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Review

Potential role of seaweeds in climate change mitigation

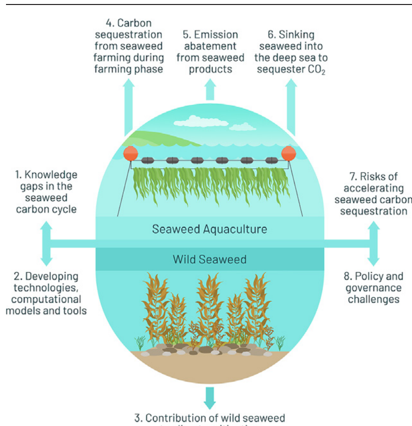
Finnley W.R. Ross [a,*], Philip W. Boyd [b], Karen Filbee-Dexter [c,d], Kenta Watanabe [e], Alejandra Ortega [f], Dorte Krause-Jensen [g,h], Catherine Lovelock [i], Calvyn F.A. Sondak [j,k], Lennart T. Bach [b], Carlos M. Duarte [l,m], Oscar Serrano [n,o], John Beardall [p,q], Patrick Tarbuck [r], Peter I. Macreadie [a]

[a] Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University, Burwood Campus, Burwood, VIC, Australia
[b] Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia
[c] Institute of Marine Research, 4817 His, Norway
[d] UWA Oceans Institute, University of Western Australia, Crawley, WA 6009, Australia
[e] Coastal and Estuarine Environment Research Group, Port and Airport Research Institute, 3-1-1 Nagase, Yokosuka 239-0826, Japan
[f] King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
[g] Department of Ecoscience, Aarhus University, Ole Rømers Allé, building 1131, Aarhus C 8000, Denmark
[h] Arctic Research Centre, Aarhus University, Ole Worms Allé 1, Aarhus C 8000, Denmark
[i] School of Biological Sciences, The University of Queensland, St Lucia, QLD 4072, Australia
[j] Department of Oceanography, Pusan National University, Busan 46241, South Korea
[k] Faculty of Fisheries and Marine Science, Sam Ratulangi University, Manado 95115, Indonesia
[l] King Abdullah University of Science and Technology, Red Sea Research Center (RSRC), Saudi Arabia
[m] Computational Bioscience Research Center (CBRC), Thuwal, Saudi Arabia
[n] Centro de Estudios Avanzados de Blanes, Consejo Superior de Investigaciones Científicas (CEAB-CSIC), Blanes, Spain
[o] School of Science & Centre for Marine Ecosystems Research, Edith Cowan University, Joondalup, WA, Australia
[p] School of Biological Sciences, Monash University, Clayton 3800, Australia
[q] Faculty of Applied Sciences, UCSI University, Kuala Lumpur, Malaysia
[r] Sea Green Pte. Ltd., 60 Paya Lebar Road #06-12, Paya Lebar Square, Singapore 409051, Singapore

HIGHLIGHTS

- Seaweed carbon accounting is yet to be fully constrained.
- Seaweed products have the potential to lower industrial emissions.
- Seaweed farms sequester carbon at site but at a limited scale to date.
- Quantifying carbon seqestration from wild seaweed restoration remains ellusive.
- Sinking seaweed has scalability but carries many risks and uncertainties.

GRAPHICAL ABSTRACT



* Corresponding author.
E-mail address: fwross@deakin.edu.au (F.W.R. Ross).

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A B S T R A C T

Seaweed (macroalgae) has attracted attention globally given its potential for climate change mitigation. A topical and contentious question is: Can seaweeds' contribution to climate change mitigation be enhanced at globally meaningful scales? Here, we provide an overview of the pressing research needs surrounding the potential role of seaweed in climate change mitigation and current scientific consensus via eight key research challenges. There are four categories where seaweed has been suggested to be used for climate change mitigation: 1) protecting and restoring wild seaweed forests with potential climate change mitigation co-benefits; 2) expanding sustainable nearshore seaweed aquaculture with potential climate change mitigation co-benefits; 3) offsetting industrial CO_2 emissions using seaweed products for emission abatement; and 4) sinking seaweed into the deep sea to sequester CO_2. Uncertainties remain about quantification of the net impact of carbon export from seaweed restoration and seaweed farming sites on atmospheric CO_2. Evidence suggests that nearshore seaweed farming contributes to carbon storage in sediments below farm sites, but how scalable is this process? Products from seaweed aquaculture, such as the livestock methane-reducing seaweed *Asparagopsis* or low carbon food resources show promise for climate change mitigation, yet the carbon footprint and emission abatement potential remains unquantified for most seaweed products. Similarly, purposely cultivating then sinking seaweed biomass in the open ocean raises ecological concerns and the climate change mitigation potential of this concept is poorly constrained. Improving the tracing of seaweed carbon export to ocean sinks is a critical step in seaweed carbon accounting. Despite carbon accounting uncertainties, seaweed provides many other ecosystem services that justify conservation and restoration and the uptake of seaweed aquaculture will contribute to the United Nations Sustainable Development Goals. However, we caution that verified seaweed carbon accounting and associated sustainability thresholds are needed before large-scale investment into climate change mitigation from seaweed projects.

Contents

1. Introduction

Atmospheric carbon dioxide has risen to 420 ppm from pre-industrial levels of 280 ppm, triggering climate change impacts on biodiversity and society (Bolin and Doos, 1989; Houghton, 1996; Bennett et al., 2016; Pecl et al., 2017; IPCC, 2019; Pörtner et al., 2019; Smale et al., 2019; Straub et al., 2019). Whereas reduced consumption, increasing energy efficiency and transitioning towards renewable energy and more sustainable agricultural systems are essential to achieve climate goals, enhancing removal of excess atmospheric CO_2 is crucial to limit warming to 1.5 °C (IPCC, 2022).

Half of the global CO_2 fixation occurs in the oceans (Nellemann et al., 2010). As such, management of blue carbon – the organic carbon that is captured and stored by coastal and marine ecosystems, is of importance as it provides opportunities to increase oceanic sequestration of atmospheric CO_2 (Mcleod et al., 2011). Vegetated coastal ecosystems are in the spotlight as their protection and restoration may offer pathways for climate change mitigation, hereafter referred to as climate change mitigation, and adaptation in the coastal ocean (Duarte et al., 2013; Macreadie et al., 2021).

Seaweeds are fast-growing marine macrophytes with modelling suggesting a global area and net primary production comparable to the Amazonian forest (Duarte et al., 2022). In addition to wild seaweed forests, seaweed farming contributes about half of the production of marine aquaculture (Duarte et al., 2021). Seaweed has been suggested to contribute to climate change mitigation through four potential pathways (Krause-Jensen et al., 2018; Duarte et al., 2021; Troell et al., 2022): 1) protecting and restoring wild seaweed forests with potential climate change mitigation co-benefits; 2) expanding sustainable nearshore seaweed aquaculture with potential climate change mitigation co-benefits; 3) offsetting industrial CO_2 emissions using seaweed products for emission abatement; and 4) sinking seaweed into the deep sea to sequester CO_2.

Protection and restoration of blue carbon ecosystems has focussed on mangroves, saltmarshes and seagrass – macrophytes that contribute carbon in roots and other tissues to sediments and facilitate the accumulation of organic-rich sediments below the habitat (Ouyang et al., 2017; Macreadie et al., 2021). However, recent reviews suggest that seaweed-dominated ecosystems are also important contributors to nearshore and offshore carbon-sinks (Kennedy et al., 2010; Krause-Jensen and Duarte, 2016; Macreadie et al., 2019; Ortega et al., 2019; Ortega et al., 2020b; Williamson and Gattuso, 2022), leading to arguments that these ecosystems should also be used for climate change mitigation (Krause-Jensen et al., 2018; Duarte et al., 2022). The area of seaweed that grows on soft-sediments, where organic carbon may accumulate, is estimated at 1.5 million km^2 – relative to the 7.2 million km^2 of total global seaweed extent (Duarte et al., 2022). Moreover, seaweed release and laterally export dissolved and particulate organic matter beyond their habitat, thereby providing a potential long-term carbon sink in the deep ocean (Hill et al., 2015; Trevathan-Tackett et al., 2015; Krause-Jensen and Duarte, 2016; Paine et al., 2021). Although the process of lateral carbon export and potential sequestration beyond the habitat boundaries is inherent to all coastal vegetated ecosystems (Duarte and Krause-Jensen, 2017), it constitutes the main carbon storage pathway in seaweed ecosystems (Krause-Jensen and Duarte, 2016).

Seaweed cultivation may also, during the growth period, contribute to organic carbon sequestration in sediments beneath seaweed farms and beyond, hence providing opportunities for climate change mitigation (Duarte et al., 2017; Sondak et al., 2017; Yong et al., 2022). Global seaweed aquaculture has been expanding at 6.4 % annually from 2000 to 2019 (FAO, 2021), propelled by the development of new applications and markets for their products (Duarte et al., 2021). Whilst there are clear socio-economic benefits for coastal livelihoods, there are potential negative consequences of upscaling seaweed aquaculture for coastal ecosystems, like transfer of disease to wild seaweed populations (Campbell et al., 2019), altered structure and genetics of wild populations (Graf et al., 2021), or changes in biodiversity and thus it is important to examine environmental and societal trade-offs as seaweed farming expands globally as a strategy to mitigate climate change (Duarte et al., 2021).

While there is increasing interest in promoting blue carbon sequestration by seaweed through the four pathways described, currently there are no standardised methodologies to verify and document seaweed carbon sequestration like there is for other vegetated coastal ecosystems (Emmer et al., 2015). It remains unclear which actions involving seaweed can be viable for climate change mitigation. Challenges to defining whether seaweed projects are scalable for climate change mitigation include evidence of permanence, additionality, verification, consequences and potential uptake of the solution (Krause-Jensen et al., 2018; Macreadie et al., 2021; Hurd et al., 2022). Moreover, there is a need to document that such solutions are also sustainable and under which sustainability thresholds. Here, we provide context, via eight key research and policy challenges, to the viability of seaweed projects for climate change mitigation (Fig. 1). The consensus of those challenges is summarised in Box 2 at the end of this paper. The authorship represents a wide range of opinions on the topic, hence not all statements in the paper were unanimously agreed upon. However, collectively we convey some of the wide ranging issues over which there is a diversity of viewpoints across the research community. We explore the state of knowledge and key gaps related to these eight key challenges and discuss the possibilities of seaweed projects being viable for climate change mitigation. This review aims to provide context for assessing the viability of four pathways to use seaweed for climate change mitigation, identifying when, where and what can be done to unlock the potential of seaweed for climate change mitigation.

2. Challenge 1 - resolving knowledge gaps in the seaweed carbon cycle

First-order estimates of seaweed primary production on a global scale have suggested that about 173 Tg OC yr^{-1} (with a range of 68–268,173 TgC yr^{-1}) (Krause-Jensen and Duarte, 2016) could be sequestered in the oceans. Of this, about 97 % has the potential to be sequestered beyond seaweed habitats by outwelling (lateral) followed by downward export. However, there are few experiments and modelling studies that verify these estimates. Quantifying carbon fluxes across all components of the seaweed carbon cycle is difficult, owing to the large spatial and temporal scales

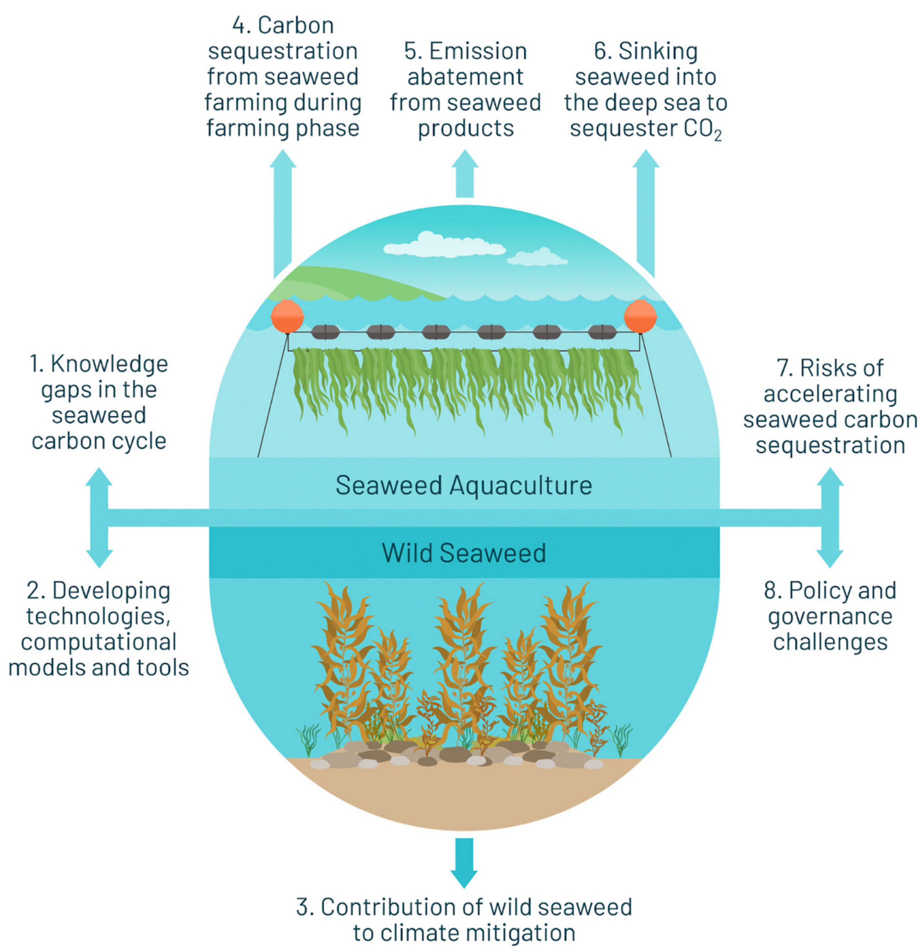

Fig. 1. Diagram detailing how the identified research challenges relate to either seaweed aquaculture and/or wild/naturally occurring seaweeds. The research challenges have been abbreviated.

Box 1
Seaweed carbon credits.

Blue carbon is becoming increasingly included in national carbon inventories (Herr and Landis, 2016; Martin et al., 2016; Bertram et al., 2021). Carbon credits are frequently referenced as a way to finance climate change mitigation. Voluntary carbon market methodologies currently exist for other blue carbon ecosystems, for example in the Verified Carbon Standard (Emmer et al., 2015), but not for seaweed. The sale of seaweed carbon credits may make seaweed projects more profitable if managers receive income for climate change mitigation (Duarte et al., 2021). Based on our review, there appears to be five separate distinct methodologies for potential seaweed climate change mitigation pathways, of which only two (A and C) are immediately actionable; A) Carbon deposited in sediment below seaweed farms, B) transport of POC and DOC to OC-sinks offshore from seaweed aquaculture, C) emission abatement credits from seaweed products, D) restoration and protection of wild seaweed habitats and their related carbon sinks, and E) sinking seaweed in the deep sea.

Both D) seaweed restoration and E) sinking seaweed in the deep sea do not appear to be viable for carbon credits in the short term due to concerns raised in Challenges 3, 6 and 7, as well as challenges of attribution of seaweed carbon sequestered beyond the habitat boundaries to a particular action (Challenge 2). Likewise, due to concerns around traceability and quantification of carbon in Challenge 2, (B) transport of POC and DOC offshore from seaweed aquaculture is unlikely to be viable in the short term, as issuing of carbon credits requires evidence that the carbon is in a stable form and remains sequestered for a significant time period - usually over 100 years (Boyd et al., 2019, Bach et al., 2021, Siegel et al., 2021). However, our review suggests there is enough evidence to support a development towards a global standardised methodology for the accumulation of carbon beneath sediments of seaweed farms (A) and for seaweed product carbon abatement credits (C), providing that sustainability standards for seaweed aquaculture are developed and adhered to. If seaweed farmers can access this value via a global standardised methodology which enables payments from sale of carbon credits as a co-benefit to their production, this may further incentivize the expansion of seaweed aquaculture (Duarte et al., 2021). We note this research is already underway via (https://www.oceans2050.com/seaweed and https://verra.org/project/vcs-program/projects-and-jnr-programs/seascape-carbon-initiative/). The development of methodology A should consider and subtract the baseline carbon sequestration from natural ecosystems, e.g., phytoplankton in areas where seaweed growth will compete for nutrients with other primary producers. Similarly carbon credits for emission abatement via, for example, methane reduction from seaweed as suggested by some industry groups (https://www.future-feed.com/-faqs, www.weeklytimesnow.com.au%2Fagribusiness%2Fagjournal%2Fseaweed-may--hold-key-to-red-meats-emissions-problem), will reduce costs and encourage uptake of these projects in terrestrial farming systems. The scalability of projects, while relatively unquantified, appears significant for methodologies B, C, D and E. For methodology A, at current seaweed aquaculture expansion rates of 6 % annually, sequestration may only reach 5.5 $TgCO_2\ yr^{-1}$ by 2050 (Duarte et al., 2021). Rapid expansion of the seaweed aquaculture industry would be needed to meaningfully contribute to climate change mitigation, for example 20 % annual growth could sequester 239 Tg $CO_2\ yr^{-1}$by 2050 for methodology A (Duarte et al., 2021). The current financial scope of methodology A is limited to \$3,580,160 per year at \$10 per tonne of CO_2 (Sondak et al., 2017), with 358,000 t CO_2 sequestration per year (FAO, 2021, Challenge 4). This potential revenue from carbon credits could have a large portion used up in administration, monitoring and research cost for verification. Indeed, verification costs currently represent a significant hurdle for blue carbon projects altogether (Macreadie et al., 2021), and a need for more cost-effective methods is evident. We suggest that any development of a methodology to assess carbon stored below seaweed farms uses the forensic carbon accounting approach described in Hurd et al. (2022) and should be carefully considered against the potential scalability of this solution.

involved (Hurd et al., 2022). Understanding these carbon fluxes is crucial for better constraining the carbon sequestration capacity of seaweeds.

The location (e.g. within different coastal geomorphologies, water depths and ocean circulation patterns), and the life cycle of seaweeds (e.g., growth, mortality, and reproduction) determines the magnitude of net primary productivity and the potential for subsequent carbon flows (Fig. 2a; Pessarrodona et al., 2018). Organic seaweed carbon (OC) that is not grazed and/or decomposed or deposited in the habitats in which it is produced can be laterally exported as seaweed thalli or detritus (i.e. particulate organic carbon [POC]), and as dissolved organic carbon (DOC) from coastal habitats (Gilson et al., 2021), to sites in the deep subtidal or deep ocean (Filbee-Dexter et al., 2018; Ortega et al., 2019; Queirós et al., 2019) and within other adjacent blue carbon ecosystems (Wernberg et al., 2006; Ortega et al., 2020b) (Fig. 2c-g).

Although the offshore export of seaweed depends on oceanographic processes (e.g., currents, waves, and tides) and ocean bathymetry (e.g., the distance to the deep sea), seaweed detritus can be transported thousands of kilometres away from their sites of origin at varying depths (Nikula et al., 2010; Kokubu et al., 2019; Ortega et al., 2019). The long-distance transport of seaweed biomass and detritus depends on the decomposition rate and physical characteristics of the seaweed material, particularly the buoyancy and density (Trevathan-Tackett et al., 2015; Filbee-Dexter and Wernberg, 2020; Smale et al., 2021). For example, positively buoyant seaweeds, such as *Sargassum*, *Macrocystis* and other Laminariales, can be transported as rafts offshore (Fig. 2c; (Kokubu et al., 2019)). When floating seaweeds lose buoyancy and sink, part of their biomass (OC) may be transported to carbon sinks in shelf sediments or to the deep sea, depending on their size, currents, sinking speed, and distance to the deep sea (Fig. 2h). Likewise non-buoyant seaweed can be exported in the bedload (Krause-Jensen and Duarte, 2016). As OC is laterally exported, biotic and abiotic processes continuously fragment the seaweed biomass, resulting in reduction in the particle size and leading to continuous dispersal of POC, which in turn influences the location of potential POC burial and the efficiency of carbon sequestration (Fig. 2a, b, (Filbee-Dexter et al., 2020)). The decomposition of buried seaweed OC in shelf, coastal and beach sediments also influences the rates of carbon sequestration (Fig. 2k). Anaerobic conditions reduce the decomposition rate of seaweed biomass, which will potentially enhance the preservation of OC (Pedersen et al., 2021), along with chemical compositions that render seaweed organic material, such as their cell walls, recalcitrant to microbial degradation (Costa et al., 2021).

The production and release rates of seaweed DOC has been measured using in situ observations and lab experiments (Smale et al., 2021; Weigel and Pfister, 2021). However, the subsequent transport and processes

Table 1
Summary of key variables and pathways for the sequestration of carbon from wild macroalgal beds. The structure follows an earlier review (Krause-Jensen and Duarte, 2016) but values are updated based on more recent information.

Variable/pathway	Mean	Standard deviation
Global brown algal area (million km^2)	1.68[a]	–
NPP ($gC\ m^{-2}\ yr^{-1}$)	536[b]	706
Global NPP ($TgC\ yr^{-1}$)	1320[a]	–
Percentage of NPP buried within algal beds (%)	0.4[c]	0.54[c]
Percentage of NPP exported laterally from algal beds (%)	43.5[c]	48[c]
DOC exported laterally from algal beds ($gC\ m^{-2}\ yr^{-1}$)	16–4400[b]	–
Percentage of DOC exported below the permanent pycnocline (%)	30[d]	–
POC exported laterally/offshore from algal beds ($TgC\ yr^{-1}$)	323[e]	907[e]
Percentage of POC exported to the deep sea (%)	11[f]	1.7[f]
POC export retained in the shelf environment ($TgC\ yr^{-1}$)	288[g]	808[g]
POC buried in shelf sediments ($gC\ m^{-2}\ yr^{-1}$)	4.65[h]	2.47[h]
Percentage of beach-cast macroalgae biomass converted into semi liable or refractory DOC	18.3[i]	–

[a] (Duarte et al., 2022) with modelled individual estimates ranging 1.43–1.79 million km^2.
[b] (Pessarrodona et al., 2022).
[c] From the mean and standard error reported in Duarte et al. (1996), for $n = 30$, where n is the number of observations.
[d] This mean estimate is supported by the finding that the net oceanic primary production (around 50 $PgC\ yr^{-1}$), of which about 13 % (6.5 $PgC\ yr^{-1}$, Baines et al., 1991) is released as DOC, supplies a downward DOC export of 2 $PgC\ yr^{-1}$ (approximately 30 %) below the mixed layer (fig. 6.1 in Ciais et al. (2013)). We assume that the same fraction of macroalgal DOC is exported below the mixed layer and potentially reaches the deep sea.
[e] Calculated as the total export − DOC export through the uncertainty analysis by Krause-Jensen and Duarte (2016).
[f] The mean and standard error of three independent studies reported by Krause-Jensen and Duarte (2016).
[g] Calculated as total POC export − POC exported to the deep sea through the uncertainty analysis by Krause-Jensen and Duarte (2016).
[h] Calculated from two experiments reported in Hardison et al. (2013).
[i] From a case study in Perkins et al. (2022).

Box 2
Summary of key issues and consensus statements for each challenge.

Challenge	Key issues	Consensus statement
1. Resolving knowledge gaps in the seaweed carbon cycle	• DOC production and advective fluxes and fate. • POC fluxes and fate. • Controls on decomposition rate • Benthic oxidation state. • Alkalinity interactions.	The empirical quantification of seaweed carbon pools and cycles remains elusive and needs technological developments in monitoring, tracing and modelling seaweed organic carbon fluxes.
2. Developing technologies, computational models and tools to measure seaweed carbon fluxes	• Tools to distinguish seaweed signatures (e.g. eDNA). • Remote sensing methods. • Seaweed transport models.	Advances in tracing and measuring seaweed carbon fluxes are key for inclusion of seaweed in the blue carbon framework.
3. Understanding the potential contribution of wild seaweed to climate change mitigation	• Anthropogenic impact on seaweed forests • Restoration techniques • Refined estimates available for global seaweed primary production. • Contribution of kelp detritus to carbon storage. • Effects of protection and restoration on climate change mitigation and co-benefits.	Restoring and protecting wild seaweed forests is critical because of the numerous co-benefits they provide, however, it is unlikely that the climate change mitigation benefits of seaweed restoration will be quantifiable/have a reliable accounting framework.
4. Contribution of seaweed aquaculture to undeliberate carbon sequestration during the farming process	• Potential contribution of shedded cultivated seaweed to carbon sequestration under seaweed farms. • Export of seaweed carbon from the aquaculture site to sink sites beyond the farm.	Seaweed aquaculture accumulates carbon in the sediment below seaweed farms, this has quantifiable climate change mitigation potential at small scales. Export of seaweed carbon during the growth phase has the same quantification challenges as for wild seaweed, i.e. unlikely quantifiable climate change mitigation benefit (see point 3).
5. Understanding future opportunities from seaweed aquaculture products for emission abatement	• Current development of seaweed products. • *Asparagopsis*and other species for reduction of methane emission from ruminants. • Future opportunities for avoided emissions from seaweed products.	Many new seaweed aquaculture products are being developed and the industry is growing rapidly. Seaweed aquaculture could have an increasing climate change mitigation impact as seaweed aquaculture products can potentially result in emission abatement by having a lower carbon footprint than products they replace, as well as contributing to reduce methane emission from ruminants
6. Sinking seaweed into the deep sea to sequester CO_2	• Ethics of sinking seaweed. • Risks of sinking seaweed. • Effects on carbon storage.	Purposeful seaweed sinking remains controversial for climate change mitigation although the scale of opportunity could be significant. Major challenges around ethics, ecological risks, as well as carbon accounting for offshore seaweed cultivation would need to be resolved before a feasibility assessment would be relevant.
7. Environmental benefits and risks of accelerating seaweed aquaculture to enhance carbon sequestration	• Quantification of benefits and risks • Seven possible impacts of seaweed farming were identified.	Seaweed cultivation offers many co-benefits to society, but is relatively limited in extent outside Asia. While relatively few negative impacts have been documented to date from seaweed aquaculture, caution should be given to the various potential impacts of seaweed cultivation as it expands globally.
8. Understanding the key policy and governance considerations surrounding the potential role of seaweed for climate change mitigation	• Relevant international treaties. • Global collaboration on seaweed. • Assigning responsibility for seaweed management.	International guidelines and standards for seaweed protection/restoration and sustainable seaweed aquaculture are needed to unlock the potential of seaweed for climate change mitigation and the numerous co-benefits from seaweed activities while avoiding negative impact.
Box 1 - Seaweed Carbon credits	• Five methodologies for potential seaweed-based climate change mitigation are outlined. • Only two of these are viable for development of carbon credits. • A seaweed carbon accounting methodology is lacking.	Activities linked to seaweed forest restoration, the export of carbon offshore from seaweed farms during the farming process, or deliberately sinking seaweed, do not appear to be ready to be implemented for climate change mitigation while carbon sequestration in sediments below farms and emission reduction via seaweed products may offer potential carbon credits in the short term.

determining sequestration of DOC are poorly understood and indeed, difficult to determine. One of the mechanisms proposed to contribute to carbon sequestration is the persistence of refractory DOC in the water column (Fig. 2c). Microbial decomposition experiments show that about half (range, 28–85 %) of the DOC persists as potential recalcitrant DOC (RDOC) over annual timescales (Wada et al., 2008; Watanabe et al., 2020) and that the recalcitrance of seaweed DOC depends on the species and environmental conditions (Paine et al., 2021), therefore experiments on DOC cannot easily be extrapolated reliably. Future studies could assess how variation in microbial assemblages and chemical and physical conditions affect the long-term recalcitrance of DOC during transport to offshore sink sites. Another mechanism contributing to carbon sequestration is the downward transport (downwelling) of DOC into the deep sea (Fig. 2b). The fraction of seaweed DOC that reaches the deep sea will largely depend on its recalcitrance and on hydrodynamic, oceanographic, and bathymetric factors.

If we consider the carbon cycle in seawater, CO_2 from the atmosphere ($CO_{2(g)}$) dissolves in water to form $CO_{2(aq)}$, which can also be formed from the breakdown of organic matter. $CO_{2(aq)}$ is in equilibrium with carbonic acid, bicarbonate and carbonate as shown below.

$$CO_{2(g)} \leftrightarrow CO_{2(aq)} + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^{\ -} + H^+ \leftrightarrow CO_3^{\ 2-} + 2H^+$$

Increasing $CO_{2(aq)}$ causes a decline in seawater pH (increase in H^+) thereby reducing carbonate ion concentration. Conversely, autotrophic assimilation of CO_2 causes an increase in seawater pH (decrease in H^+) and an increase in CO_3^{2-}. The other important component to consider is change in alkalinity and there are a number of processes contributing to changes in alkalinity in marine systems, see Table 1 of Sippo et al. (2016). Increasing alkalinity shifts the equilibria towards HCO_3^- and CO_3^{2-}, thereby "making new space" for CO_2 in seawater, which can be absorbed from the atmosphere. Ocean alkalinity and the DIC system are considered in detail by Middelburg et al. (2020) and the dynamics of DIC in coastal systems by Ouyang et al. (2022). Seaweed OC reaching anaerobic sediments may promote mineralization in ways that increase total alkalinity (Santos et al., 2021 and references therein). If this alkalinity is transferred to the water column through diffusion or outwelling, it would, as mentioned above, shift the DIC equilibrium towards HCO_3^- and CO_3^{2-} and would thus facilitate drawdown of CO_2 in oceanic waters.

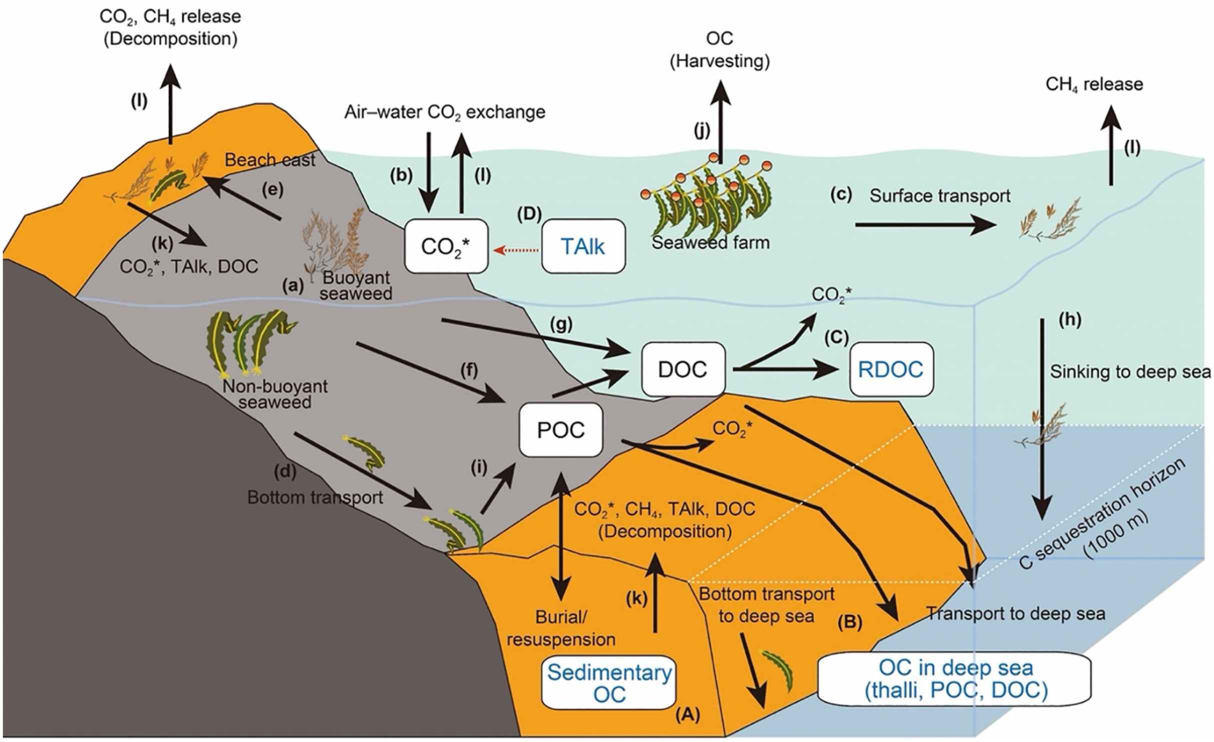

Fig. 2. Potential pathways for sequestration of seaweed carbon. Net primary production lowers CO2 concentration in the surrounding water (a), facilitating atmospheric CO2 uptake through fixation into macrophyte biomass (b). CO2* indicates the chemical equilibrium between dissolved CO_2, carbonic acid, carbonate ions, and bicarbonate ions in the ocean, which is controlled by total alkalinity (TAlk). Floating thalli (or POC which is usually defined as particles >0.2 μm) of buoyant seaweed can be transported offshore (c), where they sink to the deep sea when buoyancy is lost (h). Non-buoyant seaweeds sink near the sites of origin and are transported via bottom currents and accumulate along bottom slopes (d). A portion of the biomass and detritus of floating and non-buoyant seaweeds is washed onto beaches (e). Particulate organic carbon (POC) and dissolved organic carbon (DOC) are released and transported offshore (f, g). Seaweed biomass is continuously fragmented during these processes, promoting dispersal of POC and DOC (i). For seaweed farms, most of the biomass is removed from nearshore waters when seaweed is harvested (j), but about half of their net primary production is released to the environment as DOC and POC before harvest (Duarte et al., 2021). CO2 and CH4 gases and TAlk are released to the water column depending on the seaweed decomposition pathways (k) (see text for details of DIC speciation and the role of alkalinity). Degassing of CO2 and CH4 gases (l) produced by decomposition (see text for details of DIC speciation). The potential carbon pools which contribute to long-term carbon sequestration are: burial of OC in coastal, shelf and deep sea sediments (A); OC transported to the deep sea (B); and refractory DOC (RDOC) and DOC transported below 1000 m depth, and excess bicarbonate produced from TAlk release (red dashed arrow) – which both remain in the water column (C, D). Key quantitative and semi quantitative values associated with Fig. 2. are summarised in Table 1.

The processes leading to increased total alkalinity under anaerobic conditions include denitrification, reduction of metals such as manganese and iron and, especially, sulphate reduction (Perkins et al., 2022, see also Fig. 2 in Santos et al., 2021). Alkalinity released through the anaerobic mineralization of seaweed OC thus locks CO_2 into inorganic carbon ions in the ocean, which would be one of the carbon pools to sequester carbon over long time scales ((D) in Fig. 2)). Similarly the release of alkalinity due to providing substrate for calcifiers could in theory drawdown CO_2 (Challenge 3). Another process that has been suggested to lead to increased alkalinity, at least for mangrove ecosystems (Saderne et al., 2021), is the dissolution of calcium carbonate (Ridgwell and Zeebe, 2005; Saderne et al., 2019) under the lower pH values caused by enhanced pCO_2 from the breakdown of organic matter in sediments. Under current atmospheric CO_2 levels, formation of $CaCO_3$ results in ~0.6 mol of CO_2 being released per mole of $CaCO_3$produced (Frankignoulle et al., 1994; Macreadie et al., 2017), dissolution of $CaCO_3$ would result in increases in total alkalinity and similar amounts of CO_2 being consumed. However, to what degree these processes play a role in alkalinity release from sediments and CO_2 drawdown is currently unclear.

Few studies have shed light on the magnitude of these processes across these carbon pools and fluxes, including OC in the deep sea, sedimentary OC, RDOC and alkalinity release from seaweed processes. Importantly, deposition of seaweed carbon does not necessarily directly equate to CO_2 removal (CDR), as re-equilibration and capture of atmospheric CO_2 is an essential step for CDR, which few studies have quantified (Hurd et al., 2022), although subsaturated pCO_2 in waters over seaweed forests and other seaweed communities imply capture of atmospheric CO_2 (Smith, 1981; Gazeau et al., 2005). We also note that seaweed research is strongly biased towards some species of certain geographical locations that are more accessible and therefore, little is known on seaweed carbon cycling in locations such as Antarctica, South America, Africa or many parts of Asia The empirical quantification of seaweed carbon pools and cycles remains elusive and needs technological developments in monitoring, tracing and modelling seaweed organic carbon fluxes (Hurd et al., 2022). These limitations are discussed in the next challenge.

3. Challenge 2 - developing technologies, computational models and tools to measure seaweed carbon fluxes

Advances in tracing and measuring seaweed carbon fluxes are key for inclusion of seaweed in the blue carbon framework (Krause-Jensen et al., 2018). While there are available tools to quantify these flows, tracing seaweed carbon fluxes is complex and still unprecise. Detecting the presence and quantifying stored seaweed carbon is essential to validate whether seaweed carbon reaches sink sites and how much of it arrives to depositional habitats such as the deep ocean (Smith et al., 2015; Geraldi et al., 2019; Ramirez-Llodra et al., 2021). Seaweed carbon has often been traced in sediment cores using pigment signatures (e.g., pheophytin and fucoxanthin) (Leiva-Dueñas et al., 2020; Ramirez-Llodra et al., 2021) and stable isotopes (Duggins et al., 1989; Geraldi et al., 2019). However, these tools fail at distinguishing seaweed signatures from certain types of phytoplankton (e.g., diatoms). Recent studies document that environmental DNA (eDNA) detect and provide estimations of seaweed abundance in marine sediments and water samples (Ortega et al., 2019; Queirós et al., 2019; Frigstad et al., 2021; Ørberg et al., 2021), evidencing seaweeds transport beyond coastal habitats at even 5000 km offshore, and in all ocean basins (Ortega et al., 2019). Long sediment cores can be sliced into layers and used to detect the presence of DNA from dominant seaweed species, enabling a semi-quantitative measure of seaweed-DNA concentrations over time (Frigstad et al., 2021). Suitable primers for these eDNA techniques have been developed for numerous seaweed genera which may give insight into the presence, burial rate and abundance of seaweed carbon in marine sediments (Ortega et al., 2020a, 2020b). Although eDNA can be used to estimate, for example, the proportion of various seaweed sequences in the eDNA pool of sediments, those estimates remain semi-quantitative and an accurate quantification of carbon deposition is currently challenging (Ortega et al., 2020a; Ørberg et al., 2021).

Remote sensing using satellite imagery is an important emerging tool for monitoring seaweed populations (Cavanaugh et al., 2021). For example, it has been used to monitor giant kelp canopy biomass (Bell et al., 2020; Marquez et al., 2022) and to track positively buoyant species such as floating *Sargassum*, based on distinct wavelengths absorbed by brown seaweeds (Ody et al., 2019). Improvements in the resolution of satellite images and their post-processing technology means that satellites are increasingly able to detect individual seaweeds of medium size floating on the surface (Ody et al., 2019); this could greatly improve the ability to remotely track surface floating seaweeds. Despite these advances, it is critical to understand the source location of buoyant seaweeds, and where and when they finally sink to the deeper ocean. Loss of buoyancy can be from remineralization, vesicle rupture by waves, and downward mixing and fragmentation (Johnson and Richardson, 1977; Vandendriessche et al., 2007). Experiments and simulation models exploring such processes are required to improve our understanding of the vertical flux of buoyant seaweeds.

Seaweeds are exported vertically in the water column and along the sea floor via passive processes. Early insights into these fluxes came from bottom trawls that captured seaweeds in the deep sea, in submarine canyons and along the continental shelf (Vetter and Dayton, 1999; Garden and Smith, 2015; Krause-Jensen and Duarte, 2016). These methods have allowed oceanographers to understand the role of large seaweeds in depositing rocks entrained in their holdfasts to the sea floor (Emery and Tschudy, 1941; Garden and Smith, 2015). Although coarsely resolved, trawl records can provide information on maximum transport distances, and even seasonal changes in the flow of large seaweeds (Vetter and Dayton, 1998; Filbee-Dexter et al., 2018). More recent technologies, such as ROVs and other underwater camera systems can be used to generate data on relative abundance, particle sizes, seasonal timing of detritus production, storm-induced fluxes (Filbee-Dexter and Scheibling, 2012; Pries, 2020) and areas of accumulation (Britton-Simmons et al., 2009). For example, repeated underwater surveys of detritus adjacent to coastal habitats can be used to estimate when and how much seaweed is moving beyond shallow habitats into deeper sinks (Filbee-Dexter et al., 2018; Smale et al., 2021). Seaweed DOC export can be traced by sampling water at different depths and using eDNA and other fingerprinting techniques (Geraldi et al., 2019). However, a major limitation of observational studies is that they do not directly link sources to sinks, but instead provide a snapshot evidencing transport of seaweed POC out of the coastal zone and its storage in the deep oceans. Such source-to-sink links and associated quantification may remain an unsolved challenge except in specific cases. For example, such links can be potentially established below seaweed farms, quantifying seaweed sequestration rates by comparing locations without farming in nearby sediments, or the sediment prior establishment of the farm.

There are a range of methods used to estimate the amount of seaweed biomass transported from the coastal zone to the deep ocean. Morphological characteristics (Vanderklift and Wernberg, 2008), physical tags (Kirkman and Kendrick, 1997; Filbee-Dexter et al., 2018) and genetics (Queirós et al., 2019) have been used to attribute seaweed detritus to its source location. However, use of ocean circulation (i.e., currents) models will likely provide the most comprehensive understanding of total seaweed flux beyond their habitat (Hurd et al., 2022). Where ocean currents are highly resolved, seaweed export can be quantified using particle tracking models (Filbee-Dexter and Wernberg, 2020). In the past, ocean current models were not suitable for modelling seaweed fluxes out of the coastal zone because they did not have sufficient spatial resolution. However, advanced regional models now have improved spatial and temporal resolution to better capture coastal zone processes (e.g., Regional Ocean Model, (Haidvogel et al., 2008)). To parameterize models, estimates of settling velocities of seaweed detritus (Filbee-Dexter and Wernberg, 2020) and decomposition rates (Pedersen et al., 2021), as well as thresholds for resuspension and movement across the seafloor are required (Oldham et al., 2010).

Ultimately, linking management actions at the seaweed habitat remains a key challenge for seaweed carbon accounting. The vast expanse of the ocean and distance between source and sink sites will make accounting for seaweed carbon transport difficult, even with improved monitoring techniques. Accuracy for higher resolution on tracking and quantifying seaweed carbon is needed to enable and support research to meet carbon offset assurance requirements (discussed in Challenge 8).

4. Challenge 3 - understanding the potential contribution of wild seaweed to climate change mitigation

Seaweed forests (e.g., kelp, *Sargassum*) are globally significant ecosystems with high biodiversity (Teagle et al., 2017). In some regions, wild seaweed is at risk from anthropogenic stressors (Wernberg et al., 2019), including pollution (Munda, 1993) and overharvesting of wild populations (Buschmann et al., 2017). Perhaps the most important stressors are ocean warming and the increasing frequency and intensity of marine heat waves, which have led to mortality of seaweed forests in some areas (Filbee-Dexter and Wernberg, 2018). Simultaneously at the poles, recent evidence points at a realised and projected poleward expansion of seaweed with climate change (Deregibus et al., 2016; Krause-Jensen et al., 2019; Goldsmit et al., 2021; Assis et al., 2022). Over the last 50 years, despite high regional variability in seaweed forest expansion or contraction, around 60 % of all long-term records of seaweed forests show a decline, attributed to multiple pressures including harvesting, pollution, invasive species, overgrazing and/or warming (Krumhansl et al., 2016; Wernberg et al., 2019). There is a need to better identify trends in wild seaweed ecosystems to target relevant sites for restoration and protection, which could include the revegetation of lost areas or the facilitation of poleward expansion.

Local scale management can reduce the impacts of climate change on seaweeds (Smale et al., 2019; Arafeh-Dalmau et al., 2020). For example, coastal managers can support local seaweed forests by protecting these forests from other threats like overharvesting, pollution and bottom trawling (Norderhaug et al., 2020). Reducing the impact of these stressors can promote conservation of seaweed forests by increasing their resilience against climate change impacts (Smale et al., 2013; Araújo et al., 2016; Rogers-Bennett and Catton, 2019). Restoration of seaweed forests (Fig. 3) can also be potentially facilitated through other means such as artificial reef restoration (that provides substratum for new algal forests), by selective harvesting of grazers like sea urchins, and by genetic modification to increase resilience for stressors like heatwaves (Steneck et al., 2002; Laffoley and Grimsditch, 2009; Hamilton and Caselle, 2015; Wood et al., 2019; Layton et al., 2020; Eger et al., 2022). A new promising management strategy for restoring kelp involves translocating small kelp planted on gravel to be dropped from the surface, called 'Green gravel' (Fig. 3) (Fredriksen et al., 2020). While in some areas survival of green gravel could be limited by being covered in sand or sediment this restoration activity shows promise in several restoration projects (Fredriksen et al., 2020). Similar to what is currently being done for corals, seaweed conservation efforts could also focus on species that are more resilient to future temperature stress to avoid local or regional extinctions (Smale et al., 2019; Thomsen et al., 2019; Vranken et al., 2021). Marine protected areas may

Fig. 3. Seaweed forest restoration. A - *Laminaria ochroleuca* on green gravel in Peniche, Portugal, B - *Phyllospora comosa* transplanted on a crayweed matt as part of operation crayweed, C- *Saccharina latissima* attached to a wooden frame on artificial reefs in the Gulf of St Lawrence, Canada, D - *Alaria esculenta* and *Saccharina latissima* on artificial reefs in Gulf of St Lawrence, Canada.
Photo credits: Nahlah A. Alsuwaiyan (A), John Turnball (B), Karen Filbee-Dexter (C, D).

also reduce compounding stressors on seaweed, for example by restoring the populations of predators that control sea urchin abundance (Shears and Babcock, 2002), and may subsequently protect blue carbon sequestration by seaweeds (Ling et al., 2009). The largest seaweed restoration project in the world is led by the Korean government who has invested over US $280 million from 2009 to 2019 to restore a total of 21,500 ha of seaweed forests in Korea (Hwang et al., 2020). However, a recent review of 259 kelp restoration projects shows that most have been relatively small in scale and costly, and broad uptake of large scale restoration projects are yet to be achieved (Eger et al., 2020, Eger et al., 2022).

Given the high estimates of seaweed forest primary productivity (Duarte et al., 2022) and carbon sequestration potential (Krause-Jensen and Duarte, 2016), their protection and restoration has been suggested to have climate change mitigation co-benefits (Krause-Jensen et al., 2018). Krause-Jensen and Duarte (2016), estimated that about 173 Tg OC year^{-1} (with a range of 61–268 Tg C year^{-1}), corresponding to 11 % of the estimated global net seaweed production, is sequestered by wild seaweed globally each year (Challenge 1). Wild seaweed forests are estimated to be the most extensive vegetated coastal habitat globally with an extent of 7.2×10^6 km^2 (Duarte et al., 2022), and their associated net primary production, which has recently been updated as 1.32 Tg C yr^{-1} (Duarte et al., 2022) from the previous estimate of 1.5 Tg C yr^{-1} Krause-Jensen and Duarte (2016), is also larger than that of other vegetated coastal habitats by about 60 % (Krause-Jensen and Duarte, 2016; Duarte, 2017; Raven, 2018). Around 90 % of wild seaweed carbon sequestration is estimated to be through export of carbon to the deep-sea and the remainder is buried in coastal and deep sea sediments (Krause-Jensen and Duarte, 2016).

Another important consideration for carbon budgets of wild seaweed forests, while poorly constrained as discussed in Challenge 1, is calcification. This is because some seaweeds species are calcifiers and seaweed forests can also provide habitat for calcifying organisms (Taylor, 1998; Newcombe and Taylor, 2010; Thomsen et al., 2016). Calcification reduces seawater alkalinity and subsequently lowers the CO_2 uptake capacity of seawater (Frankignoulle et al., 1994; Macreadie et al., 2017). Seaweed provides habitat for calcifiers and subsequently increases their biomass; this may partially offset the seaweed CO_2 sequestration and any deposit of organic carbon from calcifying species (Bach et al., 2021).

To quantify the impacts of any future change in carbon sequestration related to seaweed protection or restoration, estimates of historical and current carbon sequestration of wild seaweed forests and the associated change in these rates need to be improved through empirical evidence. Improved baseline estimates should therefore consider changes due to sea urchin overgrazing, ENSO cycles, extreme events, and rising CO_2 among other environmental variables. Key next steps include quantification of losses and quantification of risks of loss of seaweed habitats alongside associated rates of carbon sequestration. This will inform the potential climate change mitigation benefit of both preventing further loss and restoring already lost habitats. Research to support the management and restoration of seaweed forests should help preserve and increase their role in blue carbon storage, although precise quantification will depend upon details described in Challenge 2.

5. Challenge 4 - contribution of seaweed aquaculture to undeliberate carbon sequestration during the farming process

Seaweed aquaculture is the fastest-growing component of global food production (Duarte et al., 2017). Similar to ongoing carbon sequestration by wild seaweed forests, carbon sequestration with seaweed aquaculture could potentially be an additional CO_2 sink due to the incidental shedding of biomass and DOC during growth, some of which would be sequestered in sediments below the farm. Moreover, farmed seaweed products may have climate change mitigation benefits (discussed in Challenge 5). In 2019, seaweed aquaculture production had grown to 34.74 million tonnes fresh weight (FAO, 2021). Therefore there would be a maximum theoretical carbon drawdown of 3.16 million tonnes CO_2 per year if all of the 34.74 million tonne fresh weight produced contributed to carbon sequestration, or a minimum carbon drawdown if 0 t if all seaweed biomass was used in human consumption and respired. This is based on a dry weight content of 10 % of fresh weight, and an average carbon content of 24.8 % of seaweed dry weight (Duarte et al., 2017). If all of this seaweed was consumed, for example as food products and carrageenan, where the majority of carbon is released back into the atmosphere, there could be permanent carbon sequestration from shedding of biomass and release of DOC during growth prior to harvesting and subsequent sequestration of approximately 11 % (Duarte et al., 2017). Assuming that the estimate of 11 % of carbon becoming sequestered from wild seaweed forests is also appropriate for seaweed aquaculture (Duarte et al., 2021), 358,000 t CO_2 per year may have been sequestered unintentionally in oceanic sink sites in 2019 during the farming process. Carbon sequestration can also only be estimated during the seaweed farming season which varies by location. This estimate does not consider potential carbon sequestration via seaweed products (see Challenge 5).

This estimate is a relatively small global contribution to CO_2 sequestration being only 0.04 % of the average 841 Tg (621–1064 Tg) potential CO_2 predicted to be sequestered annually by 2030 from all other blue carbon habitats (Macreadie et al., 2021). It is also unlikely that the carbon sequestration rate of 11 % is accurate, owing to the many variables discussed in Challenges 1 and 2, meaning this number could be either lower or higher than for wild seaweed, depending on the setting. Additionally, the process of seaweed aquaculture may reduce other natural carbon sinks, for example by shading seagrass (Moreira-Saporiti et al., 2021), or nutrient robbing from endemic phytoplankton ecosystems (Challenge 7; Bach et al., 2021), and incur operational CO_2 emissions, from for example the use of boats. The use of life cycle analyses (LCAs) of such projects is needed to identify their net climate mitigation effect (Hasselström and Thomas, 2022). While impacts on other species can be mitigated through management and culture methods, project level estimates of abatement would need to include emissions and loss of CO_2 sequestration from loss of these natural carbon sinks, where they may occur (Hurd et al., 2022).

The majority of seaweed aquaculture currently involves basic infrastructure and it is located in sheltered coastal areas. If cost-effective and sustainable offshore (beyond the shelf break) aquaculture can be developed, the expansion potential for seaweed aquaculture may increase significantly (Buck et al., 2017). Further identification of ecological effects and risks (Challenge 7) of seaweed aquaculture, and assessment of new technologies, both inshore and offshore, are critical next steps in determining the potential scale for seaweed aquaculture for climate change mitigation both locally and globally. Seaweed aquaculture is presently concentrated in Asia, where it accounted for 97 % of global production in 2019. Of global seaweed production in 2019, 56.8 % occurs in China, 27.8 % in Indonesia with other countries producing <5 % of global seaweed (FAO, 2021). Therefore, detailed information on carbon fluxes from seaweed production in Asia is crucial to assess their potential contribution to climate change. If new species, aquaculture methods and geographies for seaweed aquaculture become economically and ecologically viable within sustainability limits (Duarte et al., 2021), more of the world's coastlines could become suitable for seaweed aquaculture.

In Challenge 5 we move beyond the contributions of seaweed aquaculture to blue carbon during the growth phase and instead look at specific ways of using products from seaweed aquaculture for climate change mitigation by emission abatement.

6. Challenge 5 - understanding future opportunities from seaweed aquaculture products for emission abatement

Seaweed aquaculture products can result in emissions abatement by having a lower carbon footprint than the products they replace (Spillias et al., 2023). Some seaweed products are substitutes for products from various other industries. For example, seaweed-based bioplastics could be used as a substitute to petroleum-based plastics (Rajendran et al., 2012). However, the scale of the potential substitution is unknown. Importantly, the lifecycle of most seaweed aquaculture products currently includes decomposition into CO_2 and methane emissions which are released back to the atmosphere. At present, 90 % of cultivated seaweeds are consumed as food or as additives (Duarte et al., 2021). The degree to which seaweed aquaculture products are substitutes for products from land-based sources differs between product types. In some instances, there may be an opportunity for increased emission abatement from expanding seaweed aquaculture industries so they increasingly compete with markets that produce similar products at a higher environmental and carbon footprint, such as using biofuel to partially replace fossil fuels (Milledge et al., 2014; Chen et al., 2015; Yong et al., 2022). Generally, bio-oils and bioethanol are more likely to be competitive than biodiesel (Chen et al., 2015). While biofuels can be derived from seaweed, lowering costs to compete with other fuels, particularly where petroleum based fuel receives subsidies, remains a significant barrier (Soleymani and Rosentrater, 2017). Soleymani and Rosentrater (2017) suggests an area of 129,500 ha of seaweed needs to be cultivated with a yield of 680,000 dry tonnes annually to reach a relatively competitive price of US$ 0.93/L of ethanol. For comparison, the current extent of seaweed aquaculture is approximately 198,300 ha (Duarte et al., 2021). Key impasses to unlocking emission abatement from seaweed as a biofuel include the development of cost-efficient aquaculture using kelp species, and lowering the cost and energy requirements, thereby lowering the carbon footprint of aquaculture and bioprocessing.

Recently, the red seaweed *Asparagopsis* has been recognised as a potential methane reducer in livestock (Roque et al., 2021). *Asparagopsis* can reduce enteric methane emissions when added as a supplement to the diet of ruminants, and can lead to increases in meat production (Roque et al., 2021). However, bromoform, the anti-methanogenic compound within *Asparagopsis* may have some toxicological effects and can be excreted in milk (Muizelaar et al., 2021), and at scale could be a small contributor to ozone depletion (discussed in Challenge 7). Additionally, *Asparagopsis* must be fed daily, which may not be feasible to distribute to animals in low density pastoral grazing systems until it is available in new forms like salt licks. Nevertheless, enteric methane emissions from livestock comprise 14.5 % of global emissions (Gerber et al., 2013) and, therefore, there is significant potential, should *Asparagopsis* supplements to ruminant feed be confirmed to have no negative effects, to contribute to emissions abatement. We also note that many seaweed species, including *Asparagopsis*, contain toxic components such as bromoform (Min et al., 2021) and therefore, other species than *Asparagopsis* should be investigated in the future for methane reduction in livestock.

These seaweed aquaculture markets are becoming increasingly attractive as demand for, and price of, land rises globally (Cotula, 2012). Therefore identifying emission abatement opportunities from new sustainable seaweed aquaculture sources remains a key research gap in establishing the potential scope for seaweed aquaculture. Determining the carbon footprint and life cycle analysis of seaweed aquaculture-derived products will allow for more accurate estimations of the carbon abatement potential for seaweed aquaculture derived products compared to land-derived ones. This will enable calculations of potential carbon sequestration and emissions avoidance per unit of seaweed biomass from different types of seaweed aquaculture and the fate of seaweed biomass, helping to decide which seaweed aquaculture markets may be most profitable for both industrial and climate change mitigation purposes. Overall, the demand and subsequent emission abatement opportunities for emerging seaweed products will depend upon the price, fungibility, type and fate of these products.

7. Challenge 6 - sinking seaweed into the deep sea to sequester CO_2

'Ocean afforestation' is the concept of facilitating the transport and sinking of coastal seaweed species into the deep sea to sequester CO_2 (Ritschard, 1992; Antoine de Ramon et al., 2012; Boyd et al., 2022; Ross et al., 2022). This concept was investigated in the 1980's, and was considered unfeasible then (Ritschard, 1992). The idea is currently seeing a revival due to escalating needs for atmospheric CO_2 removal at the gigatonne-scale (IPCC, 2019), and has been proposed by several companies (https://www.runningtide.com, https://southernoceancarbon.com, https://pulltorefresh.team). However, sinking seaweed is controversial (Ricart et al., 2022) as both numerical modelling and empirical investigations found high levels of uncertainty regarding its ability to sequester carbon (Orr and Sarmiento, 1992; Bach et al., 2021; Wu et al., 2022; Berger et al., 2023; DeAngelo et al., 2023), along with concerns on impacts on deep-sea biology and oxygen budgets. There are also ethical concerns on purposefully sinking biomass that could contribute to alleviate hunger and sustainably produce animal feed (Duarte et al., 2021; Ricart et al., 2022). This would be the case if the implementation of this concept meant reduced yield from, or growth of, the seaweed aquaculture industry due to resource competition between industries.

Nutrient reallocation (discussed in Challenge 7), is a key consideration for the sinking of seaweed offshore, whereby seaweed species compete with phytoplankton for nutrients and reduce their baseline carbon sequestration (Orr and Sarmiento, 1992; Bach et al., 2021). Therefore, for the concept of sinking seaweed for climate change mitigation, selecting species with a favourable C:N ratio, not just high growth rates would be important to consider. Additionally, adverse ecological impacts seaweed sinking (discussed in Challenge 7) may be significant. A key constraint on feasibility of seaweed sinking for climate change mitigation will be the return (CO_2 sequestered) on investment. While seaweed sinking remains controversial for climate change mitigation (Orr and Sarmiento, 1992, Bach et al., 2021, Wu et al., 2022, Berger et al., 2023, DeAngelo et al., 2023), the scale of opportunity could be significant given the expanse of the ocean. "Froehlich et al. (2019) calculated a hypothetical upper limit to the area possible for seaweed cultivation to be 48 million km^2, however this was only constrained by nutrients and temperature and did not consider sustainability thresholds, potential negative effects (Campbell et al., 2019) or other limiting factors such as irradiance, grazing, competition and currents. Spillias et al. (2023) #911@@author-year} constrained their even larger estimate of hypothetical global seaweed farming area to a total area of 6.5 million km^2 by considering water depth (<200 m), distance from ports, sea ice extent, wave energy, native algal distribution and avoiding marine protected areas and shipping traffic. Large challenges around carbon accounting for offshore seaweed cultivation would need to be resolved before an accurate feasibility assessment can be conducted for this concept.

8. Challenge 7 - environmental benefits and risks of accelerating seaweed aquaculture to enhance carbon sequestration

Seaweed aquaculture can provide positive environmental effects (Zheng et al., 2019), including reduced local ocean acidification and deoxygenation (Xiao et al., 2021), alleviation of eutrophication, and the provision of marine habitat restoration (Fernand et al., 2017). Increasing the scale of seaweed aquaculture also leads to job creation and social development, contributing to multiple United Nations Sustainable Development Goals (Valderrama, 2012; Boettcher et al., 2019; Larson et al., 2021). In coastal communities of developing nations, livelihoods through seaweed aquaculture may provide alternatives to sources of income from, for example, unsustainable commercial fishing (Valderrama, 2012).

Seaweed may also have a higher albedo (reflectance) than oceanic water, and this therefore could lower the potential for warming (Bach et al., 2021). However, in the long term this effect is potentially less important than the reduction of radiative forcing by removing CO_2 due to the long life-time of CO_2 in the atmosphere and also because this albedo effect could be strongly modified through cloud-forming substances seaweeds may release (Bach et al., 2021). Furthermore, the change in albedo from seaweed is unknown and will likely vary significantly with their proximity to the ocean surface (i.e., floating or fixed to slightly subsurface rafts and, more importantly, with the extent of the seaweed and amount of substances they release that can affect cloud albedo (Brooks and Thornton, 2018).

While the benefits from increasing the scale of seaweed aquaculture and wild seaweed forest restoration are for the most part widely known, the risks remain relatively unquantified. Currently, there is little evidence of negative consequences from seaweed cultivation (Boettcher et al., 2019). Yet the enormous extent of seaweed aquaculture in Asian nations may have some yet uncharacterised environmental consequences and knowledge of the natural ecosystem state pre-seaweed-aquaculture may be unknown, therefore impacts are difficult to quantify. However, seaweed aquaculture is relatively new outside Asia (Nayar and Bott, 2014; Ferdouse et al., 2018) and has not yet been successfully implemented offshore. If offshore and scalable seaweed aquaculture is to be developed, consideration should be given to possible negative environmental and ecological impacts (Campbell et al., 2020; Bach et al., 2021; Boyd et al., 2022).

If novel large scale seaweed aquaculture is to take place, there are possible impacts on wild seaweed forests and other marine ecosystems including seagrasses. For example, a high abundance of spores of particular species or genotypes could in theory reach endemic seaweed forest communities and lead to changes in community composition, therefore cultured seaweed species could be considered a threat as an invader by impacting biodiversity (Wikström and Kautsky, 2004; Williams and Smith, 2007; Russell et al., 2012). This is because there have been instances of seaweed invasions having a negative impact on coastal communities (Johnson, 2008), for example the spread of *Undaria pinnatifida* in Europe (Epstein and Smale, 2017) and spreading to coastal ecosystems from aquaculture sites in New Zealand (James and Shears, 2016). Some wild seaweed forest ecosystems are undergoing significant decline (Smale and Wernberg, 2013; Thomsen et al., 2019; Layton et al., 2020). Where this is the case, increased spore release from nearby seaweed aquaculture of similar kelp species could, in theory, aid seaweed forest recovery in a similar way to the spore bag method (Choi et al., 2000), whereby seaweed spores are released close to areas targeted for restoration. This will depend on the proximity of cultivation to coastal seaweed ecosystems and the life histories of cultivated and naturally occurring seaweed species. For this reason, it would be preferential to cultivate native or endemic macroalga species to reduce threats of invasion from non-native species (Boettcher et al., 2019; Shan et al., 2019), although the presence of cryptic species and variation in cultured and natural genotypes may add complexity (Zanolla et al., 2018; Altamirano-Jeschke, 2021). If seaweed species were genetically modified or engineered to be more resistant to marine heatwaves or for any other reason, they may face major regulatory challenges in the aquaculture industry, given a potential ecological risk of invasion in coastal ecosystems (Robinson et al., 2013; Kim et al., 2017; Cheney et al., 2019). However development of this technology may offer opportunities for restoring seaweed forests under global change threats.

We have identified seven key potential negative environmental and ecological impacts of offshore seaweed farming on natural ecosystems. 1) Large-scale production of anti-methanogenic seaweeds could potentially release volatile halocarbons that deplete the ozone layer. While this link remains somewhat unclear, it is extremely unlikely to reach any meaningful scale (Keng et al., 2020; Duarte et al., 2021). 2) Seaweeds release dissolved organic carbon (Paine et al., 2021), so their cultivation could theoretically lead to an increase of DOC in offshore and onshore ecosystems, which could have varying ecological impacts (Boyd et al., 2022), although this has not been quantified to date. Similarly if coastal seaweeds are cultivated offshore they may have different chemical ecology and could bring 'passengers', such as their microbiome, which could both have negative impacts on offshore ecology (Boyd et al., 2022). 3) Microorganisms convert CO_2 to methane in the deep sea, so there may be an unknown risk of methane release due to GHG additions in the deep sea (Whiticar, 1999; Kotelnikova, 2002; Sivan et al., 2007). However, this risk may be partially offset as the likelihood of methanogenesis may be low where high sulphate concentrations occur in the deep ocean (Sivan et al., 2007). Complex deep sea biogeochemical pathways for seaweed decomposition need to be better understood. 4) An increased abundance of dead organic matter on the seafloor will also consume more oxygen via decomposition, resulting in lower oxygen concentrations or hypoxia (Wyrtki, 1962). Therefore dumping of seaweed could also lead to localised hypoxia (Lapointe et al., 2018; Wu et al., 2022). 5) Impacts of seaweed and associated debris on deep sea benthic communities are difficult to monitor (Danovaro et al., 2020), and may be significant (Wolff, 1962; Filbee-Dexter and Scheibling, 2014; Baker et al., 2018). If deposition of seaweeds can be directed to relatively hypoxic areas with low biodiversity, these impacts may be smaller (Levin, 2002; Helly and Levin, 2004). 6) Interactions with marine life, seabirds and mammals are possible risks, as entanglement has been associated with other aquaculture systems (Würsig and Gailey, 2002; Kemper et al., 2003; Young, 2015) but has been deemed low risk for offshore renewable energy mooring systems (Harnois et al., 2015). Entanglement remains a risk alongside polluting coastlines with debris like growing lines from seaweed farms. 7) Seaweeds will likely compete for nutrients with phytoplankton which could have diverse and relatively unstudied ecological impacts (Bach et al., 2021). While seaweeds generally consume carbon more efficiently than phytoplankton relative to their N and P consumption (Baird and Middleton, 2004), the nutrients that would otherwise have been used by phytoplankton and their associated carbon sequestration should be subtracted from any seaweed carbon sequestration (Bach et al., 2021). This is because if seaweeds compete with phytoplankton for nutrients in ecosystems where there are no excess nutrients, they may reduce the potential baseline carbon sequestration of phytoplankton. The capacity of seaweed to absorb nutrients, increase water clarity and reduce phytoplankton biomass have been observed by satellite remote sensing of 'green tides' (*Ulva* blooms) (Xing et al., 2015). However, this increase in water clarity will also increase the euphotic depth and therefore potentially enhance phytoplankton biomass in deeper layers. These seven impacts are depicted in Fig. 4.

9. Challenge 8 - understanding the key policy and governance considerations surrounding the potential role of seaweed for climate change mitigation

The feasibility of engineering techniques, ecological carrying capacity, consent and permits to operate seaweed aquaculture in the coastal zone and open ocean are also all key considerations for the expansion of seaweed aquaculture (Barbier et al., 2019; Kim et al., 2019; van den Burg et al., 2020) and, specifically, the deliberate sinking of seaweed biomass in deep sea waters. International ocean-related treaties will influence implementation of seaweed aquaculture in international waters, including components of The Law of the Sea, The International Seabed Authority, The London Protocol, International Maritime Organization and the UN Convention on Biological Diversity. For example, under the Law of the Sea, there are laws guiding marine research and mineral exploration in international waters. The London Convention is an international treaty designed to protect the marine environment from pollution caused by dumping materials into the ocean. The Article III b ii) of the London Convention states: "Dumping" does not include: Placement of matter for a purpose other than the mere disposal thereof, provided that such placement is not contrary to the aims of this Convention". In addition, if nutrient additions are considered for fertilisation, the Ocean Fertilisation Assessment Framework should be considered (Boettcher et al., 2019).

Global collaboration to restore and recover natural seaweed ecosystems should include national and international policies to preserve and monitor seaweed ecosystems that can be stimulated regardless of their potential carbon sequestration. Quantitative information on the provision of ecosystem services and associated co-benefits for social development with seaweed aquaculture or restoration can provide compelling justification for restoration and protection of both habitat and sink sites, as in other blue carbon ecosystems (Vanderklift et al., 2019). Where seaweeds cross transnational boundaries, collaboration among nations will be important, as with the Great Atlantic *Sargassum* Belt (Bach et al., 2021). Also, if natural deposition of seaweed at carbon sink sites are at risk from trawling in international waters, some of these carbon stocks could potentially be released during trawling, or conversely, be protected by trawling bans (Legge et al., 2020), and international agreements on seabed management would be required.

As seaweed ecosystems are often spatially disconnected from carbon sinks, it will make policy difficult to develop as sinking sites are likely to be outside the Economic Exclusive Zone (EEZ) or jurisdiction of the zone

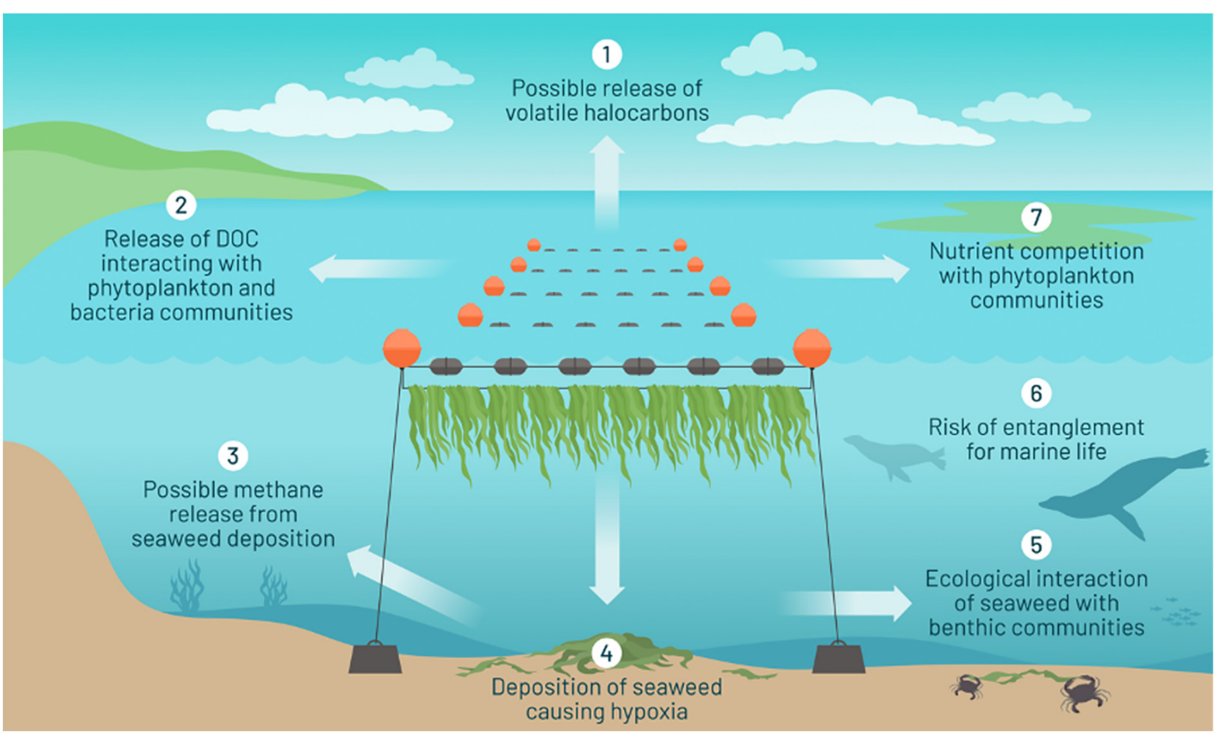

Fig. 4. Potential risks from increasing extent of seaweed aquaculture for carbon sequestration. 1. Possible release of volatile halocarbons; 2. Release of DOC interacting with phytoplankton and bacteria communities; 3. Possible Methane release from seaweed deposition; 4. Deposition of seaweed causing hypoxia; 5. Ecological interaction of seaweed with benthic communities; 6. Risk of entanglement for marine life; and 7. Nutrient competition with phytoplankton communities.

where the carbon project originated. Hence, key next steps are to determine if seaweed carbon is stored within the countries' EEZs, and how such storage impacts the contributions to national GHG inventories. This requires a policy that enables accounting for blue carbon outside of blue carbon project boundaries (remote sequestration), as well as mechanisms in place to prevent double counting of sequestration. An international approach to managing sink sites would need to fall outside the jurisdiction of a country or within Exclusive Economic Zones, thereby including the open ocean which is usually not managed or owned by any country. This will also apply to the OC exported from other blue carbon ecosystems (e.g. mangroves, tidal marshes and seagrasses), which is also not considered by current global blue carbon methodologies (Emmer et al., 2015).

Some countries may have a greater interest in global seaweed carbon policy because they have extensive seaweed forests. Similarly, some countries may have a greater interest given their large seaweed aquaculture industry, or plans to develop such industry - which to date is at an embryonic stage in the global north. This may determine which countries are more motivated to advance the importance of seaweed for climate change mitigation at the United Nations Framework Convention on Climate Change. While detection and attribution of restoration of carbon sequestration to management action is currently challenging, there are many reasons to restore seaweed forests and promote seaweed aquaculture other than just blue carbon, including biodiversity and fisheries benefits (Claisse et al., 2013; Layton et al., 2020; Hynes et al., 2021), along with contributions to many United Nations Sustainable Development Goals (Duarte et al., 2021). Carbon sequestration should, therefore, be treated as a co-benefit from seaweed restoration rather than the primary driver of the expansion of this industry. The carbon crediting market in place, however, can incentivize large scale uptake of seaweed for climate change mitigation.

10. Next steps in the science of seaweed as a means to counteract climate change

Industries and governments are increasingly being compelled to find strategies for climate change mitigation, and seaweed will continue to be considered as one of the potential climate change mitigation solutions. However, seaweed carbon accounting remains poorly developed (Hurd et al., 2022) and is more complex than accounting of terrestrial carbon sinks and other vegetated blue carbon sinks (seagrass, mangroves and tidal marshes). Such established blue carbon systems have standardised methodologies to document carbon sequestration (Emmer et al., 2015), whereas similar methodologies are not in place for seaweed projects. This lack of methodologies is due to fundamental knowledge gaps of fluxes and sinks, limited projects that have demonstrated carbon sequestration and CO_2 influx in response to a particular activity (restoration, seaweed aquaculture), and the lack of effective monitoring and evaluation techniques.

Based on the science and policy knowledge gaps reported in this paper and summarised in Box 2, activities linked to seaweed forest restoration, the export of carbon offshore from seaweed farms during the farming process, or deliberately sinking seaweed, do not appear to be ready to be implemented for climate change mitigation. However, there are many social and environmental reasons why both restoration of seaweed forests and expansion of seaweed aquaculture should be encouraged, regardless of carbon sequestration (Chung et al., 2017; Duarte et al., 2021; Filbee-Dexter et al., 2022). Emission abatement from seaweed products remains a promising way for seaweed aquaculture to reduce industrial emissions, as proven by the methane-reducing seaweed *Asparagopsis*. Defining the environmental and social impact of seaweed products compared to terrestrial alternatives is an important next step in unlocking seaweed aquaculture for climate change mitigation. Finally, investment is now needed to accurately quantify carbon sequestration that occurs below seaweed farms using forensic carbon accounting (Hurd et al., 2022), and subsequently accurately determine the scalability of this solution. Overall, seaweed shows promise for climate change mitigation, however caution should be given to ensure the interest from industry groups and governments in seaweed for climate change mitigation does not outpace the science.

CRediT authorship contribution statement

The idea for the manuscript was conceived by FR, PM and PT. FR organised and directed the writing of the manuscript. All other authors contributed to the writing and editing of the manuscript.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

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