Seaweed farming and blue carbon: an evidence review to support sustainable management in Wales

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Comisiynodd Cyfoeth Naturiol Cymru yr adolygiad hwn o dystiolaeth i wella eu dealltwriaeth o'r cysylltiadau rhwng ffermydd gwymon a storio ac atafaelu carbon glas yn yr amgylchedd morol, gyda'r bwriad o lywio cyngor rheoleiddiol a pholisïau yn y dyfodol. Bydd yr adroddiad yn cefnogi rheolwyr i ddarparu cyngor cyson sy'n seiliedig ar dystiolaeth i ymholiadau a cheisiadau i ffermio gwymon.

Archwiliodd yr adolygiad hwn lenyddiaeth academaidd a llenyddiaeth arall ar gyfraniad gwymon wedi'i drin, a elwir hefyd yn facroalgae, i garbon glas, sy'n gorwedd yn bennaf yn y meysydd canlynol:

- Storio carbon dros dro mewn biomas macroalgaidd;
- Atafaelu carbon yn y tymor hwy sy'n cael ei allforio fel malurion a'i storio yng nghynefinoedd derbyn, gwaddodion neu'r môr dwfn;
- Effeithiau amnewid cynhyrchion gwymon ar allyriadau CO_2 o ddiwydiannau eraill, megis tanwyddau ffosil, gwrtaith, porthiant a chynhyrchiant bwyd, gan gynnwys storio carbon o'r defnyddiau hyn yn dilyn hynny, megis wedi'i gymathu mewn priddoedd a bioddeunyddiau.

Yn ystod y blynyddoedd diwethaf, rhoddwyd mwy a mwy o sylw i ddyframaethu gwymon fel cyflenwad newydd posibl o fiomas, ac mae'n tyfu ar gyfradd sylweddol ar hyn o bryd. Ledled y DU ac Ewrop, mae amaethu gwymon yn cyflwyno bioadnodd addawol i fodloni'r gofynion uchel am nwyddau pwysig, ac mae nifer o fanteision amgylcheddol canfyddedig cysylltiedig, gan gynnwys ei botensial ar gyfer atafaelu carbon, mynd i'r afael â phroblemau gorfaethu lleol, a heb fod angen yr un lefel o adnoddau (dŵr croyw, gwrtaith, a phlaladdwyr) fel systemau traddodiadol sy'n seiliedig ar y tir.

Er bod corff cynyddol o dystiolaeth i awgrymu y gall gwymonau ddal a storio carbon, nid ydynt yn cael eu cyfrif o hyd mewn asesiadau o garbon glas sydd, yn hytrach, yn canolbwyntio ar ecosystemau morfeydd heli, morwellt a mangrofau, sy'n atafaelu carbon yn eu cynefinoedd uniongyrchol. Ceir trafodaethau helaeth ynglŷn â chynnwys gwymon mewn strategaethau carbon glas mewn gwledydd sydd wedi buddsoddi mewn amaethu macroalgaidd. Mae dadl barhaus ynghylch a allai gwymon a dyfir at ddibenion masnachol gyfrannu'n ystyrlon at garbon glas, gan fod gwaith ymchwil presennol yn dangos bod y carbon sy'n cael ei storio mewn biomas macroalgaidd yn cael ei ryddhau yn ôl i'r atmosffer trwy gynaeafu a phrosesu dilynol y cnwd wedi'i drin, gyda symiau bach yn unig yn cael eu cadw, ac o bosibl eu hatafaelu, yn yr amgylchedd morol.

Mae'r adolygiad hwn yn dangos angen clir i ailddiffinio'r hyn a olygir gan atafaelu carbon sy'n gysylltiedig â thyfu gwymon, yn enwedig o ran effaith wirioneddol gwaddodi carbon o wymon wedi'i drin. Mae'r dystiolaeth a gyflwynwyd yn dangos sawl bwlch gwybodaeth ynghylch cyfraniad ffermio gwymon i garbon glas, gan fod y rhan fwyaf o'r ymchwil wedi canolbwyntio ar glystyrau macroalgaidd gwyllt. At hynny, nid yw'r diwydiant yn Ewrop wedi datblygu, gan ei gwneud hi'n anodd pennu perfformiad amgylcheddol cyffredinol amaethu wrth gyfrif am ddefnydd terfynol y biomas a gynhyrchir. Serch hyn, mae'n debygol y bydd potensial atafaelu carbon gwymon wedi'i drin yn parhau drwy allforio Carbon Organig Gronynnol (POC) a Charbon Organig Toddedig (DOC) fel sy'n digwydd mewn stociau gwyllt, y mae'n bosibl y bydd cyfran anhysbys ohonynt yn cael ei storio am gyfnodau o amser sy’n berthnasol i’r hinsawdd (e.e >100 mlynedd) mewn cynefinoedd derbyn neu'r môr dwfn.

Mae’r rôl sydd gan amaethu gwymon fel rhoddwr carbon hirdymor i gynefinoedd morol eraill yng Nghymru yn debygol o gyfrannu at yr amodau arfordirol ger ffermydd môr-wiail, nodweddion gwely’r môr, hydrodynameg a yrrir gan gerrynt a thonnau a chyfansoddiad biocemegol gwahanol rywogaethau macroalgaidd a ddefnyddir gan drinwyr. Nid yw’r amcangyfrifon presennol o allforion carbon o ffermydd gwymon wedi cael eu cadarnhau o hyd i raddau helaeth gan fesuriadau maes, ac felly maen nhw’n cynrychioli bwlch gwybodaeth sylweddol y mae angen mynd i’r afael ag ef. Fodd bynnag, fel y dangosir yn yr adolygiad hwn, mae potensial carbon glas ffermio gwymon yn gymharol fach o’i gymharu â chynefinoedd morol sy’n atafaelu yng Nghymru, er y gall hyn amrywio yn dibynnu ar arferion rheoli. Mae hefyd angen rhagor o waith ymchwil i’w ymgorffori’n effeithiol ym maes cynllunio gofodol morol.

Mae perfformiad amgylcheddol cyffredinol amaethu gwymon yn cynnwys effeithiau lleol uniongyrchol ar yr amgylchedd morol ac effeithiau anuniongyrchol a archwiliwyd trwy Asesiadau Cylch Oes (LCA), sy'n cyfrif am allyriadau gweithredol a'r defnydd o ynni (drwy fonitro, cynaeafu a phrosesu), mewnbynnau seilwaith a deunyddiau, yn ogystal â defnydd terfynol y biomas. Gall cynhyrchion posibl (e.e. bwyd, porthiant, biodanwyddau, a gwrtaith) amaethu macroalgaidd gael effaith net ar allyriadau byd-eang trwy gymryd lle cynhyrchion a phrosesau a fyddai fel arall yn arwain at allyriadau CO_2 uwch. Er bod data’n gyfyngedig, mae effeithiau amnewid posibl cynhyrchion gwymon ar draws y marchnadoedd hyn yn sylweddol. Wrth i'r diwydiant barhau i ddatblygu yn y blynyddoedd i ddod, bydd angen mwy o Asesiadau Cylch Oes i wneud y gorau o berfformiad ac arwain egwyddorion dylunio systemau amaethu, cadwraeth a dulliau prosesu i wella ein dealltwriaeth o enillion/colledion carbon net ar draws marchnad gynnyrch eang.

Yn ddiweddar, bu diddordeb hefyd yn y potensial ar gyfer amaethu gwymon wrth wrthbwyso carbon (derbyn credyd am leihau, osgoi, neu atafaelu carbon), sy’n faes dadleuol ym maes dyframaeth. Er bod gwerthusiadau economaidd a thechnegol o wrthbwyso carbon wrth amaethu gwymon yn eu dyddiau cynnar iawn, ni ddangoswyd eto ei fod yn arf addas ar raddfa leol i gynyddu hyfywedd economaidd systemau amaethu, nac ar raddfa fyd-eang i wrthbwyso allyriadau o ddiwydiannau eraill yn llwyr, megis amaethyddiaeth. Fodd bynnag, mae’n dangos potensial i fod yn rhan o bortffolio lliniaru hinsawdd a allai ddatblygu ymhellach wrth i raddfa’r diwydiant gwymon gynyddu, yn ogystal â’n dealltwriaeth o allforio carbon o ffermydd gwymon.

Mae angen dybryd i gydbwyso effeithiau amgylcheddol cysylltiedig dyframaethu gwymon â manteision posibl i sicrhau nad ydym yn manteisio i’r eithaf ar gapasiti cludo'r amgylcheddau derbyn ac na chaiff amcanion lleihau carbon eu tanseilio. Mae newidiadau amgylcheddol sy’n peri’r pryder mwyaf i’r diwydiant gwymon datblygol yn Ewrop wedi’u harchwilio’n helaeth mewn adolygiadau blaenorol, a nodwyd bylchau allweddol mewn gwybodaeth, sy’n cynnwys hwyluso clefydau, newid geneteg y boblogaeth a newidiadau ehangach i’r amgylchedd ffisiocemegol lleol.

Yn y pen draw, mae cyfraniad amaethu macroalgaidd at liniaru newid yn yr hinsawdd yn debygol o aros yn gymedrol iawn o gymharu ag ynni adnewyddadwy morol yng Nghymru. Fodd bynnag, gall ffermio gwymon fod yn gyfle hygyrch i gymunedau/cwmnïau arfordirol gan fod ganddo’r potensial i gyfrannu at strategaethau carbon glas yn ogystal â darparu adnodd biomas gwerthfawr at ddefnyddiau eraill. Mae'n bwysig nodi, fodd bynnag, nad yw cyfraniadau at garbon glas yn cael eu hystyried yn rhan o'r broses ganiatáu na rheoleiddio ar hyn o bryd, ac felly rhaid ystyried ceisiadau i ffermio gwymon yng nghyd-destun eu heffeithiau amgylcheddol, fel y'u cyflwynir yn yr adroddiad hwn.

Executive summary

Natural Resources Wales commissioned this evidence review to improve their understanding on the links between seaweed farms and blue carbon storage and sequestration in the marine environment, with a view to inform regulatory advice and future policy. The report will support managers to provide evidence-based and consistent advice to seaweed farming applications and enquiries.

This review examined academic and other literature on the contribution of cultivated seaweeds, also termed macroalgae, to blue carbon (BC), which lies primarily in the following areas:

- The temporary storage of carbon in macroalgal biomass;
- The longer-term sequestration of carbon exported as detritus and stored in recipient habitats, sediments, or the deep-sea, and;
- The substitution effects of seaweed products on CO_2 emissions from other industries, such as fossil fuels, fertilisers, feed, and food production, including the subsequent storage of carbon from these uses, such as assimilated in soils and bio-materials.

In recent years, seaweed aquaculture has gained an increasing amount of attention as a potential new supply of biomass and is currently growing at a substantial rate. Across the UK and Europe, seaweed cultivation presents a promising bioresource to meet high demands of important commodities and has several perceived environmental benefits, including their potential for carbon capture and sequestration, addressing local eutrophication issues, and not requiring the same level of resources (freshwater, fertilisers, and pesticides) as traditional land-based systems.

Despite a growing body of evidence to suggest that seaweeds can capture and store carbon, they remain unaccounted for in BC assessments that instead focus on saltmarsh, seagrass, and mangrove ecosystems, which sequester carbon within their immediate habitats. Discussions surrounding the inclusion of seaweed in BC strategies feature heavily in countries which have invested in macroalgal cultivation. There is an ongoing debate as to whether seaweed grown for commercial purposes could contribute meaningfully to BC, as current research indicates that the carbon stored within macroalgal biomass is released back into the atmosphere through harvest and subsequent processing of the cultivated crop, with only small quantities retained, and potentially sequestered, in the marine environment.

This review demonstrates a clear need to redefine what is meant by carbon sequestration linked to seaweed cultivation, particularly regarding the real impact of sedimentation of carbon from cultivated seaweeds. The evidence presented shows several knowledge gaps regarding the contribution of seaweed farming to BC, as the majority of research has focused on wild macroalgal stands. Furthermore, the European industry is in its infancy,

making it difficult to determine the overall environmental performance of cultivation when accounting for the end-use of the biomass produced. Despite this, the carbon sequestration potential of cultivated seaweed will likely remain through the export of Particulate Organic Carbon (POC) and Dissolved Organic Carbon (DOC) as occurs in wild stocks, an unknown proportion of which may be stored for climatically relevant time periods (e.g., >100 years) in recipient habitats or the deep sea.

The role that cultivated seaweed plays as a long-term carbon donor to other marine habitats in Wales is likely to be a function of the coastal conditions adjacent to kelp farms, sea-bed characteristics, current and wave driven hydrodynamics, and the biochemical composition of different macroalgal species utilised by cultivators. Current estimates of carbon export from seaweed farms remain largely uncorroborated by field measurements, and therefore represents a significant knowledge gap that needs to be addressed. However, as shown in this review, the blue carbon potential of seaweed farming is relatively modest in comparison to sequestering marine habitats in Wales, although this may vary depending on management practices and requires further research to incorporate effectively into marine spatial planning.

The overall environmental performance of seaweed cultivation consists of both direct local effects on the marine environment and indirect impacts that have been examined through Life-Cycle Assessments (LCA), which account for operational emissions and energy use (through monitoring, harvest, and processing), infrastructure and material inputs, as well as the end-use of the biomass. The potential products (e.g., food, feed, biofuels, and fertiliser) of macroalgal cultivation can have a net effect on global emissions by replacing products and processes that would otherwise result in higher CO_2 emissions. While data is limited, the potential substitution effects of seaweed products across these markets are substantial. As the industry continues to develop in the coming years, more LCAs will be needed to optimise the performance and guide the design principles of cultivation systems, preservation, and processing methods to further our understanding of net carbon gains/losses across a wide product market.

Recently, there has also been interest in the potential for seaweed cultivation in carbon offsetting (receiving credit for reducing, avoiding, or sequestering carbon), which is a contentious field within aquaculture. While economic and technical appraisals of carbon offsetting in seaweed cultivation are very much in their infancy, it has not yet been shown to be a suitable tool at the local scale to increase the economic viability of cultivation systems, or at the global scale to entirely offset emissions from other industries, such as agriculture. However, it does show potential to be part of a climate mitigation portfolio that may develop further as the scale of the seaweed industry increases, as well as our understanding of carbon export from seaweed farms.

There is an immediate need to balance the associated environmental impacts of seaweed aquaculture with potential benefits to ensure the carrying capacity of the receiving environments are not exceeded and carbon reduction objectives are not undermined. Environmental changes of greatest concern for the developing European seaweed industry have been examined extensively in previous reviews, with key knowledge gaps identified, which include the facilitation of disease, alteration of population genetics, and wider alterations to the local physiochemical environment.

Ultimately, the contribution of macroalgal cultivation to climate change mitigation is likely to remain very modest compared to marine renewables in Wales. However, seaweed farming may present an accessible opportunity for coastal communities/companies as it not only has the potential to contribute to blue carbon strategies, but also provides a valuable biomass resource for other uses. It is important to note, however, that contributions to blue carbon are not considered part of the consenting or regulatory process at present, and therefore seaweed farm applications must be considered in the context of their environmental impacts, as presented in this report.

1. Introduction

1.1 Background and aims

NRW currently advises on a range of seaweed farming enquiries / applications of various size. As with other marine licence applications, advice is given by NRW specialists on the specific enquiry / application using the best available evidence and knowledge, applying the precautionary principal.

There is a rapidly growing interest in Wales in the development of seaweed farms for a variety of commercial and non-commercial purposes, which are often cited for their blue carbon potential as a climate change mitigation tool. NRW therefore commissioned this report to improve their understanding on the links between seaweed farms and blue carbon storage and sequestration, with a view to informing regulatory advice and future policy.

1.2 Outputs

This project was a desk-based contract to provide a Rapid Evidence Assessment (REA) on the links between seaweed farms and blue carbon storage and sequestration in Wales.

The project outputs consist of this report, including associated appendices, and a spreadsheet of evidence sources (available on request from NRW) used to compile the information presented within.

2. Methodology

This evidence review by SAMS Enterprise is a Rapid Evidence Review (REA; Collins et al., 2015). The first step in undertaking the review was developing a Review Protocol document to guide the review process, following the methodology outlined in Collins et al. (2015). The Protocol was approved by NRW prior to commencement of the literature review. The Review Protocol document included the conceptual framework for the review, the primary question and secondary objectives to be considered, the Population, Intervention, Comparator, Outcome (PICO) elements, search methods (databases) and terms, and quality/validity assessment criteria. Full details of the approved Review Protocol are provided in Appendix 1.

The next step of this project was to assess the overall evidence base detailing the blue carbon potential of seaweed, exploring both peer-reviewed and grey literature to provide the best outputs within the resource constraints of the project. Specific data, including study system, species, experimental design, and location were drawn from each of these sources and assessed for their significance in answering the primary research question:

> To what extent can seaweed farming in Wales contribute to carbon sequestration in the marine environment?

As blue carbon is a relatively new concept, no earliest date was used to define the range of publications included. The databases used for the searches encompass both published and grey literature (Appendix 1). However, directed searches were also included to capture additional grey literature, including that of academic institutions and environmental regulators.

2.1 Article screening and inclusion criteria

The overall search results on the blue carbon potential of seaweeds returned 769 unique sources, a total of 168 of which were retained as relevant to the questions of this review. The potentially relevant sources were assessed by a team of primary reviewers, a subset of which (>25%) was reviewed again by a technical specialist for quality assurance purposes.

Following the methodology outlined in Collins et al. (2015), each evidence source was screened to remove sources not relevant to the blue carbon potential of seaweed aquaculture, identify sources relevant to the secondary objectives of this review, and capture the information and data within an evidence review matrix provided separately to NRW, which includes details of experimental design, location, species, and main findings. Articles were assessed using inclusion criteria as defined by PICO elements in Appendix 1, first screened by the title of the article and then filtered on viewing the abstract and the full text. A flow chart of the evidence review process is included in Appendix 1.

Of the 168 unique sources retained for this review, 69 were relevant to carbon capture within wild and farmed seaweeds, 50 for environmental impacts of seaweed aquaculture, 60 relating to marine/aquaculture operations that may affect carbon emissions and losses from the marine environment, including life-cycle assessments, and 13 from studies on hydrodynamics, transport, and fate of macroalgae in the marine environment. Several sources contained evidence that was relevant to two of these categories.

2.2 Critical Appraisal

Additional information on the quality/validity of the evidence provided by the source was captured in the evidence review matrix. This was assessed against six main criteria, which are described in further detail in Appendix 1, as follows: 1) conceptual framing, 2) transparency, 3) appropriateness of methods used, 4) internal validity, 5) context sensitivity, and 6) cogency. Each evidence source was assigned confidence score low to high, with some studies assigned with a low confidence excluded from the assessment should sufficient data exist from other sources.

2.3 Limitations

Several limitations have been identified within this review. With respect to the methodology, this REA was focussed on the blue carbon potential of seaweed farming, and therefore exclusion/inclusion criteria for the environmental impacts of cultivation were not rigorously defined. Furthermore, due to resource/funding constraints in our analysis, the methodologies employed within the evidence sources were not examined in detail, reducing potential comparability between the available literature and potentially introducing some methodological bias.

There are also key limitations due to the infancy of the seaweed cultivation industry in Wales, particularly with regard to its blue carbon potential. Due to this, methods are developing rapidly and the data available to draw conclusions relevant to the Welsh marine environment are limited. Small sample sizes are problematic, resulting in low confidence assigned to carbon sequestration rates adopted within this analysis, thereby also making it difficult to draw firm conclusions throughout. Additionally, there are inconsistencies in the way methods and results are reported in different studies, which creates difficulty in making comparisons between them and in extrapolating their results to other environments. Ultimately, the findings presented here are influenced by the reliability of the literature, including grey literature, on which this report is based, and several key knowledge gaps are presented for which data is insufficient to draw conclusions.

3. Blue carbon potential of seaweed

The concept of "Blue Carbon" (BC) was first published by Nelleman et al. (2009) in the UNEP report "Blue Carbon: The Role of Healthy Oceans in Binding Carbon", which describes BC as the biological carbon captured by marine living organisms. Evidence presented in the report indicates that as much as 50% of carbon in the atmosphere is fixed by marine primary producers, hence the suggestion that oceans may play a crucial role in climate change mitigation strategies (Nelleman et al., 2009). However, the focus of the report and most subsequent studies on BC has been on mangrove, saltmarsh, and seagrass ecosystems. Indeed, the global program "The Blue Carbon Initiative" which began in 2019 in an attempt to mitigate climate change through restoration and sustainable use of coastal and marine ecosystems, solely focuses on the three aforementioned environments (The Initiative — The Blue Carbon Initiative, 2019). By comparison, the potential role of seaweed (or macroalgae) in BC strategies has largely been ignored until recently. A potential explanation as to why seaweed has been neglected from a BC perspective is that a significant (but largely unquantified) portion of seaweed produced is decomposed in the ocean, recirculating through the carbon cycle and hence, does not represent a net sink for CO_2 (Duarte et al., 2017).

However, multiple papers have since been published which suggest that seaweed, particularly wild stocks, have a greater role to play in BC and climate mitigation strategies than previously thought (Hill et al., 2015; Ahmed et al., 2016; Raven, 2018; Krause-Jensen et al., 2018; Froehlich et al., 2019; Wu et al., 2020 and Hu et al., 2021). As scientific research in this area continues to grow, more countries are recognising the potential of macroalgae in BC and mitigating the effects of climate change (Gao et al., 2017; Walls et al., 2017a; 2017b; Visch et al., 2020; Laurens et al., 2020). Discussions surrounding the inclusion of seaweed in BC strategies also feature heavily in countries which have invested in macroalgal cultivation (Sondak et al., 2017; Tang et al., 2018; Wu et al., 2020 and Gao et al., 2021), although both wild and cultivated stocks remain excluded from most BC initiatives with very few exceptions (Sondak et al., 2017 and Krause-Jensen et al., 2018). Despite the mounting evidence that macroalgae can contribute to carbon sequestration and therefore, climate change, the inclusion of seaweed in BC strategies remains a controversial subject. Although evidence suggests that seaweeds have the ability to capture and store carbon there is debate as to whether seaweed grown for commercial purposes could represent a meaningful contribution to BC (Krause-Jensen et al., 2018).

Cultivated seaweeds may have the ability to contribute to BC strategies in various ways, including through temporary storage of carbon in macroalgal biomass before being cycled through food webs or industrial systems and through longer-term sequestration of carbon into sediments or the deep sea by transport of macroalgal detritus and dislodged sporophytes. However, some research suggests that carbon stored within macroalgal biomass is released into the atmosphere when seaweed is processed (Chung et al., 2011; Ahmed et al., 2016; Sondak et al., 2017), although this does not necessarily mean that seaweed aquaculture cannot contribute to climate mitigation strategies in other ways outside of BC storage in the marine environment. Multiple uses have emerged in recent years for cultivated biomass that reduce carbon emissions by replacing products from higher carbon emitting industries, thereby providing a preventative strategy rather than a mitigative one. These so-called substitution effects include biofuel production, which reduces reliance on fossil fuels and therefore reduces carbon emissions, and agricultural uses, such as feed and fertiliser to improve soil quality and has shown potential to reduce methane production in cattle (Duarte et al., 2017; Froelich et al., 2019).

3.1 Macroalgal carbon capture and storage

Whereas mangroves, salt marshes, and seagrasses tend to grow on sandy or muddy shores, wild macroalgal communities tend to develop on hard, rocky substrates and so have little capacity for carbon storage within underlying sediments in the same manner as these other habitats (Duarte et al., 2013; Krause-Jensen et al., 2018). The potential for macroalgae, both wild and cultivated, to contribute to BC is twofold; 1) through the capture of carbon in the macroalgal biomass during photosynthesis, and 2) the subsequent storage of dead biomass in sediments (Krause-Jensen & Duarte, 2016; Pedersen 2020; Blain et al., 2021; Klinger, 2021).

The primary reason why most BC strategies do not account for macroalgae is the decision to focus on long-term carbon sequestration within the immediate habitat, as occurs in other sequestering marine habitats (Krause-Jensen et al., 2018). While macroalgae may not be able to contribute to BC in the same way as other marine habitats, there is potential for net primary productivity (NPP) to be exported in the form of Dissolved Organic Carbon (DOC) and Particle Organic Carbon (POC) to neighbouring habitats and deep-sea environments (Krause-Jensen & Duarte, 2016), which is described in detail in the following sections. Both Krause-Jensen & Duarte (2016) and Ortega et al. (2019) provide evidence that a certain amount of exported DOC and POC reaches at least 1 000 m depth, beyond which carbon can be considered sequestered and is no longer available for exchange with the atmosphere for extended time periods. In some cases, seaweed-derived carbon can be preserved for millions of years as macroalgae have been reported to be the source of a number of oil deposits (Krause-Jensen et al., 2018). One of the requirements for climate change mitigation strategies to be considered effective is the long-term or permanent storage of carbon over hundreds of years. Based on the evidence provided that macroalgal carbon can be exported to such depths, seaweed meets this requirement (Krause-Jensen et al., 2018; Ortega et al., 2019).

While it is still difficult for seaweeds to be recognized as carbon sink agents under the current concept of CO_2 sequestration as conceived by the UN Framework Convention on Climate Change (UNFCCC), there is a need to redefine what is meant by carbon sequestration linked to seaweed cultivation, particularly regarding the real impact of sedimentation of carbon from cultivated seaweeds (van den Burg et al., 2019).

The methods in which carbon is captured, exported, and subsequently sequestered from macroalgae is discussed below.

3.2 Carbon sequestration and fate of macroalgal detritus

To date, the majority of research on the capacity of seaweeds to sequester carbon has focused on wild stands of macroalgae, which is reflected here and presented with relevant studies and implications for seaweed aquaculture.

As seaweeds grow, they absorb CO_2, temporarily capturing the carbon in the growing biomass (Kim et al. 2017; van den Burg et al. 2019; Zheng et al. 2019). The carbon fixed by photosynthesis can be exported from both wild seaweed stands and seaweed farms through various mechanisms, including the transport of dislodged individuals and macroalgal detritus as particulate organic carbon (POC) or as dissolved organic carbon (DOC) (Krause-Jenson and Duarte, 2016; Ortega et al., 2019). Here, we adopt the following definitions of POC and DOC as relevant to the blue carbon potential of seaweed, which are largely consistent throughout the available literature:

- Particulate Organic Carbon (POC): Organic carbon particles ≥ 0.2 μm in size incorporating biomass from living cells and dislodged individual seaweed plants, as well as detrital material, including dead cells. (Kharbush et al., 2020)
- Dissolved Organic Carbon (DOC): Organic carbon particles that pass through a filter pore size of 0.22 – 0.7 μm in size and span from highly labile to ultra-refractory molecules that are found throughout the oceanic water column (Sondergaard & Middelboe, 1995; taken from Paine et al., 2021)

Much of the carbon exported as POC and DOC is remineralised into the carbon cycle through natural microbial metabolisation or is quickly consumed into coastal and inshore food webs by grazing organisms. This includes the breakdown of seaweed at the intertidal zone (e.g., beach cast), which can release CO_2 and methane back into the atmosphere depending on local conditions (Hansen et al., 2020). However, a proportion of this exported carbon may be sequestered for longer time periods within recipient habitats, such a seagrass beds, or accumulated within deep-sea sediments that slow the degradation process and effectively store this for climatically relevant time periods, the mechanisms of which are described in further detail below in Sections 3.2.1 (DOC) and 3.2.2 (POC).

Krause-Jenson and Duarte (2016) summarised each step of the carbon flow from global macroalgal net primary production (NPP; limited to wild stands), which is presented in Figure 1. Of the estimated NPP by wild macroalgae globally, an upper estimate of 11% was sequestered, with the majority of this (88%) being stored through export to the deep sea and the rest through burial in coastal habitats/sediments. Applying this sequestration rate to macroalgal cultivation, the annual sequestration potential can be estimated to be in the order of 0.088 Tg C per year, based on the global production of 32 M tons of macroalgae from cultivation in 2018 (Krause-Jensen and Duarte (2016). However, it is important to note the 11% figure comes from natural kelp bed systems, and the carbon flows from cultivated seaweeds are likely to differ.

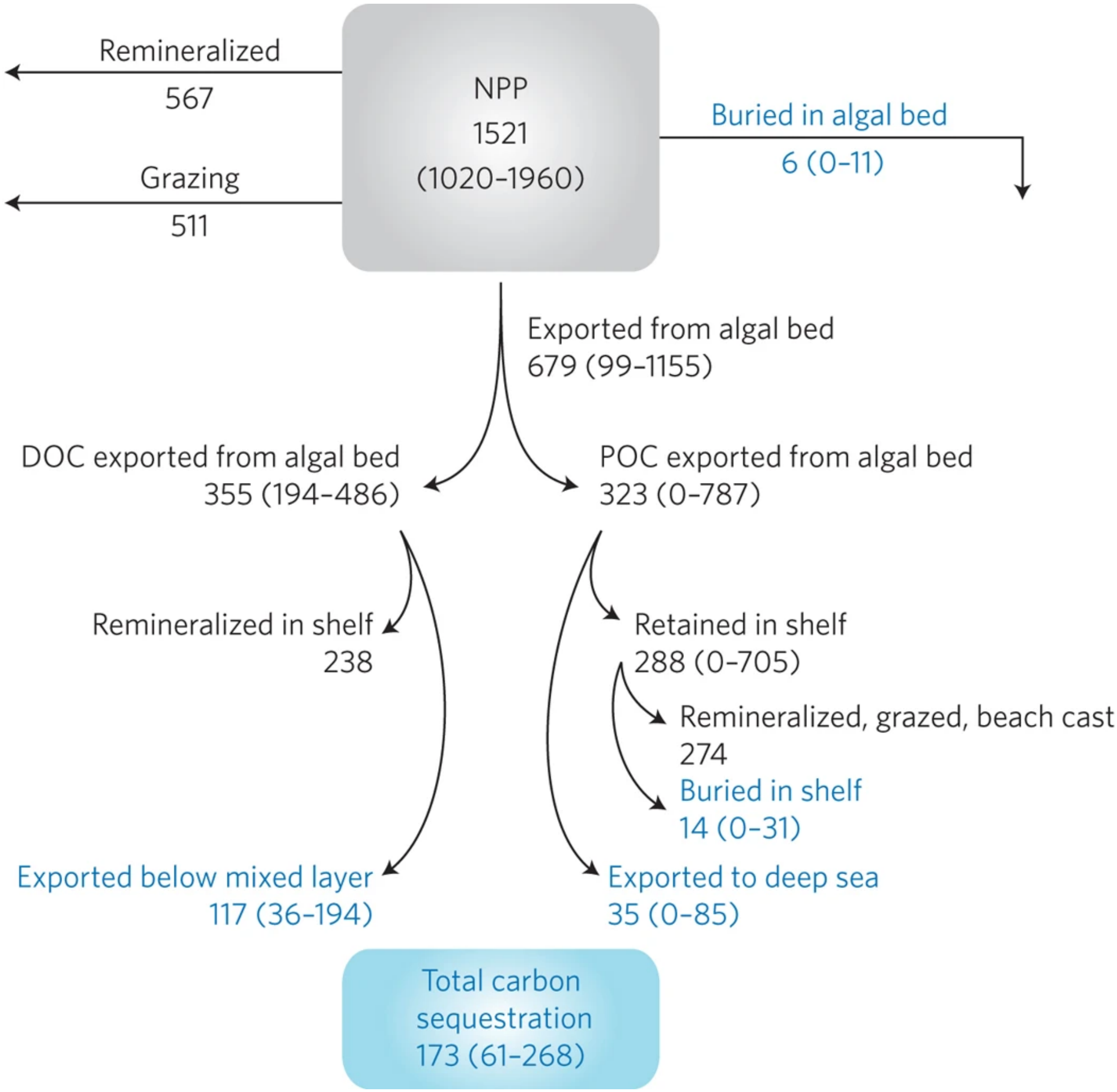

Figure 1. Carbon flow (in Tg C yr^{-1}) from global macroalgae stands, indicating routes of carbon sequestration (in blue) from wild seaweeds. Source: Krause-Jenson & Duarte (2016).

There are several important differences that distinguish the ability of cultivated seaweeds to capture and store carbon compared to wild stocks. First and foremost, while wild seaweed habitats can hold a significant amount of carbon in macroalgal stands, cultivated seaweeds are limited in this ability due to the harvesting and removal of the biomass, thereby releasing carbon back into the atmosphere, although some of this is dependent on the end-product/use (Duarte et al., 2017) as discussed in Section 5. While some of this carbon may be fixed again through the planting of new stock, it is ultimately not captured for climatically relevant timescales.

Furthermore, the growing period for cultivated seaweeds is usually restricted, with harvest timed to limit biofouling from grazing organisms, which in turn limits the potential carbon export through blade erosion and grazing in the spring and summer months. This may vary among seaweed farms, as there is a trade-off between minimising biofouling (and therefore grazing) and maximising biomass, which is dependent on the intended market of the end-product (Wildling et al., 2021). For example, bulk products (such a biofuels) will likely be subject to a late harvest to maximise the available biomass and may therefore support increased carbon export due to elevated levels of biofouling and erosion (Fieler et al., 2021).

The location of farm sites can further influence the degree of carbon export and sequestration from cultivated macroalgae (Duarte et al. 2017; Sondak et al. 2017). While cultivated seaweeds cannot store carbon in algal beds, locating the farm site over highly sedimentary environments, or in close proximity to other more efficient BC habitats such as seagrass or saltmarsh may increase the proportion of carbon sequestered in local sediments (Duarte et al. 2017; Sondak et al. 2017). Alternatively, locating the farm in areas of export to deep water such as down-welling regions or underwater canyons, or moving farms offshore, may increase the proportion of carbon being sequestered into deep water beyond the 'carbon sequestration horizon' (>1 000 m depth) (Duarte et al. 2017; Krause-Jensen and Duarte 2016). This, in turn, has led to the suggestion of sinking seaweeds for carbon sequestration into the deep sea, which at present is not economically feasible and has potential environmental impacts on deep-sea ecosystems that remain poorly understood. Such approaches will require careful consideration before use in the future (Costa-Pierce & Chopin, 2021).

Overall, the carbon sequestration potential of cultivated seaweeds will remain through POC and DOC contributions (Zhang et al., 2012; Sondak et al., 2017; Duarte et al., 2017), which are described below. However, at this stage, there is limited information available to quantify the potential contribution of seaweed farms to carbon sequestration, which will depend in part on the species being grown, local conditions, management actions, such as the timing of harvest and stocking density, as well as the size of seaweed farms and overall scale of the industry.

3.2.1 Dissolved organic carbon (DOC)

The marine DOC pool is one of the Earth's largest reservoirs of organic matter, storing a comparable amount of carbon to that which is found in the atmosphere as CO_2 (Lønborg et al., 2020). The spectrum of DOC in the ocean spans from highly labile, which can be readily broken down by bacteria and therefore has a short lifespan within the water column, to ultra-refractory, which cannot be metabolised and therefore has potential to be exported to the deep ocean where it can aggregate within sediments (Paine et al., 2021 and references therein).

Seaweed-derived DOC forms a critical component of the coastal biogeochemical carbon cycle as well as in supporting inshore food web linkages (Paine et al., 2021 and references therein). However, despite its importance, DOC release by seaweeds, and its fate, is an aspect of seaweed carbon physiology that we know relatively little about.

In a recent review of the rate and fate of DOC release by seaweeds, Pain et al. (2021) indicated that the release by seaweeds occurs either via active release or passive release, termed "exudation" and "leakage", respectively. Release of DOC by seaweeds is thought to occur through mechanisms similar to that observed for phytoplankton, which includes passive leakage of small molecules through the cell wall, active exudation of larger molecules, leakage via cell breakage due to grazing, and leakage via cell lysis or senescence, although seaweeds can also release substantial amounts of DOC through tissue fragmentation and breakage due to wave action (Weigel & Pfister, 2020; Paine et al., 2021). The cumulative effect of these mechanisms controls the overall amount of DOC released by seaweeds.

The proportion of DOC released by seaweeds through leakage of small molecules through the cell wall has not been quantified. However, it has been reported that up to 50% of carbon fixed during photosynthesis may be released as DOC via distal decay of *Saccharina latissima* in Scotland (Johnston et al., 1977, taken from Paine et al., 2021). This can be facilitated further through cell wall degradation from age and/or disease, senescence, or osmotic stress during desiccation, although rates of DOC release under these conditions remain largely unquantified.

Active exudation by seaweeds occurs to maintain cell homeostasis, deter against herbivory, as part of photorespiration, to prevent desiccation, and as parental investment in reproduction (Paine et al., 2021, and references therein). Physiological stress appears to be an important trigger of increased exudation (Sieburth 1969, taken from Paine et al., 2021), and as such healthy seaweeds are thought to release smaller amounts of DOC compared with seaweeds that have been affected by age or disease (Paine et al., 2021). This, in turn, may reduce the overall DOC export by seaweed aquaculture as new sporophytes are out-planted annually compared to wild stocks of varying age, although this has not been studied comparatively.

A portion of the DOC released by seaweeds is known to be refractory (rDOC) and therefore resistant to microbial breakdown, with a long-turnover time in coastal seawater (Bauer et al. 1992; Wada et al. 2008; Li et al. 2018). This rDOC can be considered as carbon sequestered in the oceanic pool (Hughes et al. 2012a), which undergoes slow degradation and may eventually become locked into sediments. However, there are several uncertainties regarding mechanisms, rates, and molecular composition of rDOC, which varies by species and environmental conditions, it is therefore unclear whether seaweed-derived DOC will ultimately increase the refractory pool in the ocean and enable further draw-down of CO_2 from the atmosphere (Paine et al., 2021).

Several studies have attempted to quantify the rate of DOC release but have returned a wide range of values from under 1% of net carbon assimilation to 40% or more (Fankboner & de Burgh 1977; Hatcher et al. 1977; Abdullah & Fredriksen 2004; Wada et al. 2007). However, the annual fixed carbon lost through DOC release from *Saccharina latissima* in Scotland ranged from 13 – 35% (Johnston et al., 1977, taken from Paine et al., 2021), with other species in the Order Laminariales returning similar results (Paine et al., 2021).

While data on the fate of seaweed-derived DOC is limited, approximately one-third has been estimated to reach depths capable of contributing to longer-term carbon sequestration (Krause-Jensen & Duarte, 2016) while the remainder is remineralised within the coastal shelf, whereby it is metabolised and converted into inorganic CO and CO_2 as Dissolved Inorganic Carbon (DIC) (Paine et al., 2021). However, as noted by Paine et al. (2021), it remains unknown whether this transport of DOC results in increased CO_2 draw-down from the atmosphere, as re-equilibrium timescales of atmospheric CO_2 with seawater after carbon fixation by seaweeds are of the order of months to years, and more work is needed to determine whether the export of DOC and re-equilibrium result in sequestration or release of CO_2 into the atmosphere (Bach et al., 2021, taken from Paine et al. 2021)

To date, no data has been published on the rate of DOC release of *in-situ* cultivated kelp in Europe. The available studies on wild seaweeds can provide insight on the potential of macroalgae DOC contributions to BC. Understanding the partitioning of DOC released (e.g., labile DOC remineralised into the carbon cycle and refractory DOC resistant to biological break-down) by cultivated seaweeds under varying environmental conditions, the subsequent fate of this carbon, and the resultant atmosphere-ocean interactions must be resolved to understand the implications of seaweed farming on the marine environment and carbon cycle.

3.2.2 Particulate Organic Carbon (POC)

The oceanic particulate organic carbon (POC) pool, like the DOC pool, is an important contributor to global reservoirs of organic carbon and is central to the marine carbon cycle as it creates linkages between primary production transport, including seaweeds, to the deep ocean and sediments (Kharbush et al., 2020). Seaweed-derived POC ranges in size, and can be released due to death, tissue erosion, physical damage from wave exposure, damage by grazers, dislodgment of entire plants, and, for some species, an acute pulse of detrital material known as the "May cast" due to the time of the year it occurs (Krumhansel & Scheibling, 2012; Smale et al., 2021). To date, there is limited information on energy flows, detritus production and export, and the contribution to inshore carbon cycling from seaweeds (Chen et al., 2020; Smale et al., 2021).

It has been reported that macroalgae stands could export close to 50% of their net primary productivity as POC (Krumhansel & Scheibling, 2012; Duarte et al., 2017). While only a very limited amount of macroalgal derived carbon is likely to remain *in-situ*, macroalgal detritus has the potential to be transported and stored in receiving habitats such as seagrass meadows, saltmarshes, deep (400m) coastal areas, continental shelf and slope (1800m depth) and deep sea sediments (up to 4000m depth and 4800 km from the nearest coastline) where the material has the potential to be sequestered (Filbee-Dexter et al., 2018; Smale et al., 2018; Krause-Jensen & Duarte, 2016; Ortega et al., 2019). Indeed, a study off Plymouth Sound, southwest England, estimated macroalgal derived sequestration rate of 8.75 gC m-2 yr-1 into coastal sediments from wild stocks (Queirós et al., 2019).

While it is highly likely that a proportion of the macroalgal detritus does end up sequestered, the ultimate fate of exported kelp detritus is largely unknown. The distance and direction of transport will be dependent on coastal hydrodynamic and larger-scale oceanographic processes, but in some cases macroalgal detritus has been recorded hundreds or even thousands of km from source populations (Krause-Jenson & Duarte, 2016, and references therein). The potential for long-distance transport will also depend on characteristics of the detritus itself, specifically particle size and density, buoyancy, and longevity (Hyndes et al. 2014; Wernberg & Filbee-Dexter 2018; Tala et al. 2019; taken from Smale et al., 2021). Furthermore, POC plays an important role in coastal food webs where it can be consumed by suspension feeders, detrital grazers and general consumers of organic matter (Krumhansl & Scheibling 2012).

Whereas most macroalgal stands grow on rocky shores, thereby requiring the export of carbon to depositional sites to contribute to carbon sequestration (Krause-Jensen & Duarte, 2016), seaweed farms are likely be placed over soft sediments, where detritus could be buried. Outside of this, the processes conducive to sequestration through POC export in cultivated kelps are otherwise similar to those operating in wild seaweed stands (Krause-Jensen & Duarte, 2016). However, as seaweed grown in aquaculture systems will be harvested, in most cases prior to the onset of heavy grazing in late spring (Seaweed

Farming Feasibility Study for Argyll and Bute, 2019; Wilding et al., 2021), the fraction of its net primary production available to be exported and sequestered in recipient sediments/habitats is likely smaller than that of wild seaweed stands.

Very little research has specifically investigated the rate of POC export from cultivated seaweeds in Europe. From the only available study, investigating POC export on commercial Norwegian kelp farms cultivating *Saccharina latissima*, rates of detritus export were recorded between 63–88 gC m^{-2} y^{-1} (Fieler et al., 2021), which is eight times less than has been reported from scenarios for kelp farms in Asia. This study highlighted that optimal timing of harvest is the most important management tool, suggesting that early harvest will likely result in a low carbon export, while a late-harvested bulk production could export four to six times as much carbon, with the latter offering increased potential for longer term carbon sequestration.

Regarding the fate of seaweed-derived POC, Krause-Jensen & Duarte (2016) estimated that 11% of NPP from wild macroalgal stands reaches the deep sea, where it can be effectively sequestered. However, this is a first-order estimate based on just three independent studies from disparate localities. The fate of detritus and contribution of seaweed to coastal ecosystems and their food webs is an area of active research, particularly in improving our understanding of kelp forests and other macroalgae habitats as sources of blue carbon. The ability of cultivated seaweeds to contribute to blue carbon strategies through POC export will depend on operational management (e.g., timing of harvest), as well as regional-, season-, and species-specific rates of carbon export which will need to be incorporated into production models to accurately determine the carbon sequestration potential across the cultivation life cycle and for various end-uses.

3.3 The fate of macroalgal detritus in the Irish Sea

Due to its relatively shallow nature, carbon exported from potential seaweed farms in the Irish Sea is unlikely to be exported beneath the mixed layer and locked away for climatically relevant time periods. Despite this, it has been shown that mud content in surficial sediments of the Irish Sea may act to benefit BC potential of seaweed farms, as high mud content is an important predictor for increased POC storage and sequestration (Diesing et al., 2017). As discussed above, carbon, in the form of POC and DOC, will be effectively sequestered by recipient habitats and is capable of transport across significant distances, suggesting that an unknown proportion of carbon exported from potential Welsh seaweed farms may be locked away in deeper, offshore environments of the Atlantic shelf seas.

Overall, the role that seaweed plays as a long-term carbon donor in Wales is likely to be a function of the coastal conditions adjacent to kelp farms, sea-bed characteristics, current and wave driven hydrodynamics and the biochemical composition of different macroalgal species utilised by cultivators.

The key challenges in proving the BC potential of seaweed farms to contribute to carbon sequestration in the Welsh marine environment are as follows:

- Documenting macroalgal carbon sequestered beyond the immediate habitat;
- Tracing it back to source farms;
- Identifying the implications of management actions on the rate of carbon export, and;

- Clarifying surface (ocean-atmosphere) exchange dynamics as a result of increased macroalgal production.

Furthermore, as identified by Krause-Jenson & Duarte (2018), incorporating macroalgae into BC strategies requires a paradigm shift in accounting procedures.

3.4 Carbon capture potential of cultivated species in Wales

There are several seaweed species currently cultivated across North-western Europe, although at-sea cultivation is predominantly limited to kelp species such as *Saccharina latissima* and *Alaria esculenta*, which comprise the vast majority of biomass production (European Algae Biomass Association, 2021). There is also interest in the cultivation of *Laminaria spp*., which are subject to a considerable wild harvest in some European countries.

The seaweed industry in Wales, like the rest of the United Kingdom, is in its infancy, although marine licence applications have been submitted for the cultivation of *Saccharina latissima, Laminaria digitata*, *Porphyra spp*., and *Palmaria palmata*. While all of these species have shown potential to be grown in marine cultivation systems, techniques are in the early stages of development for Rhodophytes (*Palmaria palmata* and *Porphyra spp*.) as well as simple genera which have also received considerable attention, such *Ulva spp*., all of which may be grown preferentially in land-based recirculation systems. Therefore, this section will focus on *S. latissima*, *L. hyperborea*, *L. digitata*, and *A. esculenta*.

As discussed throughout this report, there is very little direct work that has focussed on quantifying the carbon storage potential of cultivated seaweeds, carbon export through DOC and POC contributions, and sequestration potential of seaweeds in Wales. Despite the limited direct evidence from cultivation in Welsh waters, it is reasonable to assume that biomass yields at Welsh sites will be similar to elsewhere in the UK and Europe, and it is therefore possible to calculate carbon yields (as biomass standing stock) using modelled carbon content of seaweed at typical harvest times (Schiener et al., 2015). Furthermore, Fieler et al. (2021) examined rates of carbon export on commercial Norwegian kelp farms. This study provides a comparable baseline of carbon export from an existing cultivation facility, utilising a species and cultivation system that may in future be utilised in Wales. Finally, using proportional values of NPP, carbon export, and sequestration established by Krause-Jensen & Duarte (2016), it is possible to apply first-order estimates for some cultivated Welsh species.

It is important to note that the stocking density of a farm (linear meters of growing line per meter squared of cultivation area) will determine the carbon capture potential of seaweed cultivation as standing stock biomass per unit area. As there are currently no standardised farm designs utilised across Europe, it difficult to compare carbon storage and sequestration values for cultivated seaweeds as presented for other Welsh marine habitats in Armstrong et al. (2020). There are already significant bodies of research and data available on farm designs and growing methods, and it is not the objective of this report to review the pros and cons of these. For the purposes of calculating carbon storage and sequestration, we utilise a longline cultivation system as described in Stanley et al (2019), with rope separations of 3 and 5 m, which have proven to be economically viable in the UK

(Menzies at al., 2021). This equates to stocking densities of 3 333 (Scenario A) and 2 000 (Scenario B) linear meters of growing line per hectare of cultivation area, respectively.

For each species reviewed here, relevant literature on potential cultivated biomass, and therefore assimilated carbon, as well as carbon export are provided, with values summarised in Table 1. Where more relevant estimates of carbon export and sequestration potential are not available, we apply proportional values as presented in Krause-Jenson & Duarte (2016), through which 44.6% of NPP is estimated to be exported and 11% of NPP is estimated to be sequestered in the deep sea and through burial in coastal habitats/sediments.

The confidence of available information has also been assessed, using criteria set out by Armstrong et al. (2020), previously applied to carbon sequestering marine habitats in Wales.

3.4.1 *Saccharina latissima*

Observed biomass yields on *Saccharina latissima* cultivation sites are known to vary widely in Europe (Stanley et al., 2019). For example, observed biomass of *S. latissima* cultivated at a site in Spain produced approximately 16 kg m^{-1} on growing lines in one season (Peteiro & Freire, 2013; taken from Stanley et al., 2019). However, Seghetta et al. (2016) compiled literature on the harvest of *S. latissima* in Denmark, which resulted in an average biomass of 9.1 kg m^{-1}.

At the time of a typical harvest (May) carbon content of dry material is approximately 35% (Broch & Slagstad, 2012). Therefore, assuming productivity would be similar to elsewhere in Europe (9.1 kg m^{-1}), Welsh seaweed farms could produce between 18.2 (5 m line separation) and 30.3 (3 m line separation) tonnes of biomass per hectare, which equates to between roughly 2.2 and 3.6 t dry weight (*Saccharina latissima* dry/fresh weight = 0.12; Stanley et al., 2019), and between 0.77 and 1.26 t of extracted carbon, respectively.

S. latissima is the only species included within this review for which the exported annual amount of carbon has been examined from existing cultivation scenarios. This study by Fieler et al. (2020), which featured two commercial Norwegian kelp farms, recorded a carbon export rate of 63–88 g C m^{-2} y^{-1}, which provides a relevant baseline for Welsh seaweed farms, although differences are likely to occur through variability between grazing dynamics and species composition, local environmental conditions, and farm design.

3.4.2 *Laminaria digitata*

Average biomass yields of *Laminaria digitata* have been compiled by Seghetta et al. (2016) and are equal to that of *S. latissima* at 9.1 kg m^{-1}. At the time of a typical harvest (May) carbon content of dry material is approximately 27.1% (Schiener et al., 2015). Therefore, assuming biomass yields of 9.1 kg m^{-1} would apply, Welsh seaweed farms could produce between 18.2 and 30.3 t of biomass per hectare, which equates to between roughly 2.4 and 3.9 t dry weight (*Laminaria digitata* dry/fresh weight = 0.13; Gevaert et al., 2008), and between 0.65 and 1.06 t of extracted carbon, respectively.

3.4.3 *Laminaria hyperborea*

To date, there have been no reported yields of *Laminaria hyperborea* from European cultivation sites and we will therefore assume an estimate for biomass yields equivalent to *L. digitata* (9.1 kg m-1). However, *L. hyperborea* has higher rates of net primary productivity (measured by lamina [blade] extension) than *L. digitata* in the wild (Smale et al., 2020) and this is therefore likely to represent a conservative estimate.

For *L. hyperborea*, carbon content at the typical time of harvest is approximately 21.8% (Schiener et al., 2015). Assuming biomass yields of 9.1 kg m^{-1} would apply, Welsh seaweed farms could produce between 18.2 and 30.3 t of biomass per hectare, which equates to between roughly 2.9 and 4.8 t dry weight (*Laminaria hyperborea* dry/fresh weight = 0.16; Jupp et al., 1974), and between 0.63 and 1.05 t of extracted carbon, respectively.

However, it should be noted that *L. hyperborea* productivity in wave exposed sites can reach 18 kg m^{-2} of wet material, with productivity of 12.5 kg m^{-2} yr^{-1} of wet material. If 12.5 kg m^{-2} of wet material is achieved by seaweed cultivation within a single growing season, this would equate to a production of 125 tonne ha^{-1} y^{-1} of wet material, resulting in 20 t dry weight and 4.4 t of extracted carbon.

3.4.4 *Alaria esculenta*

Biomass yields of *Alaria esculenta* are not reported consistently. Of the recent studies available, biomass yields have been shown to reach 7.8 kg m^{-1} (Rolin et al., 2016). At the time of a typical harvest (May) carbon content of dry material is approximately 31% (Schiener et al., 2015). Therefore, assuming biomass yields of 7.8 kg m^{-1} would apply, Welsh seaweed farms could produce between 15.6 and 26.0 t of biomass per hectare, which equates to between roughly 2.7 and 4.4 t dry weight (*Alaria esculenta* dry/fresh weight = 0.17; Stevant et al., 2018), and between 0.84 and 1.4 t of extracted carbon, respectively.

3.4.5 Summary

Table 1 below summaries the carbon storage (biomass yield), export, and sequestration values adopted for species of cultivation interest in this study, based on the literature assessed within this report. A brief justification is included within the table alongside confidence rates of the assessed values. It is important to note that dry vs fresh weight ratios and carbon content (%) vary with species and throughout the growing season (Broch & Slagstad, 2012; Peteiro & Freire, 2013). Rates presented here assume a harvest in May, which is currently seen as best-practice to avoid heavy biofouling and prior to degradation of cultivated kelp species (Stanley et al., 2019), although this will differ for bulk harvested species allowed to grow later into the summer as well as different harvesting regimes (e.g., multiple annual harvests).

Of the species and cultivation scenarios considered, biomass yields are estimated to range from a minimum of 0.063 KgC m^{-2} yr^{-1} for *L. hyperborea* grown under low stocking densities (5 m separation) to a maximum of 0.14 KgC m^{-2} yr^{-1} for *A. esculenta* grown at high stocking densities (3 m separation). However, these values represent the carbon captured temporarily within the harvested biomass, most of which will be released back into the carbon cycle depending on the end-use. Rates of carbon sequestration in the marine environment, through DOC and POC contributions, were modest in comparison, ranging from a minimum of 0.007 KgC m^{-2} yr^{-1}, for *Laminaria spp.* under lower stocking densities, to a maximum of 0.015 KgC m^{-2} yr^{-1} for *A. esculenta* grown in higher stocking densities.

Comparably, these rates are substantially less than those of sequestering marine habitats in Wales, such as saltmarsh and seagrass, which have sequestration rates of 0.084 KgC m^{-2} yr^{-1} and 0.027 tC ha^{-1} yr^{-1}, respectively (Armstrong et al., 2020). However, it is important to note that the carbon capture implications of co-locating seaweed farming with sequestering marine habitats are not fully understood, and therefore it is unknown whether cultivation would require a trade-off with these habitats (e.g., if seaweed farming compromised their sequestration potential) or if it would complement the ecosystem services afforded by these habitats (e.g., if seaweed farming increased their carbon capture potential). Further research is required to explore the potential impacts of seaweed farming activities on other sequestering marine habitats so this can be incorporated effectively into marine spatial planning.

As presented in Table 1, there is a low confidence in many of the carbon rates adopted for this study due to the limited empirical evidence supported by the literature. Estimates of overall carbon yields are hindered by the lack of industry-reported harvest data, which is only available for *S. latissima* and *L. digitata*. This has knock-on implications for carbon export and sequestration estimates, which are calculated directly as a proportion of these yields, with the exception of *S. latissima* that has reported carbon export rates from Norwegian seaweed farms (Fieler et al., 2021).

The carbon export rates, again with the exception of *S. latissima*, and sequestration rates for all species presented in this study are adopted from work published by Krause-Jenson & Duarte (2016). This suggests that roughly 44% of NPP is exported via DOC and POC, with 11% of NPP subsequently sequestered in the marine environment. Extrapolating these rates of export and sequestration, which have been reported for wild seaweed stands, onto cultivated seaweeds is troublesome for reasons presented earlier in this report. Furthermore, this 11% figure is based on limited evidence, as rates of POC-derived sequestration have been calculated from just three independent studies, none of which investigate species found in Wales, and DOC sequestration rates are assumed to be equal to rates of phytoplankton identified in previous works. Therefore, these values are also reported with low confidence, and the estimates presented in this review will need to be revised as improved data on carbon export and sequestration for relevant species becomes available, specifically with regard to cultivation scenarios, as actual biomass yields are returned from Welsh and/or UK seaweed farms, and as cultivation infrastructure and associated systems continue to improve growing efficiency.

Table 1. Summary of carbon storage and sequestration values per studied species. Scenario A represents a longline cultivation system with 5 m separation between lines (totalling 2,000 m of linear growing line per hectare). Scenario B represents a longline cultivation system with 3 m separation of lines (totalling 3,333 m of linear growing line per hectare).

Species	Scenario	Biomass yield (kgC m^{-2} y^{-1})	Carbon export (KgC m^{-2} yr^{-1})	Sequestration (KgC m^{-2} yr^{-1})	Source	Confidence
Saccharina latissima	A	0.077	0.063	0.008	Stanley et al., 2019; Seghetta et al., 2016; Broch & Slagstad, 2012; Fieler et al., 2021	M-L
Saccharina latissima	B	0.126	0.088	0.014	Stanley et al., 2019; Seghetta et al., 2016; Broch & Slagstad, 2012; Fieler et al., 2022	M-L
Laminaria hyperborea	A	*0.063*	*0.028*	0.007	Seghetta et al., 2016; Schiener et al., 2015; Jupp et al., 1974; Fieler et al., 2021; Krause-Jenson & Duarte, 2016	L
Laminaria hyperborea	B	*0.105*	*0.047*	0.012	Seghetta et al., 2016; Schiener et al., 2015; Jupp et al., 1974; Fieler et al., 2021; Krause-Jenson & Duarte, 2017	L
Laminaria digitata	A	*0.065*	*0.029*	0.007	Seghetta et al., 2016; Schiener et al., 2015; Gevaert et al., 2008; Krause-Jenson & Duarte, 2016	M-L
Laminaria digitata	B	*0.106*	*0.047*	0.012	Seghetta et al., 2016; Schiener et al., 2015; Gevaert et al., 2008; Krause-Jenson & Duarte, 2016	M-L
Alaria esculenta	A	0.085	0.038	0.009	Stevant et al., 2018; Schiener et al., 2015; Rolin et al., 2016; Krause-Jenson & Duarte, 2016	L
Alaria esculenta	B	0.14	0.062	0.015	Stevant et al., 2018; Schiener et al., 2015; Rolin et al., 2016; Krause-Jenson & Duarte, 2016	L

4. Seaweed farming operations and life-cycle assessments (LCAs)

In recent years, seaweed aquaculture has gained an increasing amount of support as a potential new supply of biomass to already existing industries (Hughes et al., 2012a; Duarte et al., 2017; Thomas et al., 2021a) due to the perceived environmental benefits which include: not requiring the same level of resources (freshwater, fertilisers and pesticides), their potential for carbon capture and sequestration, addressing local eutrophication issues, as well as providing other ecosystem services such as temporary habitat provision (Adams et al., 2011; Langlois et al., 2012; Seghetta et al., 2017; Theuerkauf et al., 2021). In order to support this growing industry, multiple studies have carried out environmental Life Cycle Assessments (LCAs) to determine the overall environmental sustainability of holistic operations and processes within seaweed cultivation (Seghetta et al., 2016a; Seghetta et al., 2017; Van Oirschot et al., 2017; Parsons et al., 2019; Thomas et al., 2021a; Collins et al., 2021). LCA is a widely recognised tool that allows the exploration of the environmental performance of a product and its production system by quantifying the impacts across the supply chain (van Oirschot et al., 2017).

4.1 Cultivation and primary processing

Early LCA studies tended to focus on a specific aspect of the seaweed supply chain, however, van Oirschot et al. (2017) was one of the first papers to explore the optimal system design for seaweed cultivation and drying for products related to the agricultural and aquaculture sectors. Seaweed is often considered a more sustainable option regarding feed and fishmeal in these industries due to the comparative lack of fertiliser and other inputs required in traditional land-based agriculture.

Using *Saccharina latissima* as an example, an environmental LCA was used to explore optimal cultivation designs for commercial scale seaweed farms and highlight recommendations for future studies (van Oirschot et al., 2017). The analysis showed that the greatest environmental impacts came from the biomass drying process and key elements of infrastructure, such as chromium steel chains and polypropylene ropes, which has been further supported by subsequent reports (Seghetta et al., 2017; Koesling et al., 2021; Theuerkauf et al., 2021; Collins et al., 2021). As large-scale seaweed cultivation had not yet taken place in European waters at the time of this study, most of the data utilised was based on estimates from literature and direct communication with seaweed cultivation researchers.

Building on the work by van Oirschot et al. (2017), Thomas et al. (2021a) followed a similar LCA approach to determine environmental impacts of supply chain pathways for *Saccharina latissima* and was one of the first LCAs that utilised designs and processes based on an existing farm and facility in Sweden. Specifically, this study focused on the environmental impacts of different hatchery processes and alternative biomass preservation methods (Thomas et al., 2021a). Overall, the hatchery processes were found to have the least significant environmental impacts (harvest, spore preparation and seeding methods), while cultivation, which includes the infrastructure at sea, its installation, and monitoring, was found to contribute between 20 and 30% of all impact categories. Emissions from boat operations in this study, including the transport of the kelp following harvest, accounted for less than 10% of the overall impact. However, Thomas et al. (2021a) noted that this is principally due to the fact that the cultivation site was within a relatively close proximity to the landing location, and that, in general, other LCA studies have identified marine transport as an impact hotspot and there is a need to minimise transport distances and/or utilise more efficient vessels to keep these impacts low.

This further supports the argument by van Oirschot et al. (2017) that key elements of infrastructure in the cultivation stages have the most significant environmental impacts. Importantly, the study by Thomas et al. (2021a) also found that preservation or "drying" methods had the most significant environmental impacts in the overall supply chain with hang (air) drying having the lowest impact compared with freezing which had the greatest impact. However, it was also noted that the method of preservation would influence the potential end use of biomass with each process producing different end products.

Another LCA study, utilising data from a seaweed farm on the southwest coast of Ireland, cultivating *Alaria esculenta*, found that the 20-year lifetime of the farm changes the carbon balance prospect compared to one year of operation (Collins et al., 2021). Over its entire lifetime with a growth rate assumed to be 12 kg/m, the carbon balance of the system studied here was found to be carbon negative with -1.9 kg of CO_2-eq/kg of algae wet weight (ww) assimilated within the macroalgal biomass. Other results have been reported for a *Saccharina latissima* modular cultivation system in the Dutch North Sea, with recorded assimilation rates of -0.20 kg CO_2-eq/kg ww (Slegers et al., 2021).

4.2 Biorefinery

Only a small number of LCAs have examined life-cycles at the biorefinery stage, following harvest and primary processing (drying, freezing, ensiling, etc). Among these, Seghetta et al. (2016a; 2016b) assessed seaweed cultivation and biorefinery systems producing bioethanol, liquid fertiliser, and protein-rich fish feed from *Laminaria digitata* and *Saccharina latissima*. The LCAs identified multiple scenarios in which cultivation could provide climate change and marine eutrophication mitigation services through the substitution of gasoline and soybean proteins, while returning excess atmospheric and dissolved inorganic carbon into soil carbon stock.

For the net negative CO_2 performing scenarios, the results varied between $-0.1 \cdot 10^2$ and $-2.8 \cdot 10^2$ kg CO_2-eq/ha, although these scenarios were dependent on achieving a high growth rate of 12 kg/m at harvest, and the replacement of polypropylene ropes with hollow ropes filled with stones (Seghetta et al., 2016a). In a separate study, further modelled scenarios estimate cultivation and processing of 1 ton of seaweed (dry weight), evaluated over a time horizon of 100 years, results in a net reduction of 9.3 tonnes of atmospheric carbon (34 tonnes CO_2) (Seghetta et al., 2016b).

In a follow up study, using the average growth rate of 9.1 kg/m, Seghetta et al (2017) identified further net negative CO_2 scenarios. Results were recorded as high as $-18.7*10^2$ kg CO_2-eq/ha for dried *L. digitata* used in biogas production and $-12.3*10^2$ kg CO_2-eq/ha in protein production, primarily due to the replacement of energy production from high emitting coal consumption and the substitution of protein from soybeans, respectively.

4.3 Limitations of LCAs

It is important to note that not all inputs and impacts are incorporated into current seaweed cultivation LCAs. Notably, impacts on the surrounding marine environment, including export of POC and DOC as described above, associated ecosystem services, and land-use change are not taken into account, all of which have an associated level of uncertainty affected both by lack of data and by lack of standard methodology to quantify the impacts (Taelman et al., 2014). Furthermore, the LCAs assessed thus far have primarily terminated at the primary processing stage (e.g., dried, frozen, ensiled), and have not yet explored the breadth of applications and potential markets for seaweed.

One of the biggest limiting factors affecting the industry are the significant knowledge gaps as to how economically and environmentally sustainable cultivation at large scale would be in the UK (Capuzzo & McKie, 2016). Previous LCA research findings presented here can provide some valuable insight as to the most sustainable practices on scaling up the industry within the UK. However, operational seaweed processing (primary and biorefinery) facilities in Europe are limited and therefore these studies may need to be refined further as more data becomes available.

As new technologies evolve, scales increase and pathway concepts materialise into commercial enterprises for specific products and processing methods, data will become available for robust LCAs to be undertaken (Thomas et al., 2021b). This will enable reliable comparisons to be made between non-renewable or fossil-based products that can be replaced by seaweed-based products (e.g., comparisons of synthetic plastics vs. alginate biopolymers and/or other biomaterials). In summary, as the European seaweed industry emerges in the coming years, more LCAs will be needed to optimise the performance and guide the design principles of cultivation systems, preservation and processing methods, to ensure that the European seaweed industry delivers on its promise as a low-carbon, environmentally beneficial biomass (Thomas et al., 2021b).

5. Substitution effects

Products from macroalgal cultivation can have a net effect on global emissions by replacing products and processes that would otherwise result in higher CO_2 production (Duarte et al. 2017; Hasselstrom et al. 2020). The replacement of fossil fuels with macroalgal biomass for energy and plastic production, for instance, would represent an additional net CO_2 benefit from macroalgal cultivation, though challenges remain surrounding the technology, infrastructure, and supply chains required to make macroalgal production feasible at the scales required for these uses (Sudhakar et al. 2018; Gegg & Wells, 2018). More immediately, the substitution of macroalgal products for food products, as well as animal feeds and agricultural fertilisers, can contribute to the net reduction in CO_2 emissions from food production, potentially freeing up land and freshwater for more efficient use (Duarte et al. 2017; Hasselstrom et al. 2020; Leandro et al. 2020). This also has potential to facilitate active sequestration of macroalgal carbon, such as in the production of biochar and its application in farm soils, and the use of macroalgal biomass in long-term bioproducts (Sondak et al., 2017).

A detailed review of the all the existing and future uses of seaweed, and potential substitution effects thereof, is beyond the remit of this report and is not feasible at the current scale of the industry. Historically, seaweed has been utilised in the UK as food, fertiliser, and animal feed. More recently, European seaweed cultivation has been driven largely by low value, high volume applications, such as biofuel and bioremediation of aquaculture operations, however 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 biorefinery, which maximises the value of the biomass by allowing for extraction of valuable chemicals first, before secondary, lower value bulk products such as fertiliser.

The potential substitution effects of biofuels, animal feed, fertiliser, and food products, and their potential with regard to blue carbon assimilation from seaweed farming, are discussed below. However, undertaking full life-LCAs of macroalgal cultivation which incorporate end-product uses will be vital in quantifying the net carbon contributions of macroalgal products in the market (Thomas et al. 2021a; Hasselstrom et al. 2020).

5.1 Biofuels

Third generation biofuel feedstock derived from micro- and macroalgae are emerging as a renewable fuel source due to fast growth rates, potential for high biomass yields, low lignin content, high carbohydrate content, no competition for agriculture land, and higher rates of CO_2 fixation, than land crops (Suganya et al., 2016; Tabassum et al., 2017; Michalak, 2018).

Macroalgal biomass has potential to produce various biofuels (Pourkarimi et al., 2019). Conversion methods include biochemical - anaerobic digestion (biogas/methane), fermentation (bioethanol) and photobiological production of hydrogen; thermochemical conversion - gasification (syngas for heat and power generation), liquefaction (bio-oil/liquid fuel), pyrolysis (production of liquid bio-oil, syngas and charcoal) and direct combustion (heat energy) (Suganya et al., 2016; Del Rio et al., 2020; Hong & Wu, 2020; Rajak et al., 2020; Tan et al., 2020). Biogas can also be upgraded to biomethane and distributed through existing natural gas networks, during which all contaminants as well as carbon dioxide are removed and the methane content increased from 50-70% to more than 95% (Al Seadi et al., 2008).

Another way of broadly assessing the substitution effects of seaweed-based biofuels is the Energy Return on Energy Investment (EROI), a simple ratio of energy generated relative to the quantity of energy used in its production and can be valuable in assessing the feasibility of fuels (Gegg & Wells, 2017). A ratio of <1 indicates that more energy is expended than generated, with an EROI of 3 proposed as the minimum that can be considered sustainable (Murphy & Hall, 2010). The EROIs for biofuels made from biomass are frequently substantially less, with ethanol from sugar having an EROI between 1.25–8 and ethanol from corn 1–1.34 (Dave et al., 2013). Methods that use the whole biomass instead of just the fermentable compounds have higher EROIs with seaweed biogas giving an EROI of 2.4 and combined production of bioethanol and biogas from seaweed giving an EROI of 3.0 (Murphy et al., 2013).

More recently, several studies have investigated the substitution effects of biofuel production using Life-Cycle Assessments (LCAs), as described above. These studies show that under the scenarios presented in these LCAs, biofuel production provides a net negative carbon opportunity (Seghetta et al., 2016a; 2016b; 2017). Indeed, another LCA study using *Laminaria digitata* estimated that as much as 961 kg of CO_2 could be removed per ton of dry weight (DW) using macroalgae cultivation for biofuel production (Alvarado-Morales et al., 2013).

It is clear that technological and scaling up issues are still limiting the development of biofuels from macroalgae and addressing these issues will be an important step in determining the likely success, financial, and environmental viability of these energy sources (Gegg et al., 2017). Additionally, there are a number of social, environmental, political, and economic considerations that have yet to be explored under the cultivation scales required to produce suitable levels of biomass for the biofuel industry (Hughes et al., 2012a; 2012b; Gegg et al., 2017)

5.2 Animal feed

Recently, seaweeds have been seen by some as promising sustainable alternatives to conventional terrestrial animal feed ingredients as they are generally fast growing and do not compete for arable land or freshwater (Øverlund et al. 2019). Both brown (*Phaeophycae*) and red (*Rhodophycae*) seaweeds have been incorporated into diets (Gerber et al., 2013; Machado et al., 2015; Øverlund et al., 2019; Abbott et al., 2020), but it is red species, particularly *Asparagopsis spp*, which are not reliably cultivated at present, that hold the most promise to reduce ruminant methane production (Vijn et al. 2020). However, most algae-based livestock feed additives are made from milled or ensiled brown seaweeds such as kelps and *Ascophyllum nodosum*, which have an array of essential nutrients as well as numerous secondary plant compounds, but have a less substantial impact on methane reduction (Makkar et al., 2016; Antaya et al., 2019).

For kelp species, there is limited quantitative data to support their use as an anti-methanogenic feed additive, and the evidence that currently exists stems solely from trials *in vitro* (Pandey et al., 2021). Moneda et al. (2019) studied various species of seaweed in an oat/hay-based diet, including *S. latissima, A. esculenta*, and *L. digitata*, which demonstrated no anti-methanogenic properties from these species, but highlighted the varied chemical composition among seaweeds harvested at different times of the year. However, for these species, the ruminal fermentation pattern was similar to high-starch feed, and therefore may be used as a substitute a proportion of conventional feedstuff in livestock diets, although a wider assessment of their nutritional value, accounting for seasonal variations in the amino acid and protein value (Marinho et al., 2015), is necessary prior to use in commercial feeding operations (Moneda et al., 2019; Min et al., 2021).

Overall, the use of seaweeds, specifically kelps, for methane mitigation in a commercial setting is still largely untested. Variability among research designs and inconsistency of active compounds within seaweed materials used has made it challenging to build a comprehensive dataset describing the impacts of feeding seaweed to livestock (Vijn et al. 2020). Further research is needed to compare seaweed-based products with other methane mitigants currently available in the marketplace and demonstrate long-term health impacts of seaweed as a feed additive for both livestock and human consumption. Today, widespread use of seaweed as a livestock feed ingredient would require large-scale, intensive farming to produce the volumes needed for the feed industry, which could also present several supply-chain challenges and potential risks to the marine environment when operating at the necessary scales that would need to be addressed.

5.3 Fertiliser

Across the European Atlantic Coast, seaweeds have been used to enrich agricultural soils for centuries, a practice that persists in some part of the UK that still collect and spread beach cast to this day (Pereira et al., 2019). Today, seaweeds are utilised in commercial agriculture, primarily using wild harvested feedstock. Due to its high mineral content, seaweed-based fertilisers could contribute to closing the mineral fertilizer loop (Seaweed farming feasibility study for Argyll & Bute, 2019). The production of biogas can also be a supply of numerous by-products, including digestate, which is a valuable organic fertiliser rich in nitrogen, phosphorous, potassium and micronutrients. The use of digestate as organic fertiliser allows the recycling of nutrients and may offer a substitute for mineral fertiliser of fossil origin. Fresh seaweed is also a useful substitute for farmyard manure (Sandison et al., 2021).

Like biofuels, the substitution effects of seaweed-based fertilisers are best assessed through LCAs, which, although limited, have shown positive results in terms of climate change mitigation (i.e. carbon capture) potential. In one such study, an increase in soil carbon stock represents 15% of the climate change mitigation provided by the use of liquid seaweed fertilisers when replacing other conventional commercial fertilisers (Seghetta et al., 2016a). This is based on an approach to include soil carbon changes in LCAs, which considers 10% of the carbon from biofertilizers as undecomposed after 100 years, thereby increasing carbon stored long-term in soils (Peterson et al., 2013).

It is important to note that LCAs undertaken to date have yet to cover the breadth of fertiliser products and by-products that could be offered from the seaweed supply chain. Thus, the substitution effects of seaweed-based fertilisers have not explored the varying chemical composition based on seasonal harvest and have not yet investigated the utility of all kelp species. However, there is significant potential for biorefinery by-products, that would potentially have limited use in other fields, to be utilised in an agricultural fertiliser context, further increasing the circularity of the seaweed supply chain, and augmenting potential carbon capture.

5.4 Food

Seaweeds can be used in a variety of food products and are already considered to be a key element in healthy diets, particularly in Asia. Macroalgal-derived foods are characterised by high contents of fibres, minerals, essential vitamins with low fat and salt content, and rich protein fraction (Bleakley & Hayes, 2017). Although current seaweed consumption in Europe is limited, there is an increasing interest in using seaweeds for food (Barbier et al., 2019), with various commercial and research-driven initiatives cultivating seaweeds for supply into food markets (van den Burg et al., 2019).

At present, data on the environmental impacts of applying cultivated seaweeds in food applications are limited. However, a recent study quantified this in a small number of food products, taking into account the nutritional value, and found that the inclusion of *S. latissima* in vegetarian burgers or as salt replacement had multiple positive effects, reducing impact on Global Warming Potential and Land-Use from the overall diet (Slegers et al., 2021). However, Slegers et al (2021) noted that it is too early to have a definitive judgement on the environmental impacts of seaweed products compared to food products produced in mature sectors such as soy or maize.

6. Carbon offsetting

Carbon offsetting—receiving credit for reducing, avoiding, or sequestering carbon—has become part of the portfolio of solutions to mitigate carbon emissions, and thus climate change, through policy and voluntary markets, which have to date been primarily by land-based re- or afforestation and preservation (Froehlich et al., 2019). While carbon offsetting within aquaculture is a contentious field, there is rapidly growing interest in the potential use of seaweeds globally as a carbon offsetting solution (Krause-Jensen et al., 2018; Froehlich et al., 2019).

Froelich et al. (2019) assessed the extent and cost of scaling seaweed aquaculture to provide sufficient CO_2eq sequestration for several climate change mitigation scenarios to offset the global aquaculture and agriculture sectors. Under these scenarios, seaweed farming could feasibly create a carbon-neutral aquaculture sector, but is extremely unlikely to offset global agriculture, in part due to production growth and cost constraints (Froehlich et al., 2019).

At a more local scale, economic and technical appraisals of potential carbon credit systems in seaweed aquaculture are severely limited. The only such study, investigating monetisation of carbon offsets from a brown algae (*Alaria esculenta*) cultivation system in Ireland, reported that the revenue generated on the Voluntary Carbon Offset Market (VCOM) from the seaweed carbon assimilation was minimal, contributing to just 5% of the revenue, despite being carbon negative over the expected lifetime of the farm (Collins et al., 2021). Collins et al (2020) concluded that further development of the seaweed market, including stabilised prices, and production of a range of viable products from seaweed biomass will be the major factor in the economic sustainability of the industry, rather than the utilisation of carbon offsetting markets.

Beyond carbon offsetting, a growing body of work has identified pathways for seaweed aquaculture to access alternative nutrient remediation pollution markets, as it has been shown to be an effective tool for extracting anthropogenic nitrogen from GHG (N_2O) emissions, which has a global warming potential over 265-times greater than CO_2 (Armstrong et al., 2020), and agricultural runoff. One such study based in the United States identified nutrient assimilation of nitrogen and phosphorous through seaweed aquaculture as having significant conservation potential, offering a cost-effective tool for mitigating one of the most pressing anthropogenic impacts on the ocean (Racine et al., 2021), suggesting that this could heavily subsidize the industry. Costa-Pierce & Chopin et al. (2021) drew similar conclusions, suggesting that there is more economic incentive with nutrient trading credits (between US$ 1.1-3.4 billion for N and US$ 51.8 million for P) than with carbon trading credits (US$ 29.1 million).

Contrastingly, despite large nitrogen and phosphorous uptake annually (8% of N, 60% of P) identified in a separate study on the Swedish west coast, the socioeconomic value of this sequestration was counteracted by economic losses from interference with other industries, and therefore only accounted for a minor share of the potential financial value from biomass production (Hasselström et al., 2020). Thus, there are several socio-economic and environmental considerations that will determine the utility of seaweed farming for bioremediation, which will vary geographically.

7. Environmental impacts

As interest in seaweed aquaculture continues to grow, concerns are being raised regarding the environmental impact of the industry, particularly as both finfish and shellfish aquaculture are known sources of multiple environmental concerns (Visch et al., 2020). Of the different types of aquaculture, seaweed cultivation is generally considered one of the most environmentally friendly forms, primarily due to the lack of required fertiliser/freshwater inputs (Norderhaug et al., 2020). However, this does not necessarily mean that seaweed cultivation is without environmental impacts, rather that environmental impacts must be studied and understood to ensure appropriate management and support the growth of this industry (Theuerkauf et al., 2021). Several studies have highlighted some of the key environmental considerations regarding seaweed cultivation in the UK (Wood et al., 2017; Wilding et al., 2021), including the prioritisation of key knowledge gaps (Campbell et al., 2019; Eklipse EWG, 2022), which are discussed in further detail in the following sections.

A full review of the environmental impacts of seaweed farming was beyond the scope of this assessment. Applications for a marine licence to cultivate seaweed will need to follow the regulatory process as currently required by NRW, for which the assessment of impacts is a key consideration of the consenting process. The licence application must include a location plan, descriptive drawings and any supporting environmental assessments. Including:

- Navigational Risk Assessment (NRA)
- Biosecurity plan
- Marine Mammal Entanglement protocol
- Details of any protected site features
- Evidence that you have consulted with the relevant organisations to prepare your application.

Any application for works within or adjacent to a European site, such as a Special Area of Conservation (SAC) or Special Protection Area (SPA), will be subject to the provisions of The Conservation of Habitats and Species Regulations 2017 and The Conservation of Offshore Marine Habitats and Species Regulations 2017. This means that NRW will carry out a Habitats Regulations Assessment (HRA), to determine the significance of the associated pressures, for which the applicant must provide sufficient information to inform an Appropriate Assessment. The sections below highlight some of the general environmental impacts and interactions associated with seaweed cultivation, which, for prospective seaweed farms, may need to be assessed on a site-specific basis in line with NRW's regulatory process.

7.1 Hydrodynamics and sedimentation

Hydrodynamics require careful consideration during site selection for macroalgal cultivation, as it not only influences critical functions but is also influenced by macroalgal growth (Wood et al., 2017). Under conditions where water flow is too fast or slow, supply of CO_2 will significantly affect photosynthesis by macroalgae, thereby affecting their ability for nutrient uptake and subsequently their overall growth (Kerrison et al., 2015). The presence of macroalgae also has the ability to influence water flow, especially in large congregations such as commercial scale cultivation. Whereas naturally occurring seaweed populations grow from the seabed, cultivated seaweed is generally suspended in the water column which has been linked to greater drag in studies conducted in China and New Zealand (Grant & Bacher, 2001; Plew et al., 2003). In addition to this, undercurrents have been reported beneath suspended aquaculture (mussel long-lines) with velocities almost twice that within the farm, resulting in stratification and preventing mixing within the water column (Plew et al., 2005). These alterations in local hydrodynamics can affect the carrying capacity of the water body which may result in significant changes to marine chemistry, biological communities (through changes to larval dispersion and habitat suitability) and sediment transport (Campbell et al., 2019).

As with other forms of aquaculture (finfish and shellfish), changes in local hydrodynamics associated with macroalgal cultivation have been known to affect sediment dynamics and the delivery of Particulate Organic Matter (POM) to the seabed (Wood et al., 2017; Campbell et al., 2019). This is particularly crucial when considering the role of detritus, POC and DOC transport in macroalgal contributions to BC strategies. In the event that stratification occurs within macroalgal farms, their ability to contribute to BC would be severely impaired. However, while stratification may prevent delivery of POM to the seabed, reduced disturbance beneath the canopy would increase settlement rates and residence time of particles (Eckman et al., 1989; Wood et al., 2017).

Locating seaweed farms over highly sedimentary environments, or in close proximity to other more efficient BC habitats such as seagrass, mangroves or saltmarsh may increase the proportion of carbon sequestered in local sediments (Duarte et al. 2017; Sondak et al. 2017). Alternatively, locating the farm in areas of export to deep water such as down-welling regions or underwater canyons, or moving farms offshore, may increase the proportion of carbon being sequestered into deep water beyond the ‘carbon sequestration horizon’ (Krause-Jensen & Duarte 2016; Duarte et al. 2017). However, potential impacts on deep-sea ecosystems remain poorly understood, and such approaches will require careful consideration before use in the future (Barry et al. 2004).

7.2 Water quality and nutrient assimilation

Macroalgal farming differs from more traditional types of agriculture and aquaculture in that it does not require freshwater or the addition of fertilisers, feed or other supplementary materials (Walls et al., 2017b; Visch et al., 2020). By contrast, macroalgae assimilate dissolved nutrients from the surrounding environment for growth which allows them to become efficient biofilters by reducing nutrient concentrations (Wood et al., 2017). This enables seaweed farming to address local eutrophication concerns by means of bioremediation, through the uptake of nitrogen and phosphorous in particular (Marinho et al., 2015; Xiao et al., 2017; Neveux et al., 2018), and helping to manage nutrient balances in finfish aquaculture (Chopin et al., 1999; Troell et al., 1999; Sanderson et al., 2012).

Several studies indicate that Integrated Multi-Trophic Aquaculture (IMTA) provides the benefits of offsetting waste nutrients generated by other forms of aquaculture while simultaneously increasing growth rates and yield of seaweed aquaculture (Troell et al., 1997; Neori et al., 2000; Sanderson et al., 2012; Seghetta et al., 2016; Visch et al., 2020). Within the UK, both *Palmaria palmata* and *Saccharina latissima* were shown to reduce nitrogen concentrations (12% and 5%) surrounding Atlantic salmon farms in northwest Scotland with improved growth rates of 48% and 61%, respectively (Sanderson et al., 2012).

Although the bioremediation potential of seaweed can provide benefits in the context of IMTA, what remains less certain is the effect of large-scale cultivation on phytoplankton and other benthic plants. Macroalgae have especially high rates of nutrient uptake which could potentially lead to decreased nutrient availability for other naturally occurring communities (Wood et al., 2017). This phenomenon has mostly been studied in the context of coastal eutrophic waters in Asia, where the introduction of seaweed farms has reduced the occurrence of Harmful Algal Blooms (HABs) due to nutrient removal (Yang et al., 2015a; 2015b; Xiao et al., 2017). In the UK context, a study conducted by Aldridge et al. (2012) found that *S. latissima* grown in various locations around the west of Scotland would significantly affect phytoplankton biomass in the area surrounding a seaweed farm, hence site selection would require careful consideration to prevent cumulative impacts.

In addition to nutrient uptake, macroalgae also have the capacity to assimilate heavy metals from the surrounding environment (Hasselström et al., 2018). Kelp species, such as *S. latissima*, have proven to be one of the most effective types of organisms at sequestering heavy metals (Davis et al., 2003). Heavy metals are known to naturally occur in the marine environment with both natural and anthropogenic sources contributing to dissolved metal concentrations (Wood et al., 2017). Industrial and urban waste, excessive amounts of fertiliser present in water runoff and port and harbour activity are cited as the main anthropogenic sources, with the amount of metals present exceeding that of natural or "background" levels thereby creating a toxic environment for marine organisms (Evans & Edwards, 2011). Heavy metals can affect the physiological functions of a variety of organisms from phytoplankton to marine mammals, with bioaccumulation further exacerbating these effects (Evans & Edwards, 2011). Seaweed can therefore provide benefits in two ways; the first being bioremediation as with nutrients whereby seaweeds assimilate heavy metals and reduce overall concentration in the water column; and the second is employing seaweeds as bioindicators of heavy metal concentrations (Wood et al., 2017). The former requires careful consideration in the context of seaweed farming, specifically whether the seaweed being grown is being utilised for human or animal consumption.

There is currently very little guidance or regulation in place concerning the concentrations of pollutants permitted in seaweeds that are destined for human consumption, whether directly or indirectly (Besada et al., 2009; Lähteenmäki-Uutela et al., 2021). With specific reference to kelp, inorganic arsenics, cadmium and iodine are all heavy metals of concern in the commercial growth of these species (Hasselström et al., 2018). As with marine organisms, the introduction of heavy metals into human diets has the potential to pose significant health risks therefore, better guidance is required. Future research may choose to focus on the overall impacts of nutrient assimilation by combining analysis of seaweeds at different life stages and different parts of the plant with model outputs to give a better understanding.

7.3 Marine fauna and flora

Among the different ecosystem services that seaweeds can provide, supporting services such as food web dynamics, biodiversity, habitat and coastal resilience are perhaps the most important for marine flora and fauna (Wood et al., 2017; Hasselström et al., 2018; Küpper & Kamenos, 2018; Visch et al., 2020). Naturally occurring seaweed beds provide some of the most biologically diverse habitats within the UK and play a critical role in the life cycle of some commercially important fish and shellfish species (Küpper & Kamenos, 2018). Seaweed farms have the potential to behave in a similar manner by providing complex 3D habitats that would otherwise not be present (Visch et al., 2020).

Thus far, very little research has been conducted on the effects of seaweed cultivation on zooplankton, however, available literature does suggest that the provision of shelter and food from seaweed farms allows zooplankton to thrive in these environments (Pakhomov et al., 2002; Wood et al., 2017). Similarly, there are very few studies which focus on the interaction between marine mammals and seaweed farms or birds and seaweed farms. The most common marine mammals found in the UK are harbour porpoise (*Phocoena phocoena*), harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*), which are not thought to have seaweed as part of their diet (Wood et al., 2017). Although there is no evidence to currently suggest that any of these species do so, it is entirely plausible that they may forage around seaweed farms due to increased prey availability as has been observed around offshore wind farms by seals (Russell et al., 2014). Likewise, birds have been observed utilising naturally occurring seaweed forests due to prey availability (Fredriksen, 2003; Graham et al., 2008), there is no evidence to suggest that they exhibit the same behaviour at seaweed farms, although it is possible. In addition to this, the infrastructure required for a seaweed farm, such as surface floats and navigational markers may offer resting place for birds which would allow them to expand their foraging range (Vanermen et al., 2013).

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, 2017; taken from Wilding et al., 2021). It should be noted that the stocking density of the farm is likely to be an important variable influencing benthic impacts.

Naturally occurring seaweed beds provide an attractive habitat to a wide variety of benthic organisms and there is increasing evidence to suggest that cultivated seaweed beds provide a similar environment seasonally (Theuerkauf et al., 2021). Seaweed farms are generally located in near shore water on soft sediments which provides a new habitat for benthic organisms and mobile fauna to colonise (Walls et al., 2016). It is possible, therefore, for seaweed farms and associated farm infrastructure (anchors, etc). to provide a substrate for invasive non-native species (INNS). Farm infrastructure will also introduce pressures (penetration, abrasion, substrate composition changes, etc) on the surrounding marine environment that may have impacts on the existing community.

Furthermore, natural seaweed forests provide grazing opportunities for a variety of small benthic invertebrates, sometimes to the point of complete eradication if an outbreak of these organisms occur (Kerrison et al., 2015). Due to the nature of seaweed cultivation whereby seaweeds are suspended in the water column, there is less opportunity for grazing by the adult stage of these organisms but potential for settlement of the planktonic stages before developing in grazing juveniles (Wood et al., 2017). Kerrison et al. (2015) reported biomass loss of *Saccharina latissima* due to grazing by *Lacuna vincta* snails in the UK, which led to changes in the timing of harvests. Grazing has also been observed by fish species but was found to have little effect on the overall yield and indeed, overgrazing may be controlled by carnivorous fish or otters (Kerrison et al., 2015).

Fish species are thought to receive the greatest benefit from the introduction of seaweed farms (Wood et al., 2017). The majority of studies report an increase in fish assemblages in and around seaweed farms due to the provision of habitats, feeding and nursery areas for juveniles (Hasslestrӧm et al., 2018). Some studies even suggest that seaweed farms may provide crucial habitats for juveniles of commercially important species such as cod (*Gadus morhua*) (Norderhaug et al., 2005) or lumpfish which help sea-lice control in salmon aquaculture (Powell et al., 2017) although there are some instances where decreases in fish populations have been observed (Theuerkauf et al., 2021). It is important to note, however, that these impacts have not been investigated against the breadth of species found in the UK, particularly if the industry was to operate at larger scales. How fish species, particularly vulnerable/protected species such as seahorses, would be impacted by the seasonal provision and subsequent removal of habitat requires further investigation.

Despite the potential advantages of providing new, more complex habitats and grazing opportunities for many benthic species, there is also potential for significant detrimental environmental effects. The introduction of a new cultivated species may bring new diseases or hitchhiking species, potentially including INNS, which have not been previously found within an area (Theuerkauf et al., 2021). The additional substrate would also provide colonising opportunities for species not currently found within the local marine community, again potentially including INNS. This would not only create potential for significant yield loss from macroalgal farms but also risks the transfer of disease or invasive species to natural macroalgal stocks which may not have the same level of tolerance (Wood et al., 2017). Reduced light levels may also cause negative impacts for benthic primary producers, however more research is required to better understand this.

The domestication of wild seaweed cultivars will be an unavoidable consequence of large-scale seaweed cultivation practices (Valero et al., 2017; Campbell et al., 2019; Eklipse WGS, 2022). Cultivated seaweeds will most likely be characterized by a human imposed shift in their reproductive strategy (e.g., from outcrossing to self-fertilizing and from sexual reproduction to vegetative reproduction) introducing genetic bottlenecks that may narrow the genetic diversity of cultivated stands, potentially making them more susceptible to environmental changes and disease as observed in vegetative propagation of domesticated *Gracilaria* (Leonardi et al., 2006; Valero et al., 2017; Campbell et al., 2019). Studies have resulted in the production of improved varieties of kelps with respect to commercially valuable traits (e.g., size and nutrient content; Liu et al., 2014; Li et al., 2016; taken from Campbell et al., 2019) and these have been widely applied in cultivation activities (Li et al., 2007, 2008, 2016; taken from Campbell et al., 2019). The consequences of producing cultivars that are genetically and phenotypically distinct from natural populations is unknown but there is the potential for significant environmental effects, which have been identified as a priority knowledge gap by Campbell et al. (2019), through both direct competition with wild populations and hybridization with natural stands.

7.4 Volatile gases

As well as their contributions to the carbon cycle, macroalgae also play a crucial role in the biogeochemical processes of certain halogens, specifically chlorine, bromine and iodine (La Barre et al., 2010; Wood et al., 2017). The processing of chlorine is thought to only occur in freshwater macroalgae, whereas marine macroalgae actively take up iodide and bromide from the surrounding environments which are then released as halogenated compounds under stressful conditions (Küpper et al., 2008; La Barre et al., 2010). However, there are several gaps in our knowledge of halogen production and the potential release of halocarbons from seaweed cultivation.

Keng et al. (2020) reviewed the emission of volatile halocarbons, which are well documented in relation to their depletion of the protective ozone, by seaweeds and their response towards environmental changes. These compounds can contribute to global climate change and may even affect local climate through aerosol production (Keng et al., 2020, and references therein). Biogenic compounds are produced by seagrass beds, seaweeds, and phytoplankton as defence compounds, antioxidants or by-products of metabolic processes, but are difficult to quantify due to inherent biological variability as well as spatial and temporal changes in emissions. This has ultimately made it difficult to assess the role that seaweeds play as a source of biogenic halocarbons, which Keng et al. (2020) highlighted as an important knowledge gap in light of global changes in both climate and the environment, the expansion of seaweed cultivation industry, and the interactions between halocarbon emission and their environment.

Keng et al. (2020) highlighted the need for more insights into the factors affecting the production and emission of the volatile halocarbon compounds by the seaweeds. In terms of the expanding European seaweed cultivation industry, there is a need to understand diurnal and season variations in environmental factors linked to emissions of halocarbons, the effects of environmental changes on emissions, and a standardisation of methods for easy comparison between studies.

7.5 Potential negative impacts or trade-offs of scaling up macroalgal cultivation

In general, there is a lack of data on the environmental impacts of seaweed cultivation in the UK and Europe, due in part to the current size of the nascent industry. Unknown environmental impacts to deep sea, benthic and pelagic ecosystems were the most commonly identified potential negative impacts of macroalgae cultivation both among the expert responses and the reviewed articles presented in a recent Eklipse Expert Working Group on macroalgae cultivation and ecosystem services (Eklipse EWG, 2022). This point is especially relevant if the goal is climate change mitigation due to the scales required.

In addition to conflicts with other users, shifts in seaweed genetic diversity, negative impacts on ecosystem biodiversity and reductions in water flow were identified as potential negative impacts of scaling-up macroalgae cultivation in this report (Eklipse EWG, 2022). However, due to the lack of data, most negative impacts were identified as potential or unknown and few studies provided direct evidence of negative impacts of seaweed cultivation, except in cases of poor management practice (e.g., uncontrolled transport of genetic strains between sites/regions).

8. Report summary and conclusions

8.1 Summary of the blue carbon potential of seaweed aquaculture in Wales

Blue carbon is now recognized as an important factor in the new era of climate change (Chung et al., 2017). The sections above provide a number of arguments to support the consideration of seaweed aquaculture as a tool for carbon sequestration and thus, climate change mitigation and adaptation. However, these have also been presented with a number of limitations and knowledge gaps that must be addressed to ensure that seaweed farming delivers on the potential benefits of a low carbon, environmentally sustainable industry.

The extent to which macroalgal carbon can contribute to marine carbon sequestration in Wales is highly complex. Cultivated seaweed will largely be a transient carbon sequestration tool, temporarily capable of capturing carbon in macroalgal biomass, although there are pathways through which seaweed farming can contribute to longer-term, climatically relevant storage of carbon in the marine environment. This occurs through the transport, storage, and subsequent sequestration of POC and DOC in recipient habitats and sediments, or transport and deposition in the deep sea, effectively locking the carbon away. Based on the available literature, sequestration rates in cultivated seaweeds are relatively minor in comparison to other marine habitats, such as saltmarsh and seagrass, and will therefore make limited contributions to blue carbon in Wales, depending on the scale of the industry. However, the patterns and underlying mechanisms governing detritus production and transport are poorly understood, particularly with regard to seaweed cultivated at scale, and there is a pressing need to examine detrital pathways over broad temporal and spatial scales in order to better understand the blue carbon potential of seaweed cultivation at local and global scales.

To assess the overall environmental performance of seaweed cultivation, and potential for incorporation into wider GHG reduction strategies, it is important to include both direct local effects described above and impacts resulting from the biomass production, including energy and material inputs, and the end-of-life of the biomass (Thomas et al., 2021). The latter impacts can be assessed through life-cycle assessments, which, to date, have demonstrated the low, neutral, or negative carbon opportunities that exist across various markets (e.g., food, feed, biofuels, and fertiliser). While data is limited, the potential substitution effects of seaweed products across these markets are substantial, showing significant promise in the replacement of higher carbon alternatives. As the industry continues to develop, more LCAs will be needed to optimise the performance and guide the design principles of cultivation systems, preservation, and processing methods, furthering our understanding of carbon gains/losses across a wide product market.

As the scale of operation continues to increase in Wales, there is also a need to balance the associated environmental risks presented here with potential benefits to ensure the carrying capacity of the receiving environments are not exceeded and carbon reduction objectives are not undermined. Potential environmental changes of greatest concern for the developing European seaweed industry were identified in recent reviews by Campbell et al (2019) and Eklipse EWG (2022) which include: facilitation of disease, alteration of population genetics, reduction in local biodiversity, and wider alterations to the physiochemical environment.

Ultimately, the blue carbon potential of the seaweed industry will depend on its scale, which will be influenced by constraints relating to suitable space as well as interactions with other marine users. However, it is important to note that, at present, blue carbon contributions are not considered during the seaweed farm consenting process in Wales, and thus, the potential carbon sequestration in the marine environment and other greenhouse gas reductions through substitution effects are not assessed under the regulatory framework. Several priority areas of future research have been identified below, which should be addressed in order to effectively incorporate the blue carbon potential of the industry into the regulatory process.

8.2 Conclusions and priority areas of future research

Integrating the potential blue carbon value of seaweed aquaculture into decisions relating to marine management may enhance the capacity of the Welsh marine environment to act as a carbon sink. To support this, specific research is needed to better understand the carbon sequestration processes within seaweed aquaculture, including natural variability (both temporal and spatial), between cultivated species, and for various scales to which the industry may develop. This should be more closely integrated with research that focuses on other benefits associated with seaweed aquaculture (e.g., nutrient remediation or biodiversity).

Areas for future research include:

- **Lack of understanding of the rate and fate of carbon export and sequestration processes** – at present there are no standardised methods to trace sequestered macroalgal carbon back to source farms and quantify carbon flows between cultivation sites and sequestering habitats. This represents a key knowledge gap that will need to be addressed and coupled with modelled scenarios of the potential scale of the future seaweed cultivation industry under varying management scenarios.
- **Surface (ocean-atmosphere) exchange dynamics as a result of increased macroalgal production** - timescales of re-equilibrium of atmospheric CO_2 with seawater after carbon fixation by seaweeds is of the order of months to years. A concerted research approach is needed to determine if the time scale of POC/DOC export and re-equilibrium result in net CO_2 sequestration from the atmosphere.
- **Whole life-cycle approaches to calculating carbon emissions and benefits from seaweed cultivation –** as the seaweed industry continues to develop, introducing new technologies, increasing in scale, and expanding into new product markets, data will become available for robust LCAs to be undertaken. This will enable reliable comparisons to be made between non-renewable or fossil-based products that can be replaced by seaweed-based products (e.g., comparisons of synthetic plastics vs. alginate biopolymers and/or other biomaterials), which will determine the overall environmental performance of the seaweed cultivation industry.
- **Environmental impacts of seaweed cultivation at scale** – several studies have examined the impacts of seaweed cultivation in the UK. However, the majority of farms have been developed for pilot and/or research purposes, and there is a pressing need to establish research and monitoring frameworks to monitor the immediate and ongoing impacts of seaweed farming in Wales. These will ensure negative impacts are fully understood and that the carrying capacity of the receiving environments are not exceeded.
- **Technical, social, and supply chain considerations -** while data is limited, the potential substitution benefits of seaweed products across bulk markets (e.g., biofuels and animal feed) are substantial. The overall environmental performance of the supply chain can be monitored through ongoing LCAs, but there are several technical and social constraints to be considered, and it is important to identify, monitor, and mitigate these as the industry reaches scale.

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Appendices

Appendix 1 - Evidence Review Protocol

The following review protocol was approved by Natural Resources Wales prior to commencement of the Rapid Evidence Review. The Protocol document included the conceptual framework for the review, the primary question and secondary objectives to be considered, the Population, Intervention, Comparator, Outcome (PICO) elements, search methods (databases) and terms, and quality/validity assessment criteria. These are outlined below as included in the review protocol.

Primary Question

The primary question addressed by this review is ‘To what extent can seaweed farming in Wales contribute to carbon sequestration in the marine environment?’

Specific Objectives

In addition to the primary question outlined above, a series of secondary objectives were identified for this study. These are:

- To clarify what literature and evidence exists on carbon stock, storage, and sequestration potential in seaweed, with particular focus on any relevant information on commercial species of interest in Wales.
    - Where possible, estimates for carbon storage and subsequent sequestration per unit area will be presented for comparison to other sequestering marine habitats in Wales (e.g., seagrass beds, saltmarshes, etc., as included in the NRW evidence report by Armstrong et al. 2020).
- To identify available information on carbon emissions and losses from the marine environment that may arise from operational activities associated with macroalgal cultivation (e.g., boat use, maintenance, harvesting and processing), including relevant life-cycle assessments for system designs of seaweed cultivation, from seeding through to harvest, processing, and end-market.
- To present known information on the impacts of farming on the capability of existing marine communities to store and sequester carbon (e.g., from shading, nutrient uptake, changes in community structure, and other environmental impacts).
- To elucidate the potential fate of macroalgal transport to sediment stores, contributing to blue carbon stocks, specific to the Welsh environment.
- To identify knowledge gaps and uncertainties associated with seaweed cultivation’s positive or negative contribution to blue carbon stocks in Wales and internationally.

PICO Elements

The Population, Intervention, Comparator, Outcome (PICO) elements are included in Table 2 below. PICO elements have been largely described in the context of seaweed farming carbon potential. However, this review also covered the environmental impacts of carbon cycling in other environments.

Table 2. REA PICO elements.

PICO element	PICO Element for this REA
Population	Abiotic and biotic environments associated with seaweed farming in Wales, predominantly the marine environment.
Intervention	Seaweed farming
Comparator	N/A
Outcome	Blue carbon sequestration and carbon emissions and losses from operational activities associated with macroalgal cultivation (e.g., boat use, maintenance, harvesting and processing), including relevant life-cycle assessments for system designs of seaweed cultivation, from seeding through to harvest, processing, and end-market.

Search Methods

A wide search on Web of Science and Scopus using population, intervention, and outcome search terms captured a wide evidence base. The results of these searches were saved and interrogated further to answer each of the specific objectives, with data saved to the Evidence Review Matrix. A flow chart of the evidence review process is presented in Figure 2 below.

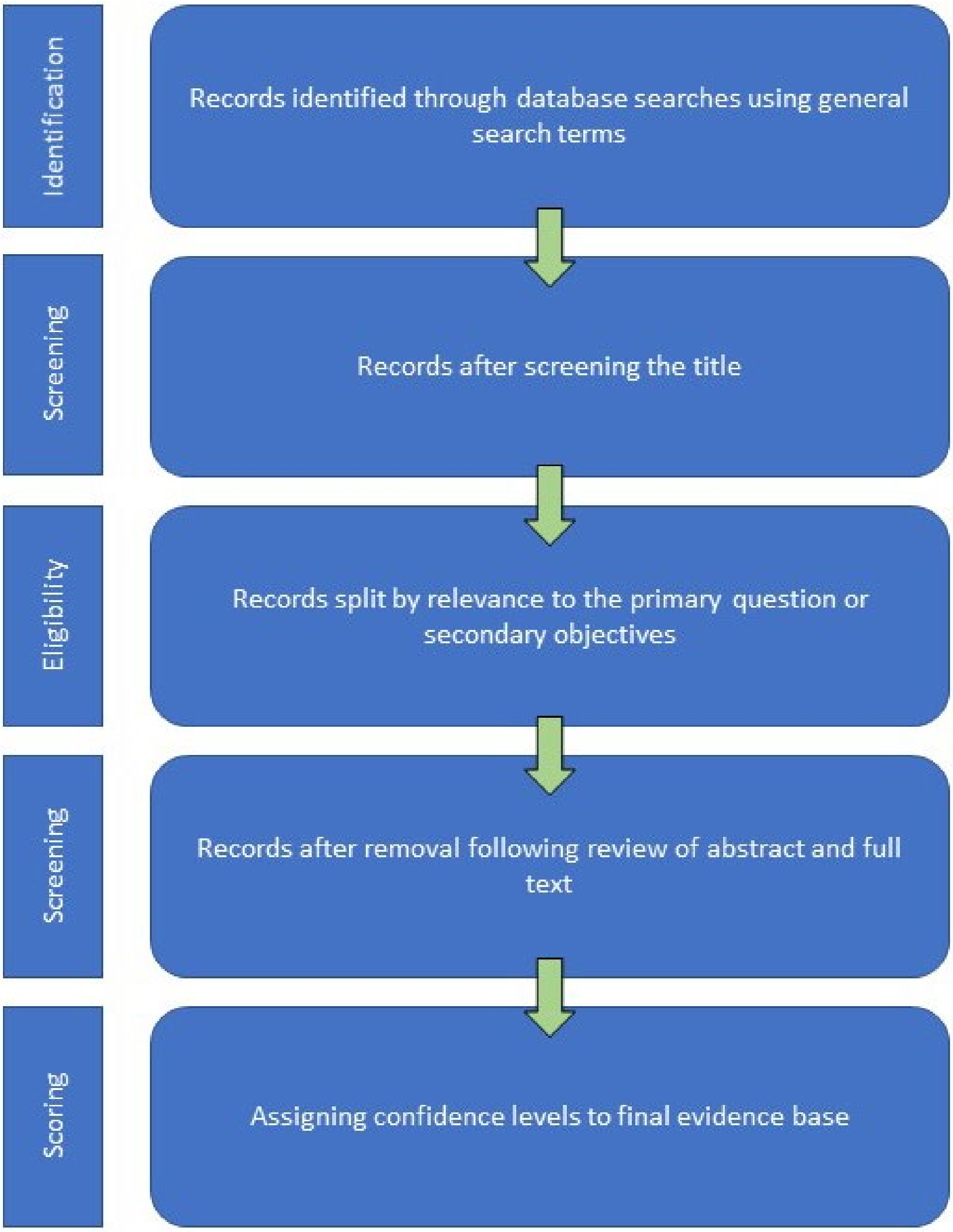

Figure 2. Flow chart of the evidence review process utilised in this report.

Due to the infancy of blue carbon, particularly with respect to seaweed farming, grey literature was also explored, including technical reports and publications from devolved administrations of the UK and statutory/non-statutory nature conservation bodies, including the use of Google Scholar. The following search terms were included in the review:

- blue carbon AND (seaweed OR macroalg* OR kelp)
- blue carbon AND (seaweed OR macroalg* OR kelp) AND (farm* OR cultivat* OR aquaculture OR mariculture)
- carbon stor* AND (seaweed OR macroalg* OR kelp) AND (farm* OR cultivat* OR aquaculture OR mariculture)

- carbon capture AND (seaweed OR macroalg* OR kelp) AND (farm* OR cultivat* OR aquaculture OR mariculture)
- carbon sequest* AND (seaweed OR macroalg* OR kelp) AND (farm* OR cultivat* OR aquaculture OR mariculture)
- carbon transport* AND (seaweed OR macroalg* OR kelp) AND (farm* OR cultivat* OR aquaculture OR mariculture)
- life cycle assessment AND (seaweed OR macroalg* OR kelp) AND (farm* OR cultivat* OR aquaculture OR mariculture)
- "environmental impact" AND (seaweed OR macroalg* OR kelp) AND (farm* OR cultivat* OR aquaculture OR mariculture)

As blue carbon is a relatively modern concept, no search limits were applied to the publication date of the results. Only English language results were explored, with no geographical restrictions applied.

Critical Appraisal

A critical appraisal of quality was undertaken using the questions below with reasons for medium/low validity recorded in the Evidence Review Matrix.

- *Conceptual framing*: Does the study acknowledge existing research? Does the study pose a research question or outline a hypothesis?
- *Transparency*: Is the geography/context in which the study was conducted clear? Does the study present or link to the raw data it analyses? Does the study declare sources of support/funding?
- *Appropriateness of method*: Does the study identify research design, data collection, and analysis methods? Does the study demonstrate why the chosen design and method are well suited to the research question?
- *Internal validity:* To what extent is the study internally valid? (E.g the extent to which a study establishes a trustworthy cause-and-effect relationship between a treatment and an outcome).
- *Context sensitivity*: Does the study explicitly consider any context-specific factors that may bias the analysis/findings?
- *Cogency*: To what extent does the author consider the study's limitations and/or alternative interpretations of the analysis? Are the conclusions clearly based on the study's results (rather than on theory, assumptions, or policy priorities)?

Data was primarily extracted as narrative outcomes with limited quantitative synthesis, reporting carbon sequestration rates and other relevant study outcomes (e.g., environmental impacts). Key variables of interest as decided through consultation with the project team and NRW (see Evidence Review Matrix), were extracted from the available evidence. Data was extracted from text and tables, including the study location, experimental design, species investigated, carbon capture and sequestration rates, and a description of main findings. No transformations were conducted on the extracted data.

Appendix 2: Data Archive Appendix

No data outputs were produced as part of this project.

Further copies of this report are available from library@cyfoethnaturiolcymru.gov.uk