, to gain social licence and improve sustainability branding, research into biodegradable (such as cotton or hemp) or recycled materials, and lifecycle assessment of sustainable production will be key (Kerrison and others, 2019; Stanley and others, 2019).

IMTA and co-location with offshore wind farms both hold great potential and is the focus of much research and development. Also, if incorporated into production models, Carbon Credit schemes have the potential to increase the long term viability of seaweed cultivation (for example the Blue Carbon project being developed for IMTA systems by GreenWave.org).

Ultimately, development will also require improved information on operational costs, potential biomass yields and ecological effects of seaweeds farms, as well as clarification of the regulatory context (Capuzzo & McKie, 2016).

3.11 Aquaculture impact monitoring

The above review of the existing evidence base for the impacts of seaweed cultivation highlights the many unknowns surrounding the influence of such activities on the marine environment. Clearly, a better understanding of how seaweed farms influence physical and biological parameters through modelling and in situ measurements is needed before the potential for effects on the wider marine environment can be determined. Even so, it is evident that seaweed cultivation offers the potential for positive ecosystem services if managed correctly, but the overall impact on the surrounding environment could be negative if risks are not monitored and managed appropriately.

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 operators and deter investment. Ideally, seaweed growers could offer to carry out monitoring and research in collaboration with scientists to obtain reliable and robust information on impacts that can then be disseminated to the wider community (Campbell and others, 2019). Doing so, in consultation with interested parties, could reassure local stakeholders that environmental factors are being suitably considered. For licensing wave and tidal energy devices in Scotland, a "survey, deploy and monitor" approach has been developed (Wood and others, 2017b). This approach provides a framework on which to base decisions on the appropriate levels of monitoring for particular infrastructure based on factors such as size of the development, environmental sensitivity of the deployment area and the type of development (Wood and others, 2017b). Adopting a similar approach could also be beneficial to the seaweed cultivation sector.

3.11.1 Monitoring: What to measure and thresholds

Inevitably the existing knowledge gaps will lead to calls for monitoring requirements to be placed upon proposed and established cultivation sites. Each operation will need to demonstrate that existing conservation objectives in the area will not be undermined, and that any potential risks identified at the consenting stage are kept within acceptable limits throughout the lifetime of the project. In the context of seaweed cultivation, careful consideration of these limits is important given the complexity of a number of potential but often subtle changes to the marine environment that may occur. It will be necessary for governing bodies to agree on levels of environmental change that should invoke different management responses. Bespoke monitoring programs can then be designed that have

the statistical power to detect such changes with a known degree of scientific certainty.

Ideally, a monitoring programme should measure a wide range of physical and biological variables of interest at the farm site and within reference areas (see below). Given the (lack of) existing knowledge of the impacts of seaweed cultivation, these parameters could include current flow, irradiance levels, oxygen and nutrient concentrations, organic enrichment in sediments and water bodies, the structure of pelagic and benthic communities, the presence of non-native species, and the diversity and abundance of marine life. In reality, however, the costs associated with a full-scale monitoring programme would be prohibitive in most cases and unnecessary or impracticable for small-to-medium sized cultivation sites.

Rather, given that evidence-to-date suggests that impacts of cultivation are minimal, the nature and scale of monitoring activities undertaken by operators as part of their consent agreement should be aligned with the scale of the cultivation, whilst taking into account any site-specific features of conservation interest which may be sensitive to the activity. In practice, this may involve monitoring key ecological indicators in nearby sensitive habitats (e.g. seagrass meadow, maerl beds) as well as measuring key parameters inside and adjacent to farm infrastructure.

In contrast, large-scale farms could have notable effects on current speed, suspended sediment loads, light penetration, wave energy, nutrient dynamics and release of organic matter. A large-scale cultivation site is also likely to provide habitat for many organisms ranging from microbes to invertebrates and fish, which in turn could attract marine mammals and seabirds, although further research is needed to understand habitat provision by seaweed farms. How physical changes to current flow, suspen ded sediment, organic deposition and light levels affect associated marine organisms is poorly understood. As such, large-scale projects will require comprehensive monitoring to be undertaken, which should be informed by predictions made from existing evid ence and accepted limits of change. Agreeing acceptable limits of change will be necessary to design robust monitoring procedures, especially given that a number of site specific 'positive' and 'negative' changes are likely to occur simultaneously in cultivation areas.

3.11.2 Designing monitoring programmes

Regardless of the specific approach, the sampling design of any monitoring programme is critical. Ideally, a fully replicated Before-After-Control-Impact (BACI) design would be established prior to commencement of any cultivation activities. This should include collection of 'before' data at sufficient timescales (i.e. 2-3 years) to document natural temporal variability (both within and between years) in the physical and biological parameters at the proposed cultivation site and at multiple nearby reference or 'control sites. Following the establishment of a reliable baseline, monitoring should continue at the farm site and at multiple reference sites to examine the impacts of cultivation through time. Alternatively, another useful approach is the Before-After-Gradient (BAG) design, which has recently been developed to monitor the often-subtle effects of offshore wind farms (Methratta, 2020). Here, rather than identify specific control sites, surveys are conducting along a gradient of distance from the proposed impact site (in this case farm location), both before and after installation of infrastructure and commencement of operations. Clearly the extent of the monitoring programme must be feasible and a reflection of the scale of the proposed development.

In reality, however, a fully replicated BACI design is not always feasible or appropriate. Where it is not possible to collect 'before' data to provide a robust baseline prior to cultivation, it may be appropriate to use a Control-Impact (CI) design to monitor temporal patterns in physical and biological parameters at the farm site and several reference sites. Regardless of which method is utilised, without a reliable baseline and a spatially explicit

survey design, the impacts of cultivation and efficacy of any management actions will be difficult to ascertain with any certainty. As with any sampling design, a priori power analyses should be used to inform the sample size needed to detect the effects of interest.

4. Mechanical harvesting of wild seaweed

4.1 Target species

In Europe, large seaweeds such as kelps and wracks are the only species suitable for mechanised harvest. In the western Atlantic, the red seaweeds *Chondrus crispus* and *Mastocarpus stellatus* have historically been mechanically harvested using drag rakes, however these species do not form such extensive beds in the UK so are unlikely to be targeted by mechanical means in England and Wales. Wild seaweed populations, mainly kelps and wracks, have been mechanically harvested in several North Atlantic countries for decades (Mac Monagail and others, 2017). *A. nodosum* is currently harvested in Scotland by the Hebridean Seaweed Co. using a combination of mechanical and hand methods, however there is no known commercial mechanised harvesting in England and Wales. Proposals have been made to harvest kelp in Scotland (Marine Biopolymers Ltd) and Ireland (BioAtlantis Ltd), and a low impact method for harvesting *Ulva* blooms is under development in Wales (GreenSeas).

4.2 Mechanised trawling and dredging

Trawling is generally used to harvest species that inhabit greater depths, such as kelp (i.e. *Laminaria hyperborea*). In Norway, *L. hyperborea* trawlers are capable of harvesting 50 – 150 t day^{-1} (Vea and Ask, 2011). This method, used since 1961, harvests whole mature plants, detaching them from the substratum whilst leaving understory juveniles behind. Following a yearlong harvesting period, a 4 year fallow period is initiated to allow recovery (Christie and others, 1998). When comparing southern and central Norway recovery rates, it was found that central Norway populations had reduced growth rates (Christie and others, 1998). A 5-year fallow period has been made advisory in mid Norway locations (Steen and others, 2016). In France, a mechanical harvester known as a Scoubidou has primarily been used to harvest *L. digitata* since 1974 (Mesnildrey and others, 2012). It is essentially a large rotary hook, suspended form the vessel by a hydraulic arm. Once lowered into the kelp canopy, it is rotated, winding the kelp blades around the Scoubidou. The harvest is then uprooted and pulled out of the water, allowing short blades and juveniles to be missed. In Brittany, France, there is no official regulation on fall ow periods for *L. digitata* due to a short regeneration time and so the species may be harvested annually.

4.2.1 Impact on the kelp forest canopy and understory community

There is generally guidance against the use of mechanical methods in the UK (Burrows and others, 2018). This is due to the possibility of wider detrimental impacts on the environment. Seaweed-dominated habitats, and kelp forests in particular, are extremely rich and diverse systems that play pivotal roles in ecosystem functioning, in terms of sustaining coastal biodiversity and benthic primary productivity (Steneck and others, 2002; Smale and others, 2013). If managed incorrectly, commercial-scale mechanical removal of kelp has the potential to severely alter the structure and functioning of these critical ecosystems (e.g. Norderhaug and others, 2020), yet the likely impacts on seaweed populations and associated communities in the UK has not been formally examined. Currently, the only work on the impact of mechanical harvesting in the UK was conducted on *L. hyperborea*, in Scotland, in 1990 (Angus, 2017: H.T. Powell, pers. comm. 4.12.12). However, this work remained incomplete and unpublished due to the company closure of Kelco, a seaweed processing plant. According to Angus (2017), results from the study showed kelp population recovery varied greatly between sites. The research focused only

on the kelp populations themselves and did not examine recovery of associated communities and biodiversity.

To date, not a single long-term disturbance experiment conducted in UK kelp forests has been published. Information on ecological impacts is therefore often inferred with caution from the monitoring programs of other countries, such as Norway and France (Steen and others, 2016). Findings from other regions may not be directly transferrable to the UK, due to differences in the physical (i.e. temperature) and ecological (i.e. urchin grazing) environment. Unpublished research conducted in several UK kelp forests suggests that recovery rates of kelp communities are highly variable between regions and sites, although formal examination of these trends is still required (Smale, unpublished data).

The method of mechanical harvest tends to be species-specific, as different vessels and equipment are generally required to access seaweed at different depths. Typically, trawling or dredging methods are used to harvest kelps (i.e. *L. hyperborea, L. digitata*) and mechanical cutting, employed for wracks (i.e. *A. nodosum*). For the purpose of this review evidence available on the environmental impacts of mechanical trawling and cutting will be discussed separately. The review will firstly discuss the different methods of mechanised harvesting, followed by their impacts on seaweed populations and associated communities. The overall physical and biological impacts of mechanised harvesting of wild populations will then be discussed.

The impacts of mechanical harvesting will depend on geographic location, algal regenerative ability and harvesting pressure (technique, volu me, frequency, intensity). The magnitude of impacts can be reduced through management actions such as implementing quotas, seasonal closures, spatial zoning (e.g. rotation, no take zones, fallow areas), gear restrictions and community co-management (Lotze and others, 2019).

Ecological performance, in terms of growth and productivity, has been known to vary depending on location and latitude (King and others, 2020; Rinde and Sjøtun, 2005). For a sustainable commercial harvest, it is therefore necessary to consider different harvesting regimes at different latitudes due to varying optimal growth rates. When considering UK kelp populations, the monitoring of standing stock biomass before and after harvest should be implemented into management procedures so to correctly monitor recovery rates.

Several studies in Europe have found that new kelp forests are able to establish after mechanical harvesting or artificial removal (Vea & Ask, 2011). Recovery is more rapid if the harvest area is in close proximity to an untrawled area (Christie and others, 2003), and the rock surface is not scraped entirely clean of small kelp recruits (Kain and Jones, 1 975). Generally, fast growing opportunistic algae tend to colonise the rocks immediately af ter *L. hyperborea* is removed, but through the process of natural succession *L. hyperborea* becomes the dominant species 2-3 years after harvesting (Kain and Jones, 1975). However, the rate of recolonization and recovery is highly variable and seemingly af f ected by multiple physical and biological factors. As such, repeated harvesting every 3 years or less will not allow *L. hyperborea* to re-establish as the dominant species. The season in which kelp is cleared (summer, autumn, winter, spring) does not have a strong effect on the rate of recovery to virgin biomass, and similar patterns of species succession are observed for all seasons (Kain and Jones, 1975; Christie and others, 1998).

In France, repeated annual harvesting of *L. digitata* by Scoubidou has reportedly reduced the average age of plants in the canopy to <3 years old (Werner and Kraan 2004). This age-shift may reduce harvest yield in the long-term because highest plant biomass is recorded for the 3-4-year-old cohort (Arzel, 1998 In Werner and Kraan 2004). In addition, *L. digitata* are fertile in their second year but their reproductive capacity/potential is greatest at 3-4 years old. Therefore, lowering the average age of canopy plants to <3 years may negatively impact recruitment in the long-term (Werner and Kraan, 2004).

In Norway, the density of understory juveniles immediately after the first harvest substantially contributes to the regrowth of the canopy, however, the recovery of understory juveniles 4 years after harvesting was depleted. This suggests recovery will slow with future harvests until the understory juveniles are restored (Steen and others, 2016). The decrease in kelp population age can also affect associated communities. In Norway, epiphyte communities have been found to only achieve 1/3 of their recovery potential during a 4 year fallow period (Steen and others, 2016), and 5 year fallow periods in central Norway (Christie and others, 1998). The biomass of epiphyte communities increases with the age of the kelp. Reportedly, epiphyte diversity is not fully rest ored until individuals are approximately 7 years old (Waage-Nielsen and others, 2003). Associated epiphyte communities increase the heterogeneity and complexity of kelp habitats, creating provisions for a variety of organisms, and ultimately increasing biodiversity. These communities can support commercially important fish populations. As such, to allow for the complete recovery of both kelp populations and their associated communities it is necessary to consider longer harvesting cycles of >7 years.

There is a lack of long-term studies on spatiotemporal variation in the structure of wild kelp populations in the UK (Smale and Moore, 2017). Generalisations from other countries can provide insights into management procedures, however, it is important to note that these should be applied with caution as they may not be wholly transferrable, due to geographical variations in physical conditions and recovery rates. For example, kelp have been found to exhibit higher rates of primary productivity, greater standing stock biomass, and larger sizes per individual plant at colder, more northerly latitudes than souther n sites within the UK (Pessarrodona and others, 2018; Smale and others, 2020). The structure of mobile species composition in kelp hold fast assemblages is also linked to temperature (Teagle and others, 2018).

4.2.2 Impacts on other associated marine life

In Norwegian trawled areas, ecological models have indicated a 45% loss of primary production and a 70–98% loss in secondary production, although recovery rates were not predicted (Rinde and others, 2006). In addition, although kelp canopy cover is able to recover partially or fully in 4-6 years, associated stipe and holdfast assemblages had not recovered at either site within 6 years following harvesting (Christie and others, 1998). The dispersal of fauna between and within harvested areas will depend on the size of the areas, and the mobility of the species. A study in Norway found that 87% of mobile species within large cleared areas (~ 5000 m^2), were able to recolonise suitable substrates (e.g. nearby kelp holdfasts) within 35 days (Waage-Nielsen and others, 2003). The amount of kelp 'plant' that remains intact after harvesting influences both the regrowth of the kelp, as well as the impact to wider ecosystems. For example, food-web modelling studies of Chilean kelp forest found that if only the kelp blade was harvested, as opposed to the whole plant, then there was only a small impact at the ecosystem-level and harvesting could be 'ecologically sustainable' (Ortiz 2008).

Removal of kelp forest habitat may affect the abundance and diversity of fish species which, in turn, may affect higher trophic levels. For example, in Norway the number of small gadoid fish was 92% lower in harvested areas (up to at least 1 year post-harvest) compared to un-impacted kelp forest and the number of cormorants seen foraging in harvested areas was significantly lower, presumably due to lower prey availability (Lorentsen and others, 2010). However, these results are in contrast to those published by the Institute of Marine Research in Norway, which found that mechanical kelp harvesting (on a 5-year rotation) has 'a minor to non-existent impact on the density and distribution of fish (Vea and Ask 2011).

There is currently limited understanding of the extent to which marine mammals rely on or utilise kelp forests in the UK and wider Europe. However, it is likely that kelp habitats provide important foraging areas for a number of marine mammals.

Organic matter from kelp detritus is an important trophic subsidy to adjacent habitats and is a vital resource in nearshore food webs (Bustamante and Branch 1996; Krumhansl and Scheibling 2012). A reduction in detrital production (e.g. due to large-scale kelp harvesting) could weaken the links between kelp forests and the other ecosystems that depend on detritus as a food subsidy, ultimately reducing ecosystem functioning of the entire nearshore (Orr, 2013). In addition, seaweed decaying on beaches or on the seabed is broken down and re-mineralized (e.g. by microbial activity and invertebrate grazers), and the nutrients are exported to the nearshore environment (Revell and others, 2011). The process of nutrient recycling is broadly recognized as being essential in maintaining ecosystem functioning, by facilitating the growth of primary producers such as phytoplankton and kelp (Soares and others, 1997; Raffaelli 2006; Bulling and others, 2010).

4.2.3 Phase shifts

The complete removal of individual mature plants in trawled areas leaves a somewhat barren track with smaller individuals (Lorentsen and others, 2010). This has been known to cause phase shifts in communities. In Norway, the sea urchin (*Echinus esculentus*), has negatively impacted harvested kelp populations, where densities of *L. hyperborea* are low, by slowing or inhibiting regrowth of the kelp canopy after harvesting (Sjøtun and others, 2006). These areas have subsequently been closed to harvesting to allow recovery.

Grazing by herbivores can influence the rate at which kelp forests regenerate, and sea urchins have been known to create extensive 'barrens' within kelp beds by feeding on young plants. Urchins can encroach on an area of seabed after kelp has been removed, such as after large storm events, harvesting, or die-back of kelp due to high sea temperatures (Vea and Ask, 2011). The issue can be exacerbated if there is a corresponding decline in sea-urchin predators (such as lobsters or otters), which can lead to an 'explosion' in urchin populations (Tegner and Dayton 1991). Established urchin populations can inhibit regeneration of kelp canopy through grazing. Urchin over-grazing has been responsible for creating barrens in Norway and Nova Scotia kelp beds, which can take decades to recover (Norderhaug and Christie, 2009) but has not been documented in the UK.

The main culprit of overgrazing *L. hyperborea* in other countries is the green sea urchin *Strongylocentrotus droebachiensis*, which has only been recorded in a few locations around Scotland. The edible sea urchin *Echinus esculentus* is more commonly found around the UK coast, and has not yet been linked with extensive urchin barrens (unlike *S. droebachiensis*). However, research in Norway found that regeneration of kelp biomass after harvesting was strongly related to the density of *E. esculentus*; with densities of 4-5 animals per m^2 inhibiting regrowth of kelp forests up to 2.5 years after harvesting (Sjøtun and others, 2006). Therefore, based on the precautionary approach kelp harvesting in Norway is closed in areas with recorded high abundances of *E. esculentus* (Vea and Ask, 2011).

The use of mechanical trawling/dredging can also upturn and disturb rocks on the seafloor (Mesnildrey and others, 2012). This, in tandem with fully removing mature plants from the population can allow recolonisation of fast growing, short lived species, such as *S. polyschides* in France (Mesnildrey and others, 2012). *S. polyschides* has an annual lifespan (White, 2008), therefore this impact is short lived as the biomass of *L. digitata* can recover after two years (Mesnildrey and others, 2012). However, regular, repeated physical disturbance could eventually favour opportunistic seaweeds (such as *S. polyschides* and the invasive *U. pinnatifida* and *Sargassum muticum*) and lead to shift in habitat structure from long-lived stable *Laminaria* species to temporally variable weedy species (Smale and others, 2013).

4.2.4 Trawling impacts on resilience of kelp communities to climate change

Arguably, repeated harvesting of kelp forests will have the tendency to homogenise the gene pool, eroding resilience to environmental change. Climate change is placing an additional pressure on *L. digitata* and *L. hyperborea* stocks at their southernmost range edges, which can have knock-on effects to seaweed harvesting industries. For example, in Brittany *L. digitata* is found towards its southerly range edge and is increasingly being outcompeted by the fast growing kelp *S. polyschides* after harvesting (Werner and Kraan 2004; Mac Monagail and others, 2017). *S. polyschides* can tolerate higher temperatures than *L. digitata*, and even a slight increase may positively affect growth and reproduction of *S. polyschides*, and negatively impact *L. digitata* (Werner and Kraan 2004). This species shift in Brittany has had an economic impact on harvesters because *S. polyschides* has a lower alginate content than *L. digitata*, and is therefore less desirable to processors (Werner and Kraan 2004). In southern Norway, summer die-off events have been recorded for both the sugar kelp *S. latissima* and *L. hyperborea*, which have been associated with high-temperature events (Vea and Ask 2011). However, management structures are in place for the Norwegian kelp fishery that allow for closure of harvesting areas where warm-water events have occurred (Vea and Ask 2011). In the UK, ocean warming is driving shifts in the distribution and performance of kelp species and their associated communities (Teagle and Smale 2018; Pessarrodona and others, 2019), most notably with a poleward range expansion of the warm-adapted *L. ochroleuca*, which was recently recorded in Ireland for the first time (Schoenrock and others, 2019). It is unclear whether physical disturbance from harvesting could interact with climate-driven shifts in kelp forest structure to alter ecosystem functioning and resilience.

4.3 Mechanised cutting

Mechanical cutting boats or mowers are used in a number of countries to harvest wracks, such as *A. nodosum* (i.e. Scotland, Iceland, Norway and Maine, USA). A variety of vessel designs exist, including paddlewheel and water-jet driven cutters, as well as suction cutters. These shallow-draft vessels usually work close to the shore at high tide, and cut or 'mow' the top of the weed as it floats. The remaining uncut plant is still attached to the rocks. Generally it is not possible to harvest kelp with this method, as in the UK kelp inhabit greater depths and lack floating air bladders, so are inaccessible to mowers (Burrows and others, 2018).

In Norway, mechanical harvest of foreshore algae such as *A. nodosum* is not regulated at the statutory/national level, but is regulated by private owner rights because the species occur in the intertidal zone. In general, ~10cm of the plant remains intact after mechanical cutting, local harvesting efficiency is ~60% and a fallow period of 4 -6 years is used to allow recovery. In addition, environmental protection laws and other regulations can restrict areas for harvesting (Mesnildrey and others, 2012). In Maine, USA, the same regulations apply for mechanical harvest as for hand-harvest of *A. nodosum*, i.e. 40.6 cm (16 inches) of the alga, including the holdfast, must remain intact, and that no more than 17% of the standing stock may be harvested (Phillippi and others, 2014), with a follow period of about 5 years before re-harvest.

4.3.1 Impact to wrack bed recovery and understory community

Cutting only the tops of *A. nodosum* with the vessels allows for fairly rapid regrowth, although, recovery time is longer if less of the plant remains intact. In general, harvest rotations of 3-6 years are utilised to ensure full recovery of the canopy (varies by country and harvester), with the longer fallow periods allowing for greater restoration of associated marine life.

Mechanical cutters select for larger individuals of *A. nodosum* which can change the size

structure of a population (Ang and others, 1993). Ang and others (1993) also found there to be a 23% reduction in density (m^{-2}). Kelly and others (2001) found that the biomass of *A. nodosum* was restored to 100%, 18 months after harvesting by both hand and mechanical means (which left 20cm and 50cm of the plants intact respectively).

Under intense harvesting pressure, if rocks are scraped clean of holdfasts then *Fucus* may become the dominant seaweed species for an extended period of 3 -12 years, and predation of new/young *A. nodosum* plants (e.g. by limpets) will slow regeneration and recovery (Jenkins and others, 2004). Leaving a greater amount of base 'vegetation' after harvesting will lead to faster regrowth rates and potentially allow for shorter time between successive harvesting events. For example, Seip (1980) predicted that if 20-30% of the base vegetation is left, the stocks could be harvested every 2 years, but if only 3 -4% then stocks could only be harvested every 4 years or more.

In Northern Ireland, the effects of cutting *A. nodosum* (10-15 cm from their base) was investigated 2.5 years after a one-off harvesting event to assess impacts to shore ecology (Boaden and Dring 1980). Findings show that noticeable (and in some cases significant) ecological changes occurred after cutting, including; an increase in the cover of green algae and *Fucus vesiculosus*; increase in the abundance of limpets (which graze on young *A. nodosum* and other algae); increase in microalgae cover on boulders; a significant decrease in the cover of marine sponges, bryozoans and barnacles, and; a 30 -60% decrease in the fauna living under/on boulders in the cleared area. Sediment transport was also altered after clearing. However, Boaden and Dring (1980) predicted up to an 80% recovery in ecology after a four-year period.

A more recent study in Ireland looked at the impacts before and after seaweed removal over an 18-month period, for both mechanical and hand-harvesting techniques (Kelly and others, 2001). Between 87-97 different taxa were associated with *A. nodosum* (which varied greatly in space and time). Overall species richness (biodiversity) was not impacted by harvesting, but it did have an impact on a several individual species. Hand harvesting led to increases in *Fucus vesiculosus* and ephemeral algae with no significant impact on other flora. Hand-harvesting also resulted in a significant decrease in periwinkles (*Littorina obtusata*) over the winter, and a reduction in total encrusting sessile fauna (such as bryozoans and sponges). However, there was a corresponding increase in periwinkles in adjacent control sites, suggesting they disperse to nearby habitat. In addition, the regrowth of *A. nodosum* within 1-year is likely to restore the habitat needs of young fish (Kelly and others, 2001). The results suggest that mechanical harvesting (which removes less of the *A. nodosum*) has less of an environmental impact than hand harvesting at a local scale, and no long-term effects on biodiversity were observed for either harvesting method (Kelly and others, 2001).

4.3.2 Impacts to other associated marine life

In terms of the impacts of harvesting to fish, there is relatively little information available. A study conducted in Nova Scotia provided no evidence of adverse effects on fish following the experimental cutting of *A. nodosum,* in which 100% of the canopy was removed from 400m^2 patches (Black and Miller 1991). However, the study only focused on fish greater than 25 mm length, which move into the intertidal zone in the early evening and morning (Black and Miller 1991, 1994).

4.4 Emerging low impact harvesting of Ulva spp.

A low impact method for mechanically harvesting 'nuisance' blooms of *Ulva* spp. from estuarine systems is under development as part of a collaboration between GreenSeas Resources Ltd. and Aberystwyth University. The method involved using a shallow draft

boat with a mechanised conveyor belt to harvest floating *Ulva* spp at high tide. The vessel has been specially designed to avoid contact with the benthos, and potential impact on wading bird behaviour is being monitored as part of a PhD project (pers comm Oliver to Wilding 2021).

4.5 Wave energy attenuation and changes in coastal hydrology from mechanised harvesting

Until recently, the majority of studies on the impact of seaweed harvesting focused mostly on the resource itself and direct impacts to associated fauna. However, with the advent of the ecosystem-based approach to managing fisheries, scientists have started to explore and document the wider reaching impacts of harvesting seaweed and how they can be mitigated. Wider impacts of harvesting on ecosystem services potentially include bio- physical impacts such as reduced wave attenuation and increased coastal erosion.

The presence of seaweed provides attributes which are essential for coastal defence on a local scale. In the water column, seaweed will absorb and divert energy from waves and currents, reducing water motion in coastal areas. Additionally, detached storm cast seaweed on beaches creates strandlines that aid in the formation of dunes (Angus, 2017). Large scale harvesting of seaweeds will reduce the height, biomass and density of wild populations. Additionally, there will potentially be a reduction in strandline organic matter from storm cast seaweed which can cause dune erosion (Angus, 2017), as seen in Norway(Løvas & Tørum, 2001).

Trawls and dredges that remove whole individuals can also disrupt 10% of the underlying bedrock (Mesnildrey and others 2012). This can cause sediment instability that can ultimately make the seafloor more susceptible to wave scour and erosion. Hypothetically, over time and repeated harvest, this may lower the seabed, reducing wave attenuation, and increasing the chance of coastal erosion.

4.5.1 Loss of carbon stores and sinks

The accumulation of detritus within kelp and other seaweed habitats is limited and these habitats are not effective in acting as long term carbon stores. The majority of carbon stored within kelp habitats is contained within the living kelps and is therefore a function of the standing stock (Laffoley & Grimsditch, 2009). Harvesting seaweeds will reduce the amount of stored carbon through removal of the standing stock but is not relevant to carbon sequestration.

Kelps have the highest rate of primary production with large amounts of kelp-derived detritus being produced. Approximately 80% of this detritus is exported to adjacent habitats (Krumhansl & Scheibling, 2012; Burrows and others, 2014) but the proportion of exported material incorporated into carbon stores is unknown but likely to be small (Burrows and others, 2014). Reducing standing stocks of kelps through wild harvesting is likely to reduce the amount of detritus produced and subsequently exported and stored in adjacent habitats, until regrowth occurs.

4.6 Management and monitoring

Commercial seaweed harvesters use a range of methods, which have different catch per unit effort and consequences for the seaweed and associated marine life (Kelly and others, 2001). The magnitude of the impact will depend on the intensity and frequency of harvest, species exploited, and local environmental conditions (Mac Monagail and others 2017). Unregulated harvesting, whether it be my hand or mechanical means can lead to the overexploitation of the resource, especially if harvesting practices do not allow for

regeneration of the seaweed canopy/bed. Well-structured management plans can help mitigate the impacts of harvesting and ensure sustainability of the resource, especially when developed in collaboration with scientists, nature conservation authorities and harvesters (Mac Monagail and others 2017). Tools that can be used to manage harvesting include licences, quotas and rotation systems (Baweja and others 2016, cited from Mac Monagail and others, 2017), which would require enforcement (Mac Monagail and others, 2017). Continual monitoring of the resource and associated marine life, and feedback into the management plan are also essential components of sustainable harvesting strategies.

The specific approach to monitoring will be dependent on a number of factors, including proposed harvesting intensity, characteristics of the site and wider region, targeted species, management objectives and available resources.

If the overriding objective is to achieve sustainability, a robust and extensive survey of standing stock and areal extent of targeted species should be conducted prior to establishment of harvesting to establish a reliable baseline against which to detect change. However, as seaweed populations can be spatiotemporally highly variable, such baseline surveys need to be designed and conducted to adequately capture variability patterns. For some species in some regions, particularly those with patchy or restricted distributions, this may require significant sampling effort and become resource intensive. For regions and species with homogenous and widespread distributions and high abundances, sampling effort and resource requirements may be relatively limited. In all cases, following an initial survey, population-level data should be explored (e.g. with power analysis) to determine what level of sampling would be required in the future to detect different thresholds of change (i.e. 10, 20, 50% loss). Data should be also be explored to offer guidance on the sampling frequency required to detect such changes.

A variety of survey methods are available when designing a monitoring programme, which will again depend on the species and region in question, its distribution, and available resources. In the UK, the dominant target species for any commercial harvesting, *L. hyperborea*, is widespread and abundant in the shallow subtidal, with a depth distribution extending from the low intertidal to depths of >30 m below chart datum in clear waters. However, monitoring kelp forests along open coastlines in the UK is logistically challenging, given the high level of exposure to the dynamic North Atlantic Ocean. As such, reliable long-term monitoring data are lacking, and natural levels of variability are poorly understood (Smale and others 2013). Even so, given adequate resources, traditional survey techniques conducted by qualified and experienced scientific divers can be used to obtain reliable data on species' abundance, biomass and distribution. Recent survey work has utilised small-scale quadrats and habitat-scale transects to quantify kelp forest structure (Smale and others 2016, Smale and Moore 2017). However, scientific diving surveys can be time-consuming and spatially constrained, and the development of remote-sensing techniques is promising. Specifically, towed video can be used to quantify (at a coarse level) the extent and structure of kelp forest habitat at much greater spatial scales (Steen and others 2016), whilst acoustic techniques (e.g. SONAR) have recently been developed that allow detection of submerged kelp canopies (Bennion and others 2019). Other monitoring techniques, including the deployment of Autonomous Underwater Vehicles (AUVs), Baited Remote Underwater Video (BRUVs), fish traps, crab pots, and echo sounders have been used to monitor natural kelp populations and associated organisms (e.g. Norderhaug and others 2020).

In some regions, particularly those with clear waters that support large kelp species which reach the sea's surface, satellite-born sensors and aerial photography have been effective, but these distant sensors cannot operate effectively in turbid waters with mostly submerged canopy-forming kelp species, as is the case in the UK.

In tandem with direct monitoring, species distribution models can be developed to predict,

given environmental conditions at a certain site, the likely abundance and biomass of targeted species, as has been developed for *L. hyperborea* in Scotland (Burrows and others 2018). Such models can be used to extrapolate from survey sites to the wider region, and to identify sites or regions where seaweed populations are less abundant and more restricted than environmental conditions would predict, thereby indicating impacts of harvesting or other local pressures.

Regardless of the specific approach, the sampling design of any monitoring programme is critical. Ideally (as with monitoring cultivation impacts), a fully replicated Before-After-Control-Impact (BACI) or Before-After-Gradient (BAG) design would be established prior to commencement of any harvesting or extraction activities. This should include collection of 'before' data at sufficient timescales (i.e. 3-5 years) to document natural temporal variability (both within and between years) in the structure of seaweed populations and association communities within the proposed harvesting region. Given the destructive nature and high sensitivity of mechanical harvesting, obtaining a reliable and robust baseline of the structure of natural populations is critical.

Monitoring is a key component of management approaches to seaweed harvesting, as effective monitoring will capture changes in population structure through time, allow for natural and anthropogenic pressures to be disentangled, provide opportunities to alter management approaches to achieve sustainability. If natural seaweed resources are not managed appropriately, overharvesting can lead to significant shifts in population structure, and localised losses of seaweed resources, as has occurred in Chile for both *Gracilaria* (Lindstrom and Chapman, 1996) and *Gigartina* (Avila and others 2003). It is therefore in the interest of the harvester, management agencies and other stakeholders to develop and implement an effective monitoring and management programme.

There are numerous examples of management and monitoring approaches of harvested seaweed resources from around the world, which can be used to develop best practice for individual species and regions. Research and monitoring programmes that have been developed in collaboration between harvesters, researchers and government agencies have generally been more successful, and can provide information on the effect of harvesting on the resource and associated species, and evaluation options for improving management. For example, in Chile, limitations on harvesting rates of the two most economically important brown seaweeds (i.e. *Macrocystis* sp. and *Lessonia* sp.), were applied only in agreement between fishermen, industry, government and scientists (Buschmann and others, 2014). The guidelines focused on the selective harvesting of sporophytes in order to allow maintenance of the reproductive stock. Similarly, in Norway, a 5-year (in some cases 4) rotational management plan for *Laminaria* spp. was implemented in in 1992, with a well-resourced plan for research and monitoring to assess the wider impacts of harvesting regimes (Meland and Rebours, 2011; Vea and Ask, 2011). The approach has generally been seen as favourable, although some concerns regarding the longer-term sustainability and impacts have been raised.

Clearly, a number of management tools are available and approaches should be tailored to meet the individual species, region and proposed harvesting regime in question. These include seasonal closures, mandated fallow periods, closed areas, selective and partial harvesting, and total allowable harvest (reviewed regularly).

4.7 Mechanical harvesting knowledge gaps

A key evidence gap for large scale harvesting is a lack of understanding of the available resource, in the form of seaweed standing stock biomass in the UK. Thresholds for sustainable harvesting volumes of most species is unclear, and generalisations from European populations may not be appropriate due to regional variations in growth and recovery rates. Further, while some evidence is available on recovery rates of seaweed

populations, this information is garnered from other nations (e.g. Norway, France, and Canada) so may not be directly transferrable to UK coastal systems due to differences in physical and biological conditions. Moreover, very limited information exists on rates of recovery of the associated communities and wider impacts on ecosystem structure and functioning. Without long-term studies on spatiotemporal variation in the structure of wild kelp populations in the UK, it is not possible to examine the impacts of mechanised harvesting with any certainty. In order to achieve sustainable management of wild seaweed populations, significant investment in research would be needed to better understand the spatial extent of species, the accessible and total standing stock biomass of different species, immediate impacts of harvesting on seaweed populations, associated communities and the wider ecosystem, and rates and trajectories of recover y following physical disturbance.

5. Report summary, recommendations and conclusions

5.1 Aquaculture summary

Seaweed cultivation in England and Wales is an emerging industry which has great potential to meet goals for blue growth and food security. Expansions of cultivation, if appropriately situated and managed, could sustainably produce large volumes of biomass for a range of applications. Kelp farming in UK and Europe is still in the very early stages of development and there are operational and technological issues that are hindering development concerning the design and placement of farm structures, biofouling by bryozoans, amphipods and other fauna (Rolin and others 2017; Walls and others 2017a) and refinement of seeding and harvest techniques.

The potential negative impacts are summarised as follows:
- Direct and indirect impacts from infrastructure and ancillary activities
  - Impact of harvesting fertile material
  - Seabed scour from mooring chains
  - Noise and visual disturbance
  - Entanglement of marine mammals and birds
  - Wave energy attenuation and changes in coastal hydrology
  - Artificial habitat creation (cumulative with cultivated seaweeds also contributing)
  - Conflict with other users of marine space
- Direct and indirect impacts resulting from crops
  - Crop-to-wild gene flow
  - Changes to nutrient cycling and carbon storage
  - Absorption of nutrients
  - Release of dissolved or particulate organic matter
  - Spread of parasites and disease
  - Habitat for non-target nuisance species
  - Artificial habitat creation
  - Introduction and movement of INNS

Most cultivation sites in England and Wales are small scale and have been developed for near-shore, relatively sheltered conditions. Optimisation of cultivation techniques is required to stabilise production, standardise seeding methods, and identify optimal stocking density and site carrying capacity. Promising approaches include diversification of seaweed species cultured, development of binder seeding methods, multiple partial harvesting, and strategies to reduce biofouling.

While near shore waters in England and Wales hold great potential, spatial constraints are likely to limit expansion. Cultivation of multiple species (in IMTA systems), offshore sites, and co-location with wind energy represent opportunities for up-scaling of production with reduced socio-economic conflict and maximised economic gains, but will require further technical developments.

Knowledge on the impacts of seaweed farming on the marine ecosystems of England and Wales is very limited, however seaweed farming is generally considered to be relatively environmentally benign, with either limited or positive impacts on marine ecosystems. Impacts are likely to be scale dependant, and minimal for a small, isolated farm, however cumulative effects or large scale farms could have a more significant impact.

Through their ability to capture CO_2, seaweed farming has the potential to mitigate climate change, however the end use of the biomass will influence the fate of the captured carbon. Although more research is needed into the role of farmed seaweeds in carbon sequestration; carbon credit schemes have the potential increase the long term viability of seaweed cultivation.

5.2 Aquaculture knowledge gaps

Knowledge gaps include biosecurity planning, determination of genetic baselines and crop-to-wild gene flow, optimisation of production and evidence of the ecological effects of seaweeds farms on the surrounding environment, including the extent to which these support and facilitate spread of INNS that may impact ecosystems. Further, the development of the seaweed aquaculture is perceived to be limited by unclear regulatory context. At ecosystem scales the consequences many of these environmental changes are tightly interwoven, such as the effects of uptake of nutrients and release of dissolved organic material, and have only really been addressed using modelling studies.

5.3 Aquaculture recommendations

Cultivation best practice guidance includes:
- appropriate sourcing of fertile material,
- biosecurity planning to monitor for pests,
- diseases and non-native species,
- maintenance of infrastructure in good working order,
- monitoring of environmental impacts,
- reporting of entanglement incidents
- reporting of production volumes,
- appropriate site selection to inform marine spatial planning, and
- community engagement to facilitate grating of social licence.

Overall, seaweed farming has great potential but is in very early development stages and requires significant investment and research and development to reach economically-feasible scales. In future, the use of seedbanks with cryopreservation, cloud-based and automated monitoring arrays, specialised vessels, mechanisation and automation of production likely to underpin industry expansion.

Seaweed farms and the movement of material and boats associated with these has the potential to move INNS and to act as stepping stones. Consideration should be given when siting farms to the current distribution of INNS and whether farms are providing suitable habitat to facilitate spread. Reducing the spread of INNS is in the commercial interest of farm managers to limit reductions in yields and increased operational costs associated with biofouling and epiphytic algae.

5.4 Mechanical harvesting summary

There was no evidence found of mechanical harvesting from England and Wales, with examples drawn from Ireland, Scotland, Brittany, and Norway. The key species for which mechanical harvesting methods are appropriate are the kelps (*Laminaria* spp) and the wrack *Ascophyllum nodosum*. Methods for kelp harvest include trawls and 'scoubidou' dredges, while the floating canopy of *Ascophyllum* is "mowed" at high tide by mechanical cutters from shallow draft boats.

The impacts of mechanical harvesting will depend on geographic location, seaweed growth rates, harvest season and harvesting pressure (technique, volume, frequency, intensity). Kelp forest recovery following harvest can take between 5 to over 7 years, with the canopy

recovering prior to the associated assemblage. Canopy removal has been found to reduce the abundance of small gadoids by 92%, reducing the prey available at higher trophic levels, so impacting on cormorant foraging. Impacts can reduce the age structure of the population (for example *L. digitata* in France), with implications for the standing stock biomass and reproductive output of the population. Further, repeated harvesting can reduce the abundance of sub-canopy juveniles, as has been documented in Norwegian *L. hyperborea*, reducing the recovery potential. Following total clearance, phase shifts to urchin barrens or more opportunistic seaweed species have also been documented.

The recovery rate of *A. nodosum* following cutting determined primarily by the length of the fronds left remaining, with faster recovery the more biomass is left. Shifts in population size structure and density, as well as phase shifts, have also been recorded for this species. A recent Irish study found limited impacts of *A. nodosum* harvesting on the species richness or associated taxa, although abundance was reduced.

A low impact method of harvesting estuarine blooms of *Ulva* spp is being developed in Wales, which involves no benthic disturbance as the floating seaweed is harvested at low tide by a specialised shallow draught vessel.

The magnitude of impacts can be reduced through management actions such as implementing quotas, seasonal closures, spatial zoning (e.g. rotation, no take zones, fallow areas), gear restrictions and community co-management.

5.6 Mechanical harvesting knowledge gaps

While some evidence is available on the recovery rate of the seaweed canopy, none was available from England and Wales. Therefore conclusions should be interpreted with caution due to strong regional defences in growth rate. There is very limited evidence on rate of recovery of the associated community, and the impacts on ecological functioning. If impacts of mechanical harvesting on ecosystem services such as coastal defence, fisheries, carbon storage and climate change resilience represent key knowledge gaps.

A lack of evidence on the available seaweed resource, in the form of seaweed standing stock biomass, exists for all species in England and Wales. Accurate measurements of seaweed standing stock should be conducted in proposed harvesting locations. Predictive modelling of seaweed biomass and distribution could be improved with more accurate seabed data showing actual area and distribution of suitable rocky reef habitat in the subtidal around the coastline.

Although rates of recovery of kelp populations and associated communities have been published in a number of countries where commercial harvesting takes place, there is considerable variation in the findings, and no data is available for England and Wales. In addition, there is little information on how recovery rates vary under different environmental conditions and after different intensity and scale of removal.

Thresholds for sustainable harvesting volumes of most species remain unclear, and are not possible without detailed information about standing stock biomass and recovery rates.

There is currently limited understanding of the extent to which marine mammals rely on or utilise kelp forests in the UK and wider Europe and hence how these may be impacted by canopy removal.

5.7 Mechanical harvesting Recommendations

Establishing a cross-sectoral cooperation between regulators, industry, researchers and environmental interests is essential to formation of effective seaweed management plans. The Norwegian management model for sustainable harvest of *Laminaria hyperborea,* involves fallow periods, seasonal and spatial restrictions for harvesting, allowance for area-based closures if required, and features a strong monitoring program.

In Brittany, *Laminaria digitata* is mechanically harvested via a 'scoubidou', and the standing stock has remained fairly stable for decades, but landings have declined as a result of changes in the number and types of vessel operating. The fishery is restricted via quota (per vessel), effort control (days at sea limited by per week), seaso nal restrictions (to protect growth/ reproduction), and spatial management to facilitate even exploitation of resource.

Ascophyllum nodosum is harvested both by hand and mechanically "mown" with cutting vessels in Ireland and Scotland. Cutting practices and regulations vary with fallow periods generally used to allow recovery of stock before re-harvest.

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Appendix 1 Invasive non-native species that may be proposed for harvesting

Macroalgal INNS present in the UK that may be proposed for harvesting and which case officers should be aware of. Note this table is based on phyla. The presence of a species on this list does not suggest that the species is likely to be proposed for harvesting, have any commercial value or occur at sizes or abundances that make them suitable as target species. Species listed in Schedule 9 of the Wildlife and Countryside Act 1981.

Scientific Name	Phylum	Risk	Commercial exploitation
Agarophyton vermiculophyllum	Rhodophyta	High	Primarily used as a precursor for agar, which is widely used in the pharmaceutical and food industries.
Anotrichium furcellatum	Rhodophyta	No evidence	No evidence
Antithamnionella spirographidis	Rhodophyta	No evidence	No evidence
Antithamnionella ternifolia	Rhodophyta	No evidence	No evidence
*Asparagopsis armata	Rhodophyta	High	Ireland identified as a commercially important species for the production of cosmetics (Sweet 2011a).
Bonnemaisonia hamifera	Rhodophyta	Medium	No evidence
Botryocladia wrightii	Rhodophyta	No evidence	Of interest for cosmetics (Malakar and Mohanty, 2021)
Caulacanthus okamurae	Rhodophyta	High	Grown Korea (Gao and others 2019)
Ceramium circinatum	Rhodophyta	No evidence	No evidence
*Codium fragile subsp. Fragile	Chlorophyta	High	*C. fragile* - grown Korea (Hwang and others 2007), possible recreational harvesting UK
Colpomenia peregrina	Ochrophyta	High	No evidence
Corynophlaea umbellata	Ochrophyta	No evidence	No evidence
Cryptonemia hibernica	Rhodophyta	No evidence	No evidence
Dasysiphonia japonica	Rhodophyta	High	No evidence
Grateloupia subpectinata (Grateloupia luxurians)	Rhodophyta	Medium	No evidence
Grateloupia turuturu	Rhodophyta	Medium	Yes- in parts of range
Melanothamnus harveyi	Rhodophyta	Medium	No evidence
*Pikea californica	Rhodophyta	Medium	No evidence
Sarcodiotheca gaudichaudii	Rhodophyta	No evidence	Commercially important California (Pacheco-Ruíz, &

Scientific Name	Phylum	Risk	Commercial exploitation
			Zertuche-González, 1996)
Sargassum muticum	Ochrophyta	High	Yes- in parts of range
Solieria chordalis	Rhodophyta	Medium	No evidence, potential source of Carageenan and investigated for pharmaceutical properties (Bondu and others, 2010)
Stenogramma interruptum	Rhodophyta	No evidence	No evidence
Ulva califomica	Chlorophyta	No evidence	No evidence
Umbraulva dangeardii	Chlorophyta	No evidence	No evidence
**Undaria pinnatifida*	Ochrophyta	High	Yes-deliberately introduced to Brittany for commercial exploitation
*Schedule 9 Species, Wildlife and Countryside Act 1981.			

Appendix 2 Habitat and UK distribution of INNS

Distribution and habitat of INNS macroalgae that may impact seaweed cultivation.

Name	Habitat	Distribution (NBN atlas)	Key references
Agarophyton vermiculophyllum	Tends to establish in muddy areas where there are few other algal species and it has not reached large enough biomass levels to adversely affect oxygen levels or water current movements.	Restricted: West coast only	Wood, 2019a
Asparagopsis armata	Sometimes attaches to other seaweeds by its barbed branchlets. The Falkenbergia stage is typically found subtidally; it is epiphytic or sometimes free-living. It is known to grow in abundance amongst eelgrass beds, for example in the Scilly Isles.	Widespread: West and south coasts	Sweet, 2011a
Bonnemaisonia hamifera	Grows predominantly epiphytically on macroalgae e.g. *Cystoseira* spp. using its characteristic hooks to attach.	Widespread: West and south coasts	Sweet, 2011b
Caulacanthus okamurae	Grows as a turf on bare rock and mussels, or mixed with other turf -forming seaweeds such as *Gelidium* spp. or *Osmundea pinnatifida*, or epiphytically on larger seaweeds such as *Fucus serratus* or *Ulva lactuca*. It has also been recorded from artificial structures such as harbour walls.	Restricted: West and south coast	Wood, 2019b
Codium fragile subsp. fragile	Occurs on rock and coralline algae in pools and on open rock or artificial structures.	Restricted: mostly south coast	Sweet, 2011f
Colpomenia peregrina	Usually epiphytic, growing on a variety of seaweeds in mid-tide rockpools and down to the sub-littoral region. It thrives in sheltered areas.	Widespread	Sweet, 2011c
Dasysiphonia japonica	Generally found subtidally, either on natural shores or in artificial habitats such as marinas and harbours or epiphytically on other species of algae. In addition, it is frequently found free-floating or washed up on beaches.	Widespread: west coast	Wood, 2021c
Grateloupia subpectinata	Recorded on artificial structures	Restricted: South coast	Sweet, 2011d, Guiry and Guiry, 2021.
Grateloupia turuturu	Has been recorded growing attached to pontoons, harbour walls,	Widespread: South coast	Sweet, 2019a
Melanothamnus harveyi	Epiphyte and found on artificial structures.	Widespread: mainly west and south coasts	Maggs and Hommersand, 1993

Name	Habitat	Distribution (NBN atlas)	Key references
Pikea californica	Bedrock-no information on fouling of artificial structures but this is possible	Restricted: SW and Isles of Scilly	Sweet, 2019b
Sargassum muticum	Not an epiphyte. Grows on bedrock and artificial structures	Widespread	Sewell, 2019b
Solieria chordalis	Not an epiphyte, grows on bedrock.	Restricted: mainly south coast	
Undaria pinnatifida	May be found on hard surfaces, including artificial structures. May also attach to bottom dwelling creatures, empty shells, loose cobbles and other seaweed species.	Widespread	Sewell, 2019a

Sheltering mobile species: evidence for habitat and occurrence among algae or associated with artificial structures and UK Distribution.

Sheltering mobile species	Habitat	Distribution (NBN atlas)	Key reference
Ammothea hilgendorfi	Observed amongst sublittoral algae in Southampton Water. NO known impacts	Restricted: South and east coast	Sweet, 2011e
Boccardia proboscidea	Occasionally, worms were reported associated with coralline algae. Not considered relevant to cultivated seaweed or artificial infrastructure.	Restricted: South coast	None.
Caprella mutica	Often found on artificial structures such as mooring buoys marinas, aquaculture sites and harbours (Ashton, 2006). It has been found on off-shore windfarms and oil platforms while on the west coast of Scotland it has been found living on mussel and salmon farm infrastructure (Ashton, 2006). Preferred habitats include fine filamentous structures such as hydroids (Ashton, 2006 and references therein), foliose surfaces of macroalgae and turf- like bryozoans that they can grab hold of rather than hard substrates like bivalves. It is also found attached to drifting algae, in particular *Sargassum muticum*.	Widespread	Tillin and others, 2020 (impacts); Cook 2019- CABI datasheet; Ashton, 2006.
Rapana venosa	A habitat generalist that can be found colonizing hard and mixed substrates either natural like rocky outcrops and seagrass beds or artificial structures like jetty legs.	No records in UK	Tillin and others, 2020

Attached and fouling invertebrate species: evidence for habitat and occurrence among algae or associated with artificial structures and UK Distribution.

Attached/fouling species	Evidence for attachment/fouling	Distribution	References
Asterocarpa humilis	Infrastructure	Restricted: West and south coast	Tillin and others, 2020 (impacts) Bishop J. 2017.
Botrylloides diegensis	Harbours and marinas on pontoon floats, ropes, other sessile animals	Restricted south coast	Bishop, 2011a
Botrylloides violaceus	Harbours and marinas on pontoon floats, ropes, floating fenders etc. Also on natural shores on seaweed and other solid surfaces in at least some place.	Widespread	Bishop, 2012
Bugula neritina	Colonies are typically found in harbours and embayments, intertidal to 5m, attached to any available hard substrate. Larvae colonise a variety of artificial substrata including hulls. Studies have shown *B. neritina* larvae prefer to attach to rougher surfaces and prefer to attach to organic material. For example, in nature they frequently affix themselves to algae and to established bryozoan colonies.	Widespread	Bishop, 2011b
Ciona robusta	Submerged substrates including rock, eelgrass and kelp, and on anthropogenic substrates such as wood, metal or concrete docks, pilings and aquaculture gear.	Restricted: West and south coast	Yunnie & Bishop, 2017
Corella eumyota	Common on ship hulls and shells of mussels and oysters, such as Ostrea edulis, and it also grows on brown algae and on other *C. eumyota* specimens.	Widespread	Bishop, 2019a
Diadumene lineata	Often found attached to shells, associated with mussels and oysters, as well as rocks, boulders, jetties, sea walls, buoys, pilings and sometimes seaweeds.	Widespread: few records on east coast of England.	Tillin and others, 2020.
Didemnum vexillum	Colonises a wide range of artificial and natural habitats, covering algae, mussels and manmade substrata including pontoons and ropes. Has been found on bivalve and salmon aquaculture facilities and on macroalgae on kelp eelgrass; aquaculture gear. It prefers some sort of epibenthos to attach to rather than a barren substrate and seems to thrive best on the shaded underside of floating objects like pontoons and boat hulls.	Restricted: West and south coast	Bishop 2010: Impacts Tillin and others, 2020

Attached/fouling species	Evidence for attachment/fouling	Distribution	References
Hydroides ezoensis	Nuisance fouler on artificial substrates.	Restricted: South coast	
Magallana gigas	Larvae require some hard substrate but can settle on small items such as shells in otherwise fine sediments. *M. gigas* is typically found on rock, concrete artificial structures or shells and stone.	Widespread, but not North east coast	Tillin and others, 2020.
Schizoporella japonica	Attaches to natural and artificial hard substratum, rocks, shells and algae. In the UK, *S. japonica* has typically been found on intertidal and subtidal artificial structures (e.g. pontoon floats, fenders, tidal turbine, vessel hulls, mussels, algal holdfasts) and their associated epi-fouling biota.	Restricted West and south	Wood, 2017
Styela clava	Attaches to hard substratum, it has been found attached to rocks, wood, cement and concrete pontoons, vessel hulls, as well as other species (e.g. *Crassostrea gigas*, *Mytilus edulis* and *Sargassum muticum*)	Widespread	Bishop, 2019b
Tricellaria inopinata	Attached to solid surfaces in shallow water, especially in harbours and marinas: pontoon floats, wave screens, buoys, hulls, kelps and other sessile invertebrates. Also found on natural shores, often on algae.	Widespread	Bishop, 2019b
Watersipora subatra	Colonises a variety of hard substrates, both natural and man-made. As an early successional species it is efficient at colonizing novel habitats found on artificial structures. It has been found in marinas, on docks, boat hulls, oil platforms, pilings and floating debris as well as natural substrates including seaweeds, shells and rocks and floating substrata.	Restricted south coast	Bishop & Wood, 2021; impacts: Tillin and others, 2020

Appendix 3. EICAT and SEICAT assessments for impacts of INNS

INNS macroalgae that may be associated with and impact seaweed cultivation. . Key to impact ranks: MC=Minimal Concern; Mr= Minor; Md=Moderate; Mj=Major; Ms=Massive; DD = Data Deficient.

Name	EICAT Assessment	Score	SEICAT	Score	Reference
Asparagopsis armata	Competition, Physical and Structural changes: Reported to dominate algal assemblages in some locations; it forms bloom-like outbreaks and is known to cover 100% of the upper infralittoral (0 – 10 metres depth) during winter in the NW Mediterranean	Mj	Impacts on infrastructure and operations .Economic losses to fisheries have been reported due to harpoon weed clogging up fishing nets when it occurs in bloom-like outbreaks. Impacts on farmed species: This species can attach to other seaweeds and may impose cleaning and processing costs. Safety: can cause nuisance by sticking to the clothing of people using its barbs	Md	Sweet, 2011a
Bonnemaisonia hamifera	Competition: While *B. hamifera* could potentially compete with other algae and seagrasses, in experiments *B. hamifera* showed a relatively slow growth rate and did not alter community biomass production rates. There is very little evidence in the literature of instances of competition with other algae No evidence was found for impacts on aquaculture operations.	Md	Impacts on infrastructure and operations. No evidence was found for impacts on aquaculture operations. Assessment based on low growth rate. Impacts on farmed species: This species can attach to other seaweeds and may impose cleaning and processing costs.	MC	Sweet, 2011b
Caulacanthus okamurae	Physical and structural changes: can create a novel turf habitat in the upper intertidal zone where turfs did not previously exist; In studies in California, it	Md	No known impacts	MC	Wood, 2019b

Name	EICAT Assessment	Score	SEICAT	Score	Reference
	displaced macroinvertebrates, such as limpets, periwinkles, and barnacles, but supported increased numbers of copepods and ostracods, and of fleshy seaweeds, including *Ulva*, *Gelidium*, and *Chondracanthus*. In Kent, within the Thanet SAC, has carpeted areas of the chalk reefs, a designated feature of the SAC.				
Codium fragile subsp. fragile	Competition: In some areas has altered community structure and composition. In the UK algal diversity is high and this species has not yet occurred in nuisance densities.	Mr	Impacts on infrastructure and operations and Impacts on farmed species: Where it occurs in high densities, green sea fingers can be a fouling nuisance .	Md	Sweet, 2011f
Colpomenia peregrina	Biofouling and Structural Impacts: May have the potential to smother species or cover areas of the shore, but no significant impacts have been reported on native species.	MC	Impacts on farmed species :When undamaged, the oyster thief can become air filled and buoyant. During the early twentieth century economic losses were reported from French oyster beds where oysters were floated away but no recent economic impacts have been recorded No records were found of seaweed species being removed by this mechanism.	MC	Sweet 2011c
Dasysiphonia japonica	Competition: *D. japonica's* dominance at some sites in Scotland as a 'virtual monoculture'. In Norway, along the southwest coast it is now the most common species in sheltered and semi-exposed subtidal locations overgrowing other benthos. In addition, at some	Ms	Impacts on farmed species: No evidence but as epiphyte may reduce yields. rapidly establish dense populations can be highly problematic for native communities. *D. japonica's* fast growth rate is attributed to its high nitrate uptake	Md	Wood, 2021c

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Name	EICAT Assessment	Score	SEICAT	Score	Reference
	localities along the western Atlantic coast of N. America, *D. japonica* can occupy up to 80 % of available space.		efficiency.		
Grateloupia subpectinata	Competition: No ecosystem impacts have been reported; however this large, fast-growing seaweed may have the potential to displace native seaweed species.	Md	Impacts on infrastructure and operations. No evidence for socioeconomic impacts. Cleaning of infrastructure potentially minor.	Mr	Sweet, 2011d
Grateloupia turuturu	Competition and physical impacts: No ecosystem impacts have been reported in Great Britain; however may have the potential to displace native seaweed species and shade neighbouring species. In North America Devil's tongue weed is a major competitor of Irish moss (*Chondrus crispus*) which provides an important winter food source for snails and other invertebrates. Winter die-back of Devil's tongue weed may therefore affect local ecology.	Md	Impacts on infrastructure and operations. No evidence for socioeconomic impacts. Cleaning of infrastructure potentially minor.	Mr	Sweet, 2019
Melanothamnus harveyi	No evidence. The extent to which *M. harveyi* has affected native seaweeds and seagrasses is unknown. It possibly displaces native species as it can become very abundant, despite its small size	DD	Impacts on farmed species: Competition: no evidence but as an epiphytes, could adversely affect growth of the host plant through shading and nutrient competition.	Mr	NEMESIS
Undaria pinnatifida	Competition: likely to compete for space and resources with native species of kelp and other brown seaweeds. It may also compete with other epibenthic animals and seaweeds.	Mj	Impacts on farmed species: Competition as an epiphyte and Impacts on infrastructure and operations: costs of cleaning fouled material and infrastructure.	Mr	Sewell, 2019

Sheltering mobile species: evidence for occurrence among algae or associated with artificial structures. Key to impact ranks: MC=Minimal Concern; Mr= Minor; Md=Moderate; Mj=Major; Ms=Massive; DD = Data Deficient.

Sheltering mobile species	EICAT	Score	SEICAT	Score	Key reference
Ammothea hilgendorfi	No known impacts	MC	No known impacts	MC	Sweet, 2011e
Boccardia proboscidea	Occasionally, worms were reported associated with coralline algae (Petch, 19950. Not considered relevant to cultivated seaweed or artificial infrastructure. No known impacts. Not assessed	DD	No known impacts	MC	
Caprella mutica	Biofouling: It has not been recorded fouling natural substratum around the UK and has been assessed as 'Minimal concern' with high confidence. Competition: May compete with native caprellids, assessed as Major for those species but with impacts on ecosystem as lower.	Mr	Impacts on infrastructure and operations and Impacts on farmed species.: *C. mutica* are recorded settling on mussel lines taking up valuable space for mussel spat. This fouling behaviour has an economic cost associated with the removal of this species as well as any loss of utility. It is assumed this would be similar for seaweed cultivation.	Major	Tillin and others, 2020 (impacts); Cook 2019-CABI datasheet; Ashton, 2006.
Rapana venosa	Predation and Structural changes: *R. venosa* is a predator of bivalves. A loss in habitat forming bivalves could impact habitat structure and therefore refugia for a diversity of marine creatures. Indirect impacts: Loss of filter feeding bivalves through predation by *R. venosa* could have indirect effects on other species and the ecosystem. Dense beds of filter feeders capture large amounts of suspended particles and can reduce water turbidity resulting in increased light penetration. This may be beneficial for adjacent macrophyte dominated biotopes such as seagrass beds.	Mj	Impacts on infrastructure and operations: Tendency to use lines as spawning substrate could cause aquaculture operators considerable time, energy and monetary loss for clearance. Safety: There are also health and safety risks associated with the extra weight from eggs when lifting gear (see health and safety below).	Md	Tillin and others, 2020

Attached/fouling species. Key to impact ranks: MC=Minimal Concern; Mr= Minor;
Md=Moderate; Mj=Major; Ms=Massive; DD = Data Deficient.

Attached/ fouling species	EICAT	Score	SEICAT	Score	References
Asterocarpa humilis	Competition*: A. humilis* attaches to bivalves and associated substrates and is a possible competitor for food and space resources (Bishop, 2017). A. humilis could negatively affect other shallow-water suspension feeding sessile organisms. It may compete for resources and could impact on native species abundance (Bishop, 2017). Little is known at present about any impacts, like local species extinctions, that it may cause (Bishop, 2017).	MC	Impacts on infrastructure and operations. Potential abundance and clump formation means it has the ability to become a significant fouler. Safety: Aquaculture gear could become clogged and cumbersome (Bishop, 2017) if significantly fouled. There is little evidence to suggest that this will be the case so these possible impacts have been assessed as 'Minimal concern'.	MC	Tillin and others, 2020 (impacts) Bishop J. 2017.
Botrylloides diegensis	Competition: Biofouling: Capable of forming large colonies, and likely to have considerable effect on pre-existing sessile communities through overgrowth interactions etc. (Bishop (2011a)	Mj	Impacts on infrastructure and operations and Safety: Potential abundance, coupled with the formation of large colonies, means it could become a significant fouler of cultivation gear, potentially rendering underwater gear and lines extremely cumbersome.	Md	Bishop, 2011a
Botrylloides violaceus	Competition: Biofouling: Capable of forming very large colonies, and likely to have considerable effect on pre-existing sessile communities through overgrowth interactions etc. Might therefore have a negative effect on the abundance and habitat occupancy of other shallow-water suspension feeding sessile	Mj	Impacts on infrastructure and operations and Safety: The species' potential abundance, coupled with the formation of large colonies, means it can become a significant fouler of gear, rendering	Md	Bishop, 2012

Attached/ fouling species	EICAT	Score	SEICAT	Score	References
	invertebrates.		underwater gear and lines extremely cumbersome (Bishop, 2012)		
Bugula neritina	Competition: Biofouling: Populations in harbours and marinas can become dense, and colonies grow to considerable size. The species will thus presumably affect the abundance and habitat occupancy of other shallow-water suspension feeding sessile invertebrates. However, it is not clear whether this would cause the local extinction of any species.	Md	Impacts on infrastructure and operations. Negative impacts on aquaculture are possible but have not been recorded	Mr	Bishop, 2011b
Ciona robusta	Potential Competition: co-occurs with the native Ciona intestinalis and possibly competes with it; additionally, limited natural hybridisation between C. intestinalis and C. robusta has been suggested in this region.	Mr	Impacts on infrastructure and operations: added cost of equipment cleaning and maintenance are likely and reported from shellfish aquaculture. As a fouling organism, operations will incur cleaning costs for ropes and buoys.	Md	Yunnie & Bishop 2017
Corella eumyota	Competition: *C. eumyota* populations might have a negative effect on the abundance and habitat occupancy of other shallow-water suspension feeding sessile invertebrates. However, it is not clear whether this would cause the local extinction of any species.	Mr	Impacts on infrastructure and operations and Safety: The species' potential abundance, coupled with the formation of dense clumps, means it could become a significant fouler of gear, rendering underwater gear and lines extremely cumbersome.	Md	Bishop, 2019a
Diadumene lineata	Competition: *D. lineata* has been recorded in large clonal aggregations that could out-compete some native species (Podbielski and	MC	No direct impacts on aquaculture operations were found in the literature. The socio-economic	DD	Tillin and others 2020.

Attached/ fouling species	EICAT	Score	SEICAT	Score	References
	others, 2016), aggregations of over 4,000 individuals per square metre have been observed along from the Atlantic coast in the USA. There is no evidence of any competitive impact from this species so this pathway has been assessed as of 'Minimal concern'		impact could not be assessed due to lack of evidence and is therefore, 'Data deficient'.		
Didemnum vexillum	Competition, Biofouling and Physical and Structural changes: Competition: Competes with other sessile organisms for space and food whilst at the same time preventing epibenthic larvae from settling on it by lowering its surface pH. It smothers sessile communities and has a tendency to monopolize resources like space and food through its ability to rapidly colonise areas. Impacts are assessed as major where sessile organisms and algae may be overgrown and smothered and where competition is therefore focussed on space occupation.	Mj	Impacts on infrastructure and operations and Safety: Forms extensive sheets (2-5 mm thick) as well as long, pendulous outgrowths or tendrils (Bishop 2010). It is highly likely that *D. vexillum* may establish on equipment and gear. They are known to establish on vertical, artificial structures mussel longlines (Bishop, 2010). It has been found in association with mussel longline cultivation in Ireland (Minchin & Nunn, 2013).	Md	Bishop 2010: Impacts Tillin and others, 2020
Hydroides ezoensis	Competition for space. Likely to compete with native fouling communities.	Md	This species is a severe fouling organism on harbour structures and ships' hulls throughout Southampton Water, adding considerably to fouling of poorly protected ships and causing buoyancy problems to buoys.	Md	Eno and others, 1997
Magallana gigas	Competition and Structural impacts: M. gigas is a trophic competitor for other bivalves and other filter feeders and dense reefs would likely impact populations of native bivalve species, including mussels and native oyster and other	Ms	Impacts on infrastructure and operations: Safety: Wild M. gigas can overgrow aquaculture infrastructure increasing maintenance costs. The shells	Mr	Tillin and others 2020.

Attached/ fouling species	EICAT	Score	SEICAT	Score	References
	filter feeders such as Sabellaria alveolata. Can form large reefs of individuals cemented together and can overgrow and transform sedimentary and biogenic habitats resulting in the loss of natural habitats. Reefs are persistent.		can be extremely sharp and handling could lead to injury.		
Schizoporella japonica	Competition: This species is a competitor for space and is known to inhibit the growth of adjacent species. However it is a poor invader of previously occupied space.	Mr	Impacts on infrastructure and operations and Safety: It could become a significant fouler of rendering underwater gear and lines cumbersome.	Md	Wood, 2017
Styela clava	Competition: an reach high densities, sometimes being the dominant species in shallow sheltered habitats. The species might thus have a negative effect on the abundance and habitat occupancy of other shallow-water suspension feeding sessile invertebrates. However, it is not clear whether this would cause the local extinction of any species. The relatively small holdfast takes up little space, while the tunic covering the body is often heavily incrusted by other sessile species.	Md	Impacts on infrastructure and operations: The species has been documented as a serious pest in long-line mussel farms in Prince-Edward Island, Canada, with reports of similar effects within the native range, in Japan. It can foul ropes, buoys, moorings, ships etc. heavily.	Md	Bishop 2019b
Tricellaria inopinata	Competition, Biofouling: Populations in harbours and marinas can become very dense, with almost all submerged surfaces bearing a pale brown 'fuzz' of *T. inopinata*. Will thus presumably affect the abundance and habitat occupancy of other shallow-water suspension feeding sessile invertebrates. However, it is not clear whether this would cause the local extinction of any species. Also, kelps can become heavily fouled, particularly in sheltered	Md	Impacts on farmed species: Negative impacts on aquaculture possible but none reported; its relatively nondescript appearance may make attribution of impact to this species less likely. Overgrowth on seaweeds may make these less valuable and impose cleaning costs.	Md	Bishop 2019b

Attached/ fouling species	EICAT	Score	SEICAT	Score	References
	sites, presumably increasing drag.				
Watersipora subatra	Competition and Structural changes: This species can form large colonies overgrowing other sessile and encrusting species. This behaviour has the ability to alter the environment structure. It has been documented dominating fouling communities increasing habitat complexity with its growth forms and ability to retain sediments. This habitat alteration can have positive effects on species richness and diversity by providing structurally complex refugia. There is little evidence to suggest the ability of W. subatra to modify habitat structure has any negative impacts.	MC	Impacts on infrastructure and operations and Safety: It has been recorded as a pest species for biofouling on artificial substrates such as boat hulls and aquaculture equipment (Bishop, 2015 and references therein; Cohen, 2011).	Md	Bishop & Wood, 2021; impacts: Tillin and others, 2020

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