



Review

Carbon removal and climate change mitigation by seaweed farming: A state of knowledge review



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HIGHLIGHTS

- Seaweed farming can contribute to climate change mitigation through several pathways.
- Not all pathways may be able to be readily integrated within carbon accounting frameworks.
- A first estimate of the current carbon sequestration capacity of global seaweed farms is presented.
- Farming emissions may currently entirely offset any CDR.

GRAPHICAL ABSTRACT

Intervention	Mitigation potential	Accountability	MRV simplicity	Technical feasibility	Profitability	Regulatory readiness	Co-Benefits	Disbenefits
Expansion of coastal aquaculture	Medium-High	Medium	Medium-Low	High	Medium-High	Medium	Medium-Low	Low
Expansion of offshore aquaculture	High	Medium	Medium-Low	Medium-High	Medium	Medium-Low	Medium	Low
Increases in sequestration efficiency	Medium-Low	Medium	Medium-High	High	Medium	Medium-Low	Medium	Low
Replacement of carbon-intensive products	Medium-Low	Medium	Medium-High	High	Medium	Medium-Low	Medium	Low

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ABSTRACT

The pressing need to mitigate the effects of climate change is driving the development of novel approaches for carbon dioxide removal (CDR) from the atmosphere, with the ocean playing a central role in the portfolio of solutions. The expansion of seaweed farming is increasingly considered as one of the potential CDR avenues among government and private sectors. Yet, comprehensive assessments examining whether farming can lead to tangible climate change mitigation remain limited. Here we examine the results of over 100 publications to synthesize evidence regarding the CDR capacity of seaweed farms and review the different interventions through which an expansion of seaweed farming may contribute to climate change mitigation. We find that presently, the majority of the carbon fixed by seaweeds is stored in short-term carbon reservoirs (e.g., seaweed products) and that only a minority of the carbon ends up in long-term reservoirs that are likely to fit within existing international accounting frameworks (e.g., marine sediments). Additionally, the tiny global area cultivated to date (0.06 % of the estimated wild seaweed extent) limits the global role of seaweed farming in climate change mitigation in the present and mid-term future. A first-order estimate using the best available data suggests that, at present, even in a low emissions scenario, any carbon removal capacity provided by seaweed farms globally is likely to be offset by their emissions (median global balance net emitter: $-0.11 \text{ Tg C yr}^{-1}$; range -2.07 – $1.95 \text{ Tg C yr}^{-1}$), as most of a seaweed farms' energy and materials currently depend on fossil fuels. Enhancing any potential CDR though seaweed farming will thus require decarbonizing of supply chains, directing harvested biomass to

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long-term carbon storage products, expanding farming outside traditional cultivation areas, and developing robust models tracing the fate of seaweed carbon. This will present novel scientific (e.g., verifying permanence of seaweed carbon), engineering (e.g., developing farms in wave exposed areas), and economic challenges (e.g., increase market demand, lower costs, decarbonize at scale), many of which are only beginning to be addressed.

1. Introduction

Limiting global warming and its pervasive impacts on Earth's ecosystems and people will require drastic reductions in fossil fuel emissions. Additionally, increases in carbon dioxide removal (CDR) from the atmosphere may be necessary to limit runaway warming and offset emissions of hard-to-abate sectors, at least in the short term (IPCC, 2022). Currently, almost all of the current CDR capacity comes from land-based solutions (Geden et al., 2023). However, the pressing need to mitigate the effects of climate change is pushing the development of novel approaches, with the ocean playing a central role in the portfolio of CDR methods (NASEM, 2021). In recent years, considerable focus has been dedicated to understanding whether seaweed (macroalgae) should be included within that portfolio (NASEM, 2021; Ocean Visions, 2022). That interest is underpinned by seaweed being one of the fastest-growing and most productive autotrophs per area on the planet (Pessarrodona et al., 2022), and the fact that a portion of the carbon that they fix during photosynthesis may get sequestered for atmospherically-relevant periods of time (Hill et al., 2015; Krause-Jensen and Duarte, 2016; Ortega et al., 2019). For instance, some fjord and shelf sediments show continuous seaweed carbon burial over 120 years (Frigstad et al., 2021), whilst seaweed DNA has been found in 350-year-old loch sediments (O'dell, 2022).

Seaweed aquaculture is the fastest-growing food production sector with intense potential to generate products with low carbon footprints for a wide range of applications (e.g., biofuel, fertilizer, livestock feed, hydrocolloids, cosmetics, pharmaceuticals) as well as seafood (Duarte et al., 2022; Jones et al., 2022). The carbon fixed in farmed seaweeds can also be stored in long-term reservoirs, theoretically contributing to CDR in a similar way than natural seaweed beds (Chung et al., 2011; Froehlich et al., 2019; Gao et al., 2022). In addition, certain seaweed products can indirectly lower emissions — but not directly remove atmospheric CO₂ — if they replace other carbon-intensive alternatives (e.g., meat heavy diets, synthetic fertilizers, fossil fuels) (DeAngelo et al., 2023). The idea of cultivating seaweed at large scales to avoid fossil fuel emissions was first trialed in the mid-1970s, where pilot seaweed farms to produce biofuels were funded by the US Government (Ritschard, 1992). In the early 1990s, concerns about rising atmospheric CO₂ levels already led several authors to propose using similar farms for a range of climate mitigation outcomes (Alpert et al., 1992; Orr and Sarmiento, 1992; Ritschard, 1992; Spencer, 1991). Recently however, numerous proposals have emerged to cultivate seaweed exclusively for CDR purposes, leading to significant public and private investment (Chung et al., 2013; Ocean Visions, 2022; Ricart et al., 2022; United States Department of Energy, 2017), as well as widespread attention in the media (Hurd et al., 2022) and the scientific literature (Bach et al., 2021; Gao et al., 2022; NASEM, 2021). Despite this growing attention, whether the industry can provide significant CDR remains highly controversial, largely because the literature is dispersed across fields (e.g., biogeochemistry, agronomy, bioenergy, material science) and remains poorly synthesized. Importantly, a clear assessment linking the scale of seaweed farming operations with its CDR capacity, technical and economic feasibility, and any potential co-benefits or disbenefits is lacking.

Here we aim to fill this knowledge gap by synthesizing evidence of the CDR capacity of seaweed farms. We focus on quantifying the different fluxes underpinning CDR with the best available evidence to date, and reviewing the outstanding barriers (e.g., technical, economic, regulatory) to implement scaling seaweed farming for climate benefits. An in-depth review of the outstanding scientific challenges to accurately

measure and verify carbon fluxes in seaweed systems, as well as the climate impacts of the different stages of seaweed value chains, are outside the scope of this manuscript, as they have been discussed elsewhere (Hurd et al., 2022; Pessarrodona et al., 2023). Our review begins by synthesizing the different pathways through which seaweed farming can contribute to CDR. We then examine the current status of seaweed farming and provide a first-order estimate of the current CDR capacity of seaweed farming globally. We finish by discussing the interventions through which seaweed farming may contribute to mitigate climate change, which largely depend on whether farming can increase the ocean's overall CDR capacity over a natural baseline or contribute to greenhouse gas emission reductions. Our synthesis concludes that whilst seaweed farming is currently not able to combat climate change at scale, it is a key step towards greater sustainability in seafood production.

2. Methods

Literature search. To identify relevant publications in the field, we conducted a search in the Scopus database (accessed 09/12/2023) with the following search terms (seaweed OR macroalga*) AND (farm* OR mariculture OR aquaculture OR IMTA) AND (sequestr* OR CDR OR “blue carbon” OR “carbon storage” OR “carbon sink” OR “carbon footprint” OR “CO₂ sink” OR “afforestation” OR “CO₂ bioremediation” OR “life cycle assessment”). Our search yielded 172 different publications, with additional publications being obtained by following the references of publications outlined in the original search. We then scanned the title and abstract to determine whether they focused on wild seaweed habitats or seaweed aquaculture and its products, with only the latter being included.

Global estimate of the current CDR capacity of seaweed farming. We scanned the list of potentially relevant studies meeting our search criteria to collate information and data on carbon fluxes in seaweed farms (cf. Fig. 1) to compute a first-order estimate of the current net CDR capacity provided by seaweed farming. We assumed that the carbon fixed by seaweed farms eventually led to a direct removal of atmospheric CO₂, and that farming did not displace any natural CDR or enhance natural carbon emissions (see discussion of the all assumptions in “Overview of seaweed farming and its present CDR potential”). For the estimate, we preferentially included data from aquaculture studies, as the conditions wild seaweeds grow in (rocky substrates, mesohaline exposed waters) may not necessarily reflect where most seaweed farming takes place (over soft sediments, moderately hyposaline waters in shallow embayments). Data from commercial seaweed farms at sea, as opposed to hypothetical and research or land-based aquaculture facilities, were also selectively preferred, as they better reflect the present seaweed aquaculture sector. Our net CDR estimate was based on two main terms: the amount atmospheric CO₂ fixed by seaweeds and sequestered in long-term carbon reservoirs (C_{SEQ}), and the CO₂ emissions generated during farming (C_{EMIT}), so that:

$$\text{net CDR capacity} = C_{\text{SEQ}} - C_{\text{EMIT}} \quad (1)$$

To calculate the carbon sequestered (C_{SEQ}), we compiled data on the net carbon fixed by seaweeds during cultivation, the amount of it that is harvested, and the fate of the unharvested carbon. We only included data obtained during a one-year cultivation period and expressed on a per-area basis (i.e. gC m⁻² yr⁻¹). If studies did not provide data in these units, but provided information that enabled their calculation (e.g. size of farm, number of months cultivated during a year), their values were converted. Following a modified model of Krause-Jensen and Duarte

(2016), we considered fixed carbon could be sequestered long-term (C_{SEQ}) in four potential pools so that:

$$C_{SEQ} = C_{DEEP} + C_{PROD} + C_{SED} + C_{RDOC} \quad (2)$$

In our analysis, carbon sequestered via transport and storage to the deep sea (C_{DEEP}) was considered negligible as most of the world's farming occurs within sheltered embayments, which typically have reduced exchange with the open ocean (Liu et al., 2019), and cultivation rafts with seaweed reduce the water exchange rate (Zeng et al., 2015), likely precluding carbon transport away from the farm (Hancke et al., 2021; see "Transport to the deep sea"). Sequestration through conversion to long-lived biomass products (e.g., biochar) (C_{PROD}) was also considered negligible, as currently most of the world's production is used for short-lived products that do not store carbon long-term (Ferdouse et al., 2018; Hwang et al., 2019; Liu et al., 2014). We considered that sequestration occurs when fixed carbon is released as detrital particulate organic carbon (POC) and buried in marine sediments long-term (C_{SED}), or fixed carbon is released as dissolved organic carbon (DOC) a fraction of which resists degradation entering the refractory dissolved organic carbon pool (C_{RDOC}). C_{SED} was calculated as:

$$C_{SED} = C_{POC} \cdot \%_{POC\ LOSS} \cdot \%_{POC\ BURIAL} \quad (3)$$

where C_{POC} is the amount of carbon fixed by farmed seaweeds that is assimilated into POC, $\%_{POC\ LOSS}$ is the percentage of assimilated POC that is lost as detritus before harvesting, and $\%_{POC\ BURIAL}$ is the percentage of detrital POC that is buried in marine sediments. Given that the loss of POC increases with the amount of time crops are left unharvested (Hancke et al., 2021; Zhang et al., 2012), we considered farmers would optimize harvest time to minimize biomass losses and maximize profits, thus choosing the lowest value of $\%_{POC\ LOSS}$ reported within each study. C_{RDOC} was calculated as:

$$C_{RDOC} = C_{FIX} \cdot \%_{DOC} \cdot \%_{RDOC} + C_{POC} \cdot \%_{POC\ LOSS} \cdot \%_{POC-RDOC} \quad (4)$$

where C_{FIX} is the carbon fixed by farmed seaweeds, $\%_{DOC}$ is the percentage of this carbon that is released as DOC, $\%_{RDOC}$ is the percentage of DOC that is refractory and $\%_{POC-RDOC}$ is the percentage of lost POC that turns into refractory DOC. In both instances, C_{POC} was calculated as

$$C_{POC} = \frac{\text{Harvested POC}}{1 - \%_{POC\ LOSS}}, \text{ whilst } C_{FIX} \text{ was calculated as } C_{FIX} = \frac{C_{POC}}{1 - \%_{DOC}}.$$

In the case of CO_2 emissions generated during farming (C_{EMIT}) we only included emissions incurred during the cultivation of a given mass of seaweed stock (cradle-to-gate emissions), which included emissions from the hatchery and at-sea operations, but not those to preserve the biomass or dispose of it (i.e. cradle-to-grave emissions). As a result, to be included in our calculations, emissions had to be expressed based on the production of fresh, dry or carbon mass of seaweed (i.e. kg CO_2 emitted per g of seaweed), or provide information that enabled calculation in this units. All data were standardized to a carbon mass basis (i.e. CO_2 emitted per g C of seaweed) using conversion factors provided by the studies or using the conversion factors from Brey et al. (2010), with CO_2 ultimately being converted to carbon mass using its molar mass.

In this way, for a given value of harvested carbon biomass, we could calculate the amount of carbon that ended up sequestered long-term (C_{SEQ}) and the amount of carbon emitted during its production (C_{EMIT}). The balance between the two was equal to the per-area net CDR capacity, with positive values indicating net carbon removal and negative values indicating net carbon emissions. To estimate the current potential CDR capacity of all farms globally, this net (per-area) CDR value was multiplied by the estimate of total area of seaweed farms obtained from the literature. We then combined the literature values compiled (Table 1) with a Monte Carlo approach to derive a crude estimate of the potential contribution of seaweed farming to global carbon sequestration and its uncertainty. For each term in Table 1 and Eqs. (1)-(4), 10,000 randomly generated values were obtained by sampling randomly from a uniform distribution with the minimum and maximum values obtained from the literature. This distribution was chosen as in many cases there was only a minimum and maximum value available in the literature. Individual estimates of the sequestration, emissions and balance were calculated by combining each of the 10,000 simulated values, yielding 10,000 estimates that combined the uncertainty in each parameter. The median, mean, and standard deviation were then retrieved.

We tested two additional scenarios to explore possible optimization strategies to increase the global CDR capacity of seaweed farms. In the first alternative scenario, the crop was left untouched to increase carbon sequestration under seaweed farms, so that $\%_{POC\ LOSS} = 100$. In the

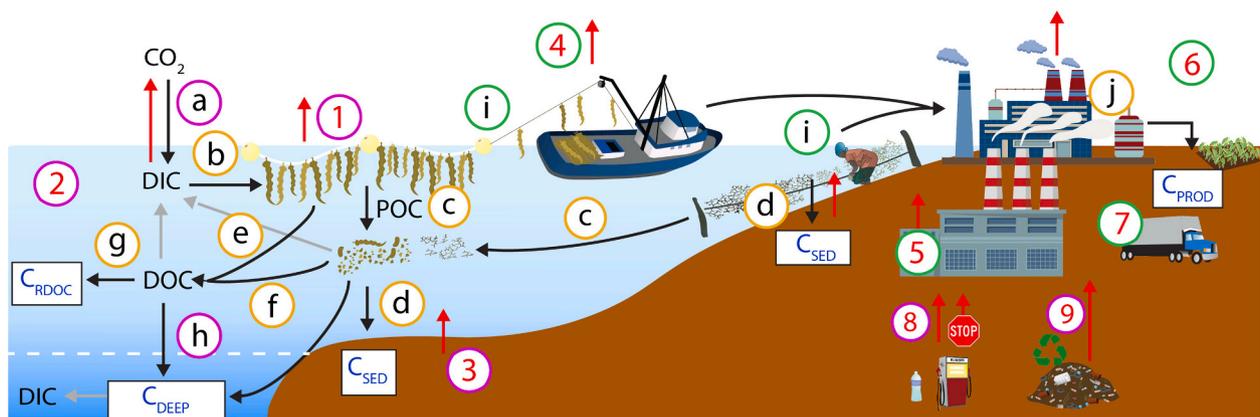


Fig. 1. Schematic representation of the carbon cycle in seaweed farming. Black arrows denote carbon flows leading to sequestration, grey arrows denote remineralization of organic carbon, and red arrows denote emissions. Similarly, red numbers denote fluxes leading to carbon emissions (C_{EMIT}), whilst black letters denote fluxes leading to carbon sequestration (C_{SEQ}), with long-term carbon reservoirs being shown in blue text. Circles around the numbers and letters denote the relative simplicity to estimate the fluxes, reflecting the availability of data (green: easy; yellow: moderate; purple: hard). The following fluxes are denoted: (a) air-sea flux of CO_2 , (b) carbon fixation by seaweeds (C_{FIX}), (c) loss of particulate organic carbon (POC LOSS) before harvesting, (d) burial of POC in marine sediments (C_{SED}), (e) release of dissolved organic carbon (DOC), (f) transformation of POC to DOC, (g) transformation of DOC to refractory DOC (C_{RDOC}), (h) transport of POC and DOC to the ocean interior (C_{DEEP}), (i) harvested POC, and (j) long-term storage of carbon in seaweed products (C_{PROD}). The following emissions are denoted (red numbers): (1) release of GHGs by seaweeds (e.g. halocarbons); (2) change in carbon sequestration due to farming; (3) GHG emissions from enhanced burial of OC (e.g. methanogenesis); (4) maintenance and harvest emissions, (5) emissions from farm material manufacturing and hatchery facilities, (6) emissions from processing seaweed into products, (7) transport and distribution emissions; (8) product use emissions or emission avoidance; (9) post product use emissions. Note that the emissions and carbon emissions and pathways are likely to differ depending on whether seaweed farms are in shallow water (e.g. Indonesia) or suspended in the water column (e.g. China).

Table 1
Details of the data used in the uncertainty propagation analysis.

	Min	Max	References
Harvested POC (kg C·m ⁻² ·yr ⁻¹)	300	1400	Supplementary data
POC loss rate (%POC _{LOSS})	8	45	Table 2
POC RDOC transformation rate (%POC-RDOC)	0.3	0.12	(Feng et al., 2022; Zhang et al., 2023)
POC burial rate (%POC _{BURIAL})	4	9	(Queirós et al., 2019)
DOC rate (%DOC)	15	39	(Chen et al., 2020a; Gao et al., 2021)
Percentage RDOC (%RDOC)	5	58	(Gao et al., 2021; Li et al., 2018; M. Zhang et al., 2022a)
Emissions (kg CO ₂ -eq·Mg C produced ⁻¹)	159	4472	Table 4
Macroalgae area (km ²)	1369	4000	Table 5

second alternative scenario, we used emission values from farms cultivating *Saccharina japonica* and *Kappaphycus alvarezzi*, which tend to have lower carbon footprints when compared to the typically small-scale farms of Europe and America and constituted a 39 % emission reduction in our calculations (i.e. maximum emissions value 1,742 CO₂-eq Mg C produced⁻¹).

3. CDR capacity of seaweed farms

Unlike natural seaweed beds, the CDR capacity of seaweed farming depends on the balance between any atmospheric CO₂ that may be sequestered by seaweeds (C_{SEQ}; Fig. 1, processes d, g, h, j) and the additional CO₂ emitted during the farming supply chain and at sea operations (C_{EMIT}; Fig. 1, processes 4-9) (Coleman et al., 2022; Hasselström and Thomas, 2022). Additionally, the net CDR effect will also depend on whether seaweed farming enhances natural greenhouse gas (GHG) emissions (Fig. 1, processes 1-2) or displaces any naturally occurring CDR in the environment seaweeds are farmed in, such as CDR by phytoplankton or seagrass (Bach et al., 2021; Duarte Moreno et al., 2021) (Fig. 1, process 3). This section briefly discusses well-established pathways through which farming could lead to carbon sequestration, and whether these can be accounted for in existing carbon accounting methodologies. Other pathways, such as the permanent reduction of metabolic products formed via alkalinity production have been proposed, but remain poorly understood in seaweed systems (Perkins et al., 2022; Reithmaier et al., 2021). We also explore the potential sources of carbon emissions arising through seaweed farming. We focus on emissions and removals of CO₂ rather than other GHGs like methane, nitrous oxide or halocarbons because their removal/emissions are only beginning to be understood (Hasselström and Thomas, 2022; Roth et al., 2023).

3.1. Carbon sequestration

For atmospheric CO₂ to be sequestered, the carbon fixed from the water column by seaweeds first needs to remove CO₂ from the atmosphere (Fig. 1, process a). As seaweeds fix carbon from the water, the water around the farm will become depleted of carbon, leading to a CO₂ air-sea flux that is strongly related to seaweed growth (Han et al., 2021; Jiang et al., 2013; Xiao et al., 2021). For a true 1:1 ratio between the carbon fixed by farmed seaweeds and the CO₂ removed from the atmosphere however, waters with a CO₂-deficit need to be completely replenished before losing contact with the atmosphere (Bach et al., 2023). This condition may be relatively easily satisfied along the coast and estuarine embayments where most seaweed farming currently takes place, as re-equilibration times there are typically short (days to weeks) (Akhand et al., 2021; Van Dam et al., 2018). In contrast, re-equilibration times are substantially longer (months to years) in open waters (Jones

et al., 2014), and can be longer than the residence times that water masses are in contact with the atmosphere (Bach et al., 2021). A useful first step to calculate the CDR capacity of seaweed farms may be then to evaluate the risk of incomplete CO₂ equilibration, and adjusting it accordingly (Bach et al., 2023).

CDR also requires some of the carbon fixed by seaweeds to be ultimately transported and stored in a carbon reservoir away from the atmosphere for periods of time long enough to affect the climate system (typically defined as >100 years; (UNFCCC, 2022)). These long-term reservoirs are namely the pool of refractory dissolved organic carbon (C_{RDOC}), the pool of particulate organic carbon stored within marine sediments (C_{SED}), and/or carbon in any form transported to water masses with low exchange rates with the atmosphere, such as those of many deep-sea areas below 1000 m (C_{DEEP}; Siegel et al., 2021). The carbon assimilated into biomass that is harvested will not directly contribute to CDR unless it is stored in a long-term reservoir (e.g., bio-char) (C_{PROD}). Substituting products with carbon intensive footprints (e.g., fertilizer, plastics, fuel, food) with replacement products made from seaweed biomass can however contribute to climate change mitigation if the greenhouse gas emissions of seaweed products are lower than the products they replace (i.e. leading to emission avoidance; Poore and Nemecek, 2018; Vijn et al., 2020; Laurens et al., 2020; Singh et al., 2018). This will require thorough accounting of the emissions of seaweed products and their alternatives throughout their whole life cycle. Currently, the widespread adoption of seaweed-based products faces several technical and legislative challenges affecting their scalability and economic performance, but these are reviewed elsewhere (Yong et al., 2022).

3.1.1. Refractory dissolved organic carbon

Around one third of the carbon fixed by commonly cultivated seaweed species is released as DOC (Chen et al., 2020a; Gao et al., 2021). Cultured seaweed are important sources of DOC to coastal waters, where they can increase the DOC concentration by 20-40 % compared to reference sites (Li et al., 2022; Mahmood et al., 2017). This contribution can far exceed those from phytoplankton in intensively cultivated areas (Gao et al., 2021), but is highly dependent on the life-cycle of the species cultivated and the timing of seeding and harvesting (Chen et al., 2020b; Li et al., 2018). A range of studies have identified numerous refractory components (e.g., phlorotannins, fucans, xylans, long-chain lipids, sulfated-polysaccharides) in the DOC from cultivated seaweed that can avoid degradation or undergo slow decomposition over years, decades, or millennia, constituting a potential long-term carbon reservoir known as refractory DOC (RDOC). Estimates of the RDOC fraction from cultured seaweeds vary between 5 and 56 % of the total DOC (Gao et al., 2021; Li et al., 2018; Zhang et al., 2022a), albeit the methodology to determine that fraction varies between studies (for a discussion see Pessarrodona et al., 2023). A minor fraction (0.3-1.2 %) of the carbon lost as detrital POC may also be transformed into RDOC (Feng et al., 2022; Zhang et al., 2023). The production of RDOC by seaweed thus represents a potentially important pathway of CDR (Buck-Wiese et al., 2022; Krause-Jensen and Duarte, 2016; Reithmaier et al., 2021; Zhang et al., 2023). Critically, this pathway cannot be currently accounted for in any of the international climate mitigation policy and finance frameworks (IPCC Task Force on National Greenhouse Gas Inventories, 2014; Needelman et al., 2018).

3.1.2. Burial of POC in sediments

Before being harvested, a portion of the carbon assimilated into seaweed biomass is usually lost due to erosion of distal tissue, breakage of seaweed parts (e.g., blades), or the loss of entire individuals (Dolliver and Connor, 2022)—collectively termed POC. In kelp farms, the amount of carbon biomass lost has been found to vary from 63 to 460 g C m⁻² yr⁻¹, constituting between 8 and 61 % of the total carbon assimilated into biomass (Table 2). Estimates from other farmed seaweeds are largely lacking, but are likely high as losses of entire individuals are

Table 2

Estimates of the biomass lost as particulate organic carbon (POC) during cultivation of seaweed. Minimum values correspond to harvesting at optimum times (i.e., when there are relatively low losses and high biomass), whilst the maximum values correspond to harvests later in the season.

Location	Species	POC loss (g C m ⁻² yr ⁻¹)	Component measured	Reference
Trøndelag, Norway	<i>Saccharina latissima</i>	63-390 (8-50 %)	Erosion	(Hancke et al., 2021)
Troms, Norway	<i>Saccharina latissima</i>	88 (13 %)	Erosion	(Hancke et al., 2021)
Sungou Bay, China	<i>Saccharina japonica</i>	300-460 (45-61 %)	Erosion	(Zhang et al., 2012)
Strangford Lough, Ireland	<i>Saccharina latissima</i>	(43 %)	Dislodgment, Erosion, Exudation	(Dolliver and Connor, 2022)
Otsuchi Bay, Japan	<i>Undaria pinnatifida</i>	(19 %)	Erosion	(Yoshikawa et al., 2001)

common, particularly during months of stronger water currents and wave action (Reis et al., 2009; Sobuj et al., 2023). Whilst the majority of biomass lost from cultivation sites will be decomposed and remineralized back to CO₂ by microbial respiration (Zhang et al., 2023), a fraction can end up buried in marine sediments, where it may be stored long term. Overall, burial rates will depend on the amount of carbon fixed by farmed seaweed (which will depend on farm size, production, and species), local sedimentary conditions, and factors affecting transport to long-term reservoirs (e.g., depth, hydrodynamic conditions). For instance, carbon burial rates can be highly seasonal depending on the life-cycle of the species cultivated and harvesting times (Broch et al., 2022; Cai et al., 2003). Seaweed and abalone farms have been found to increase organic carbon burial in sediments (Liu et al., 2015; Pan et al., 2021), with seaweed burial intensity being related to the proximity to the farm (Pan et al., 2019) and the magnitude of production (Wang et al., 2023b). The relative contribution of seaweed to total sedimentary carbon burial is however highly variable (Table 3), which may suggest that the incorporation of seaweed into sediments varies seasonally and yearly as well as according to its state (fresh versus degraded; Ren et al., 2014).

The fraction of the buried seaweed carbon that remains sequestered long-term is still largely unresolved, as most studies have examined burial in shallow sediments (Table 3), where sediment is often highly mixed (Pan et al., 2021; Wang et al., 2023b). Assessing long-term sequestration in sediments requires dating of sediment cores, which is typically expensive and logistically complex. Studies conducted in adjacent areas have reported contrasting findings. Liu et al. (2015) reported that the total organic carbon burial rate did not increase following development of aquaculture in Sanggou Bay (China), with the highest values being recorded prior. In contrast, Pan et al. (2021)

suggested that sediments showed an increase in organic carbon after kelp and abalone farming developed in Ailian Bay, <15 km from Sanggou Bay. These contrasting results are surprising given the proximity of the cores, the fact that Ren et al. (2014) found little contribution of degrading detritus in the sediments of Ailian Bay, and that production of kelp and shellfish in Sanggou Bay is several orders of magnitude higher than that of Ailian Bay. More evidence is thus needed to link seaweed farming with permanent carbon removal, as well as understanding its drivers. Despite these important uncertainties, carbon buried in the vicinity of farms seems to fit well within existing carbon accounting frameworks (Vanderklift et al., 2022), as sources and sinks can be more easily monitored, verified, and linked to a specific farming operation. Developing model-based approaches to estimate CDR robustly but simply has been useful in other ecosystems (Lovelock et al., 2022a, 2022b), and may be particularly promising for seaweed given the complexity of its carbon flows (Hurd et al., 2022).

3.1.3. Transport to the deep sea

Transport and storage of DOC or POC in the “deep sea”, where water masses typically take long periods of time to exchange carbon with the atmosphere, is an important sequestration pathway in wild seaweed ecosystems (Pessarrodona et al., 2023; Braeckman et al., 2019; Krause-Jensen and Duarte, 2016; Ortega et al., 2019). Evidence so far suggests that most of the carbon fixed in conventional seaweed farms is deposited and remineralized near cultivation sites, suggesting this pathway may be less important. Using transport models and in situ observations, it was estimated that POC from Norwegian kelp farms deposited within a 10 km radius, with 90 % of the material settling within 4 km from the farm (Hancke et al., 2021). A farm producing 100 t of fresh weight (FW) per hectare was therefore expected to deposit between a few mg up to 25 g C m⁻² yr⁻¹ on the sediment surface, with quantities >1 g C m⁻² yr⁻¹ occurring within 1 km of the farm (Hancke et al., 2021). Using stable isotopes, Pan et al. (2019) documented that kelp organic carbon was present in the sediments of sites approximately 10 km offshore from the farming area. Sediments directly below farms however had relatively higher concentrations of kelp, further suggesting that the carbon exported from farms is mostly retained locally (Pan et al., 2019). From a carbon accounting perspective, carbon sequestered in the high seas or outside of national jurisdictions (e.g., outside Exclusive Economic Zones; EEZs) cannot currently contribute to national GHG inventories or GHG reduction targets (Gitarskiy, 2019; Sutton-Grier and Howard, 2018). Deep ocean carbon sinks are currently not accounted for in national greenhouse gas inventories (IPCC Task Force on National Greenhouse Gas Inventories, 2014), but carbon transported to the deep sea may be accounted in voluntary carbon markets. No approved methodologies to do so are available by the major carbon crediting organizations (e.g., Verra, GoldStandard) to date.

Table 3

Estimates of the biomass particulate organic carbon burial in sediments under seaweed farms, and their relative contribution to total burial in sediments. When available, values are expressed as mean ± standard error, with ranges indicated in parenthesis.

Location	Cultivated species or genus	Sediment depth sampled (cm)	Biomarker	Burial (g C m ⁻² yr ⁻¹)	Relative contribution (%)	Reference
Sansha Bay, China	<i>Saccharina</i> , <i>Gracilaria</i> , <i>Porphyra</i>	3	C:N ratio, δ ¹³ C	25 ± 14	16 ± 9	(Wang et al., 2023a)
Sansha Bay, China	<i>Saccharina</i> , <i>Gracilaria</i>	22	C:N ratio	71 ± 32	23 ± 7 ^a 53 ± 8 ^b	(Wang et al., 2023b)
Sanggou Bay, China	<i>Saccharina</i>	0-5	C:N ratio, δ ¹³ C		15.3 ± 6.63	(Pan et al., 2019)
Sanggou Bay, China	<i>Saccharina</i>	0-2	δ ¹³ C		36.6 (20.1-86.5)	(Sui et al., 2019)
Ailian Bay, China	<i>Saccharina latissima</i> , scallops	0-3	δ ¹³ C		(1.1-1.6)	(Ren et al., 2014)

^a 1963-1990.

^b 1990-2022.

3.1.4. Long-term storage in seaweed products

On its own, the carbon stored in harvested seaweed biomass cannot be considered “sequestered” (Zhang et al., 2017), as the range of products seaweed is used for (e.g., food, biofuel) have very short lifespans, and its carbon will eventually return to the atmosphere through respiration or combustion (Hurd et al., 2022). Around 80 % of the production is presently used for human consumption (Ferdouse et al., 2018; Hwang et al., 2019; Liu et al., 2014), including the production of the hydrocolloids agar (e.g., *Gracilaria* spp.), alginate (e.g., *Saccharina* spp., *Lessonia* spp.) and carrageenan (e.g., *Eucheuma* spp. and *Kappaphycus alvarezii*) (McHugh, 2003), and therefore does not contribute to carbon sequestration. Carbon stored in biomass can however be bound into long-lived products such as biochar, a fertilizer produced from the pyrolysis of seaweed biomass whose stable and recalcitrant carbon may be stored for hundreds of years when applied to the soil (Sun et al., 2022). Additionally, some of the CO₂ emitted during the biomass digestion and pyrolysis of certain industrial processes (e.g., biofuel production) can be captured and stored underground, although the deployment of such technology remains severely limited.

3.2. Carbon emissions

Emissions generated by seaweed farming can occur during the farming stage at sea, throughout the supply chain for the farming operation (e.g. energy, materials used in the farm) as well as during the use-phase of seaweed products and at the end of their life (e.g. emissions associated with how the product is disposed). Seaweed farming emissions are generally lower and less variable than other types of aquaculture (Jones et al., 2022), with cradle to gate emissions ranging between 3 and 174 kg of CO₂ per metric ton of fresh seaweed produced (Table 4). Farming emissions can substantially offset any carbon sequestered in long-term reservoirs, and must be therefore be thoroughly accounted for. For instance, emissions due to enhanced microbial respiration during the later stages of kelp growth can offset the carbon removed from the atmosphere during early cultivation phases (Xiong et al., 2024), and emissions can offset between 61 and 90 % of the carbon potentially sequestered even in farms designs to optimize seaweed CDR (Coleman et al., 2022; Lian et al., 2023). Despite this, the emissions associated with seaweed farming are often not included in

assessments of the carbon removal and climate change mitigation capacity of seaweed farming (Duarte et al., 2017; Erlania and Nyoman Radiarta, 2015; Froehlich et al., 2019; Sondak et al., 2017; Wu et al., 2020). Life Cycle Assessments, commonly known as LCAs, constitute a powerful tool to quantify the environmental impacts of products or systems during their entire life cycle in a systematic manner, and examine which processes and materials are responsible for the bulk of climate impacts (reviewed in Hasselström and Thomas, 2022). LCAs are typically individually conducted for a specific seaweed product or farming system, and may use different methodological assumptions, data, and system boundaries (e.g. whole life cycle versus at sea and supply chain operations only), making comparisons not always straightforward. Still, most studies to date find that a large portion of seaweed farming emissions arise from energy use (e.g., electricity consumption in the hatchery and boat fuel use during cultivation; Coleman et al., 2022; Lian et al., 2023; Nilsson et al., 2022) and the fabrication of components used in farms (e.g., polyethylene rope, buoys; Li et al., 2023)—all of which still largely rely on fossil fuels (Fig. 1, processes 4-5). Finally, if harvested seaweed biomass is converted into products, there are other emissions associated with the processing (e.g., packaging), use (e.g., transport), and end-of-life (e.g., landfill, compost) phases of the value chain (Hasselström and Thomas, 2022) (Fig. 1, processes 6-9). Storing carbon from harvested seaweed biomass into more permanent forms (e.g., biochar) has also associated emissions, as there are CO₂ losses during the combustion process and this process requires substantial energy inputs (Leung et al., 2014; Wen et al., 2022).

Currently, our understanding of the magnitude of emissions generated throughout the whole life cycle of seaweed farming is hampered by most estimates being from research or pilot-scale farms (but see Li et al., 2023; Lian et al., 2023) and from a few locations using different approaches. As a result, there is considerable variability in the system boundaries considered, the degree of detail in the inventories, and the energy and materials data used (Hasselström and Thomas, 2022). For example, farming a ton of fresh kelp uses between 0.0002-60 kg of diesel and 0.6-11 kg of rope depending on the farm considered (Li et al., 2023 and references therein, Alvarado-Morales et al., 2013; Coleman et al., 2022; Lian et al., 2023). There is currently limited data on the emissions from eucheumatoid (red sea moss) farms, which are responsible for around a third of the world’s production and are farmed using different

Table 4

Estimates of the cradle-to-gate emissions (C_{EMIT}) to produce a metric ton of seaweed biomass. The operations included in the life cycle assessment inventory are the following: SEA: At sea operations; HAT: Hatchery operations; CONS: Hatchery construction. Note emissions from electricity consumed in each study are based on the regional electricity mix, which may vary between locations. ns = not specified. DW:FW = dry weight to fresh weight ratio.

Farmed seaweed	Size (ha)	Scale	Location	C _{EMIT} (kg CO ₂ t FW ⁻¹)	DW:FW	C _{EMIT} (kg CO ₂ t DW ⁻¹)	Inventory	Reference
<i>Alaria esculenta</i>	ns	Commercial	Ireland	14.4	0.100	552.0	SEA, HAT	(Collins et al., 2022)
<i>Asparagopsis taxiformis</i>	ns	Hypothetical	Australia	3.3	0.125	441.6	SEA, HAT	(Ridoutt et al., 2022)
<i>Kappaphycus alvarezii</i>	ns	Commercial	India	3.9	0.110	35.8	SEA ^a	(Ghosh et al., 2015)
<i>Laminaria digitata</i>	ns	Hypothetical	Denmark	24.9	0.209	119.0	SEA, HAT	(Alvarado-Morales et al., 2013)
<i>Laminaria digitata</i>	20,800	Hypothetical	Denmark	83.4	0.148	563.5	SEA, HAT	(Seghetta et al., 2017)
<i>Laminaria digitata</i>	20,800	Hypothetical	Denmark	81.9	0.148	553.4	SEA, HAT	(Seghetta et al., 2016)
<i>Laminaria digitata</i>	1	Hypothetical	Ireland	22.2	0.177	125.5	SEA, HAT	(Czyrnek-Delêtre et al., 2017)
<i>Laminaria digitata</i>	1	Hypothetical	Ireland	24.7	0.197	125.5	SEA, HAT	(Czyrnek-Delêtre et al., 2017)
<i>Saccharina japonica</i>	320	Commercial	China	34.6	0.140	247.2	SEA, HAT	(Lian et al., 2023)
<i>Saccharina japonica</i>	400	Commercial	China	57.5	0.100	574.6	CONS, SEA, HAT	(Li et al., 2023)
<i>Saccharina japonica</i>	1	Hypothetical	Korea	15.1	0.150	100.5	SEA, HAT	(Jung et al., 2017)
<i>Saccharina latissima</i>	20,800	Hypothetical	Denmark	83.4	0.248	336.3	SEA, HAT	(Seghetta et al., 2017)
<i>Saccharina latissima</i>	20,800	Hypothetical	Denmark	81.9	0.248	330.2	SEA, HAT	(Seghetta et al., 2016)
<i>Saccharina latissima</i>	404	Hypothetical	USA	60.1	0.133	451.2	CONS, SEA, HAT	(Coleman et al., 2022)
<i>Saccharina latissima</i>	ns	Commercial	Ireland	160.0	0.105	1200.3	SEA, HAT	(Nilsson et al., 2022)
<i>Saccharina latissima</i>	2	Commercial	Sweden	55.2	0.155	356.1	SEA, HAT	(Thomas et al., 2021)
<i>Saccharina latissima</i>	1	Commercial	Denmark	86.1	0.081	1063.4	SEA, HAT	(Zhang et al., 2022b)
<i>Saccharina latissima</i>	1	Commercial	Denmark	123.5	0.221	558.7	SEA, HAT	(Zhang et al., 2022a, 2022b)
<i>Saccharina latissima</i>	1	Commercial	Denmark	173.9	0.135	1287.9	SEA, HAT	(Zhang et al., 2022a, 2022b)

infrastructure. Data from Chinese and other Asian farms may be considered as a proxy for a low emissions scenario, as high competition in that area demands highly efficient production, energy use, and therefore lower emissions per kg of seaweed produced (Li et al., 2023, Lian et al., 2023); values from Europe or North America on the other hand may represent a higher emissions efficiency scenario (Table 4). However, as 97.4 % of seaweed farming production comes from Asia, compared to 0.8 % from Europe and 1.4 % from North America (FAO, 2018), this low emission scenario is likely the most representative of current global emissions. Following standardized accounting frameworks (e.g., LCAs; Hasselström and Thomas, 2022), agreeing on system boundaries, and using data from industry-scale farming operations is a promising way to better understand the emissions generated by farming practices, and their offset of any potential CDR capacity. Nevertheless, it is clear that decarbonizing supply chains, powering facilities and operations with renewable energy, and using farming materials with low GHG footprints is the way forward to drastically reduce the emissions associated with farming. For instance, sourcing electricity for the nursery stage from renewable energy would reduce farming emissions by 8–10 % (Coleman et al., 2022), whilst using buoys and ropes made from recycled plastic and recycling them after use would reduce the emissions of a large-scale farm by 40 % (Li et al., 2023).

3.3. Life cycle perspective on GHG emissions

Besides CO₂ emissions, aquaculture activities can also result in the release of other greenhouse gases such as methane, nitrous oxide, or halocarbons (Fig. 1, processes 1,3). Methane emissions in coastal environments largely result from anaerobic methanogenesis during the degradation of organic matter in sediments (Rosentreter et al., 2018; Roth et al., 2023). Unlike wild seaweed ecosystems, which grow on rocks, most seaweeds are cultivated over sediments in near eutrophic and meso- and hyposaline waters, all of which facilitate methanogenesis (Rosentreter et al., 2021). It is therefore possible that excess input of organic matter under farms will lead to conditions prone to methanogenesis, as it is often the case in animal aquaculture farms (Liu et al., 2023). Like phytoplankton, seaweed have been found to emit volatile very short-lived brominated halocarbons (see Keng et al., 2020 for a review). These compounds are involved in the catalytic destruction of ozone in the stratosphere and may contribute to climate change due to alterations in atmospheric circulation patterns and cloud formation. This observation has opened the debate on whether wild and cultivated seaweed could play a role in exacerbating climate change (Leedham et al., 2013; Mithoo-Singh et al., 2017; Phang et al., 2015), particularly in tropical regions, which transport large quantities of halogenated compounds to the stratosphere due to deep convection (Phang et al., 2015). Extrapolations from small-scale experiments on tropical seaweeds in Malaysia suggested that aquaculture is currently a minor contributor to total brominated halocarbon emissions (Leedham et al., 2013), although aquaculture growth could lead to relevant increases in the future. Overall, the contribution of seaweed farming to the release of such gases is still poorly understood, and large uncertainties associated with the lack of spatial and temporal data on seaweed GHG production preclude any conclusions on whether they contribute significantly to climate change (Keng et al., 2020).

4. Overview of seaweed farming and its present CDR potential

Understanding the present status and trends of seaweed farming is necessary to gauge its current CDR capacity, but also the technical and economic feasibility to enhance it in the near- or mid-term future. Global seaweed production has steadily grown at an average yearly rate of 6.5 % since the 2000s, reaching 32 Tg (million tons) of fresh weight in 2018 (FAO, 2018), which translates to almost 1.5 Tg of carbon using group or species-specific fresh-to-dry-weight and dry-to-carbon-weight ratios derived from Brey et al. (2010). Globally, around 221 seaweed species

are of commercial value, but 98 % of the world's cultivated seaweed production is represented by only six genera – *Saccharina*, *Undaria*, *Porphyra*, *Eucheuma*, *Kappaphycus* and *Gracilaria* (Fig. 2A). Production is led by China (57.5 % of the total seaweed farming, producing mostly kelp) and Indonesia (28.5 % producing mostly carageen-containing seaweed, Fig. 2B). It is important to note that global production values are based on Food and Agriculture Organization (FAO) Fisheries and Aquaculture database, which are derived from the numbers provided by each country. Reported “official” volumes can be however multiple times higher than those reported by farmers, traders and exporters in industry (Hatch Innovation Services, 2022; Pratama and Albasri, 2021), given that different calculations frameworks are used. Although not all countries have reported the area under seaweed cultivation, the global areal extent is likely to be under 4000 km², as China, Indonesia and Korea (i.e. 90 % of the world's production) report a cultivated area of 3680 km² (Table 5). Estimates of the total area potentially farmable range from 100,000 to 48,000,000 km² globally (Arzeno-Soltero et al., 2022; Froehlich et al., 2019; Lehahn et al., 2016; N'Yeurt et al., 2012; Wu et al., 2023), being mostly offshore or in open ocean waters. These estimates, however, rarely consider growth limitation by micronutrients (e.g., iron, Paine et al., 2023), nor the economic costs or the logistical and technical feasibility of farming in open waters (Coleman et al., 2022; DeAngelo et al., 2022), and should therefore be considered as overestimates of the actual realizable potential.

Our first-order estimate suggests that currently seaweed farming is a global net emitter (i.e. negative net CDR capacity) at $-0.77 \text{ Tg C yr}^{-1}$ (range -5.65 – $1.80 \text{ Tg C yr}^{-1}$), with carbon sequestration (median $0.35 \text{ Tg C yr}^{-1}$; range 0.01 – $3.18 \text{ Tg C yr}^{-1}$) being entirely offset by farming emissions (median $1.14 \text{ Tg C yr}^{-1}$; range 0.03 – $6.37 \text{ Tg C yr}^{-1}$). POC burial in the vicinity of farms only accounted for $0.04 \text{ Tg C yr}^{-1}$ (range 0.002 – $0.33 \text{ Tg C yr}^{-1}$). This latter value is on par with the 0.14 Tg C estimated to be buried every year as a result of aquaculture (all types) in China, based on the rates of organic matter deposition, the percentage of carbon in surface sediments, and the total farm area (Zhang et al., 2017). It is important to note that seaweed farms are usually anchored on very shallow sediments (e.g., ca 7–10 m depth in China; Fang et al., 2016; Pan et al., 2021) so carbon buried in the surface sediment layers is more likely to be subject to remineralization, precluding long-term burial and sequestration (Liu et al., 2015). In contrast, our estimate suggest that the majority of carbon sequestration from farms is driven by transformation of DOC and POC into RDOC ($0.30 \text{ Tg C yr}^{-1}$; range 0.01 – $2.98 \text{ Tg C yr}^{-1}$). Whilst seaweed RDOC may well constitute a long-term carbon reservoir, this pathway is currently not integrated into any mainstream carbon accounting framework (reviewed in Pessarrodona et al., 2023). If global farming emissions were assumed to reflect those from *Saccharina japonica* and *Kappaphycus alvarezzi* farms, which lie at the lower end of carbon footprints reported in the literature (Table 4, Li et al., 2023), but may represent a more likely scenario emission given these species provide the bulk of the production, the net balance of seaweed farming would be closer to zero but still negative (median $-0.11 \text{ Tg C yr}^{-1}$; range -2.07 – $1.95 \text{ Tg C yr}^{-1}$). This finding suggests that intensive decarbonization and decreases in emissions throughout the value chain will be key ways to increase the net CDR capacity of seaweed farming. Increasing the flux of carbon available to be buried and sequestered under seaweed farms by leaving the crop unharvested only achieved a modest improvement in the net CDR capacity, which remained net negative (median $-0.66 \text{ Tg C yr}^{-1}$; range -5.31 – $2.49 \text{ Tg C yr}^{-1}$). Diverting a fraction of the production to long-term storage products (e.g., biochar) or enhancing the ways seaweed carbon gets naturally sequestered (e.g. by placing farms near areas that favor long-term sequestration) may thus be more promising ways to boost the sequestration capacity of seaweed farms. For example, assuming that producing 1 ton of biochar requires $80 \text{ kW}\cdot\text{h}^{-1}$ of electricity (Lian et al., 2023), an emission factor $0.997 \text{ kg CO}_2\cdot\text{kW}^{-1}\cdot\text{h}$ (Lian et al., 2023), and a biochar yield of 59 % with a mean C_{org} content of 30 % (Lian et al., 2023), diverting 10 % of the world's seaweed production (1.5 Tg C or roughly 5

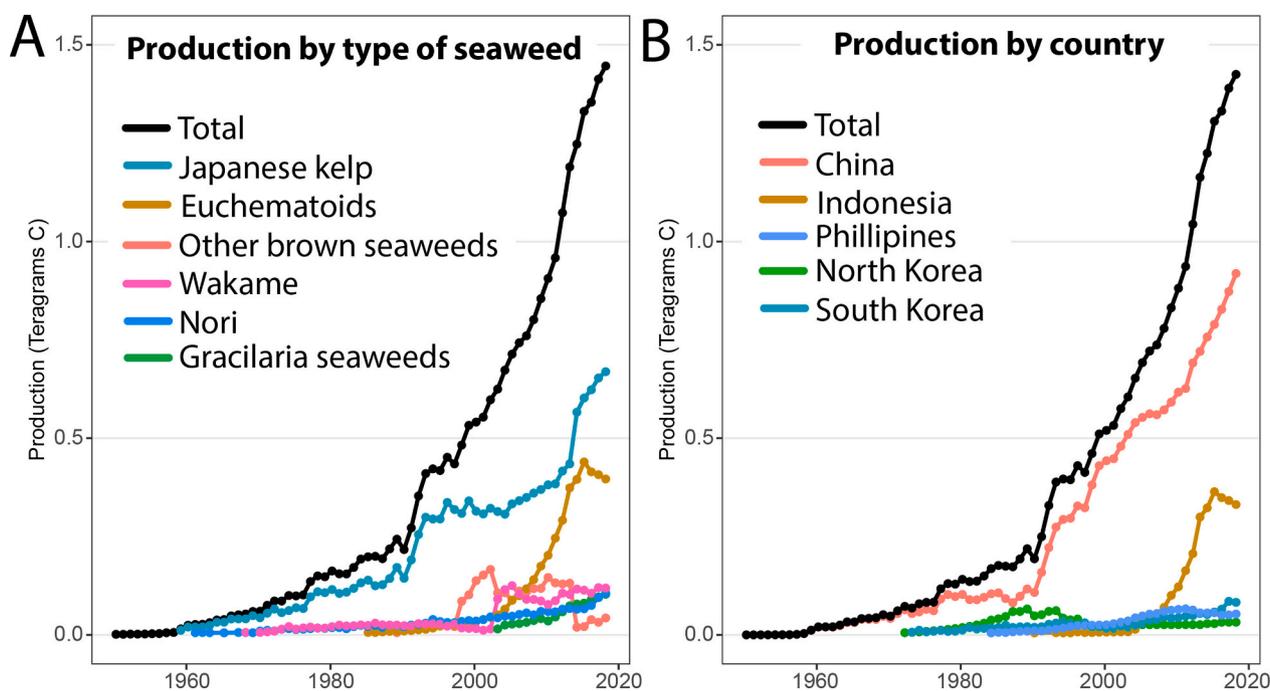


Fig. 2. Seaweed aquaculture production over time by type of seaweed (A) and country (B). Species or countries with a production $< 0.005 \text{ Tg C yr}^{-1}$ are not shown but are accounted for in the total. Raw data source is (FAO, 2018), converted to carbon units using the values from Brey et al. (2010).

Table 5
Area occupied by seaweed farms in several countries.

Country	Species	Year	Area (km ²)	Reference
China	<i>Saccharina japonica</i>	2016	444	China Fishery Statistical Yearbook in (Hwang et al., 2019)
		2017	442	China Fishery Statistical Yearbook in (Fan et al., 2019)
	<i>Pyropia</i> spp.	2013	152	(Li et al., 2008)
		2016	730	(Wu et al., 2017)
	<i>Undaria pinnatifida</i>	2016	73	China Fishery Statistical Yearbook in (Hwang et al., 2019)
	<i>Gracilariopsis lamaneiformis</i>	2016	99	(Hwang et al., 2019)
	<i>Hizikia fusiformis</i>	2016	12	
	<i>Euचेuma denticulatum</i>	2016	4	
Korea	<i>Saccharina japonica</i>	2015	91	(Hwang et al., 2020)
Indonesia	<i>Euचेuma</i> ,	2013	2222	(Zamroni and Yamao, 2011a)
	<i>Kappaphycus</i> ,			
	<i>Gracilaria</i> spp.	2018	2750	(KKP, 2018)

Tg DW) to biochar storage would generate an additional 0.078 Tg of sequestration. Overall, given that most of the 1.5 Tg C harvested in seaweed biomass every year globally is typically destined to short-lived carbon reservoirs, and the current farmed extent represents only 0.06 % of the wild area, any additional CDR capacity from seaweed farms will be several orders of magnitude less than the natural sequestration capacity of wild seaweed habitats (Krause-Jensen and Duarte, 2016).

Although our calculations were grounded on the best available data and provide the most up-to-date estimate of the CDR capacity of seaweed farms to date, our approach was based on multiple assumptions and has several limitations. First, we assumed a 1:1 ratio between the CO₂ fixed by farmed seaweeds and the CO₂ removed from the atmosphere, as most current seaweed aquaculture takes place along the coast and estuarine waters, where re-equilibration times are typically shorter (days to weeks) than the time water masses are in contact with the

atmosphere (Akhand et al., 2021; Van Dam et al., 2018). For instance, the waters of the Yellow Sea where most of Chinese farming takes place are well mixed and show equilibration with the atmosphere during periods of maximum seaweed growth (Zhai, 2018). Secondly, given little available quantitative data, our analysis did not incorporate several pathways that may enhance (e.g. alkalinity production) or decrease the actual CDR efficiency of seaweed farms (e.g., displacement of any natural CDR, production of halocarbons; stimulation of methanogenesis) (Bach et al., 2021; Leedham et al., 2013; Reithmaier et al., 2021). Third, given that we only considered sequestration pathways occurring at sea, we only included emissions incurred during the growing and planting phases at sea and from the farm supply chain (e.g. energy and materials to run the farm). Fourth, emissions associated with farming were modelled as being linearly dependent on the farmed yield, but emissions may vary with the scale of production (Li et al., 2023). Fifth, our analysis and uncertainty propagation sampled from a uniform distribution as in many cases there were only maximum and minimum values available, but data may approximate other distributions as more studies are conducted. Sixth, data for our analysis were mostly available from Chinese farms cultivating kelp (*Saccharina japonica*), and so our analysis assumed that the literature values are representative of seaweed farming all over the world. This is clearly not the case, as farm sizes; cultivation line densities; and yields (and therefore the amount of seaweed biomass per hectare of farm) vary widely across farming operations (Broch et al., 2019) and even seasonally due to local environmental conditions (Langford et al., 2021). Additionally, most of the area farmed globally is destined to non-kelp species (*Pyropia*, *eucheumatoids*, 4), which have lower rates of carbon fixation (Fig. 2). Similarly, seaweeds in other key producing regions such as Indonesia are typically grown nearshore on ropes subject to tidal action, where the export and burial of carbon may be very different than that in floating farms. The sequestration values from the analysis should therefore probably be taken as a best-case scenario. Still, it is worth noting that adjusting the carbon fixation to a more realistic value based on the mean global harvested yield (ca. 350 g C m⁻² yr⁻¹) did not massively change the outcome of the analysis, which was more sensitive to other parameters. Specifically, given that ca. 85 % of the farming CDR was achieved through the DOC pathway, our

analysis was highly sensitive to the percentage of carbon fixed during seaweed photosynthesis that is released as DOC and the fraction that eventually is stored as RDOC, both of which remain poorly constrained. Resolving the contribution of this pathway to total carbon sequestration should thus be a priority for future research.

5. Seaweed farming and climate change mitigation

Although without decarbonization seaweed farming appears to not have the scale to remove globally relevant amounts of CO₂ from the atmosphere in the near- and medium-term future, numerous interventions have been proposed to enhance any potential climate benefits. These interventions may contribute to climate change mitigation by either increasing the CDR capacity achieved with seaweed farming, or by decreasing overall GHG emissions when substituting seaweed-based alternatives into products (e.g., fuel, plastics, food) that have higher carbon footprints. This section briefly explores several of the proposed interventions, and some of the current and future challenges to implement them (Fig. 4). In particular, there are specific ways in which climate benefits get accounted for in international policy and climate finance frameworks (Vanderklift et al., 2022). Inclusion in these schemes requires rigorous measuring, reporting and verification (MRV) of any atmospheric CO₂ removal, and often the satisfaction of a set of criteria (e.g., no disbenefits to the environment). Additionally, interventions may be subject to different legal and regulatory frameworks depending on the location of their operation. Finally, there are several other important considerations (e.g., profitability and technical feasibility) that may restrict the applicability or scalability of seaweed farming or the adoptability of its products.

5.1. Expansion of seaweed farming in the coastal ocean

Expanding seaweed farming would increase the amount of carbon fixed by seaweeds, and potentially enhance the amount of carbon sequestered. The scope for expansion of coastal seaweed aquaculture varies between countries. Forty-seven countries produce seaweed commercially or have done so at some point in time, but global production is led by a handful of nations (Fig. 2B), with China and Indonesia being the dominant producers by far (aggregated production of 28.5 Tg fresh weight; 86 % of the total production). The potential for expansion is somewhat limited among well-established producer countries. Seaweed farming in China is conducted mostly within enclosed or semi-enclosed bays, with most of the area estimated suitable for seaweed farming (ca. 90 %) being already occupied (Wu et al., 2020). Expansion of farming therefore must take place in open, more exposed waters. By contrast, in Indonesia, the Ministry of Marine Affairs and Fisheries estimates that only around 25 % of the potential area for seaweed aquaculture (11,109 km²) is currently occupied (KKP, 2018; Zamroni and Yamao, 2011b). Despite the government's drive to support and expand the seaweed industry, growth in production remains limited. A recurring limiting factor is the increase in outbreaks of diseases (Kambey et al., 2020). Additionally, a complex set of social and market factors dictate the amount of area cultivated beyond environmental suitability (Langford et al., 2022, 2021). Theoretically then, countries with little to no seaweed aquaculture have great potential for expansion, although they may lack the technical knowledge to achieve the large-scale expansions within the short timeframes required to achieve climate change mitigation.

Potential co-benefits of seaweed farming include local reductions in acidification (Xiao et al., 2021) and eutrophication (Fan et al., 2019). Large-scale expansion of seaweed farming may have range of negative impacts on the environment and human well-being, which would have to be considered in most carbon accounting frameworks (Howard et al., 2023). Impacts are typically scale-dependent (Hancke et al., 2021), but include: reduced oxygen levels and increases in methane emissions due increased inputs of organic matter, nutrient depletion in oligotrophic

areas, habitat destruction and the facilitation in the introduction and spread of alien species (Campbell et al., 2019; Hancke et al., 2021; Hu et al., 2021; Kelly et al., 2020; Liu et al., 2023; Zemke-White, 2003). Farms may also increase sediment deposition and reduce light on the seabed (Pan et al., 2019), affecting the biota living below farms. This may be particularly problematic in tropical regions, where farms are often anchored on top of seagrass beds, which can reduce their productivity and carbon sequestration capacity (Kelly et al., 2020).

5.2. Expansion of seaweed farming in the open ocean

Expansion to offshore waters offers promising opportunities to increase carbon sequestration, as nutrient availability is typically higher offshore and farms over deeper habitats may be more conducive to sequestration (Broch et al., 2019; Froehlich et al., 2019). However, seaweed growth in offshore waters may be limited by micronutrients or other factors such as light or temperature (Paine et al., 2023; Pessarrodona et al., 2022). Despite a huge potential area suitable for cultivation (Arzeno-Soltero et al., 2022; DeAngelo et al., 2022; Froehlich et al., 2019; Wu et al., 2023), the success of offshore cultivation remains limited to date, with the majority of the industry currently based in inshore waters (Bak et al., 2020). Recent technical improvements have allowed cultivation systems to withstand large oceanic wave forces in water depths of up to 150 m (Bak et al., 2020; Buck and Buchholz, 2004), but significant challenges remain to make cultivation profitable and feasible (Fig. 4). Currently, revenues are often unable to cover investment and operation costs without increases in yields (Bak et al., 2018; Zuniga-Jara et al., 2016). At present prices, economic incentives resulting from carbon finance are not enough to make cultivating seaweed solely for the purposes of CDR profitable (Firman et al., 2023), with retaining the seaweed biomass (for climate mitigation purposes or not) being by far a more profitable enterprise (Coleman et al., 2022; DeAngelo et al., 2023). There are also important regulatory challenges outstanding, as farming may be subject to a range of international, national, state, and/or local laws and regulations depending on the jurisdictional area where operations occur (Webb et al., 2021). Given that seaweed typically does not naturally occur in offshore waters (with a few notable exceptions), large-scale farming may have negative environmental impacts, including alterations to the ecology and chemistry of offshore ecosystems (Boyd et al., 2022). Finally, there are numerous ethical considerations associated with disposing valuable, nutritional seaweed resources into the deep ocean instead of using to meet other sustainability goals opposed to using them (Ricart et al., 2022).

5.3. Increases in carbon sequestration efficiency

Increases in the potential sequestration efficiency of existing farms can be achieved by enhancing the amount of carbon sequestered per unit area of farm or the amount of carbon sequestered per unit of carbon fixed. For example, enhancements in the amount of carbon fixed by farms can be achieved through the selection of high-productivity cultivars, alleviating factors limiting productivity, or optimizing spacing and the timing of seeding and harvesting (Boderskov et al., 2023). Several high-yield cultivars have been developed through selection, mostly in Asian countries, which have long-established breeding programmes to improve cultivated varieties (Fang et al., 1983; Hu et al., 2021; Hwang et al., 2019; Li et al., 2007). Bred varieties can increase average yield by as much as 75 % compared to natural populations and other established varieties (Li et al., 2008; Liu et al., 2007; Zhang et al., 2007) (Fig. 3), although higher carbon fixation may negatively covary with other traits of interest (e.g. organoleptic properties). Productivity can also be increased by strategically placing farms in areas where potential nutrient uptake rates are higher, such as exposed coasts (Broch et al., 2019; Visch et al., 2020) or near fish farms (Fossberg et al., 2018), or by modifying the cultivation depth (Boderskov et al., 2023; Ganesan et al., 2006). Artificial upwelling of nutrients has been proposed as an

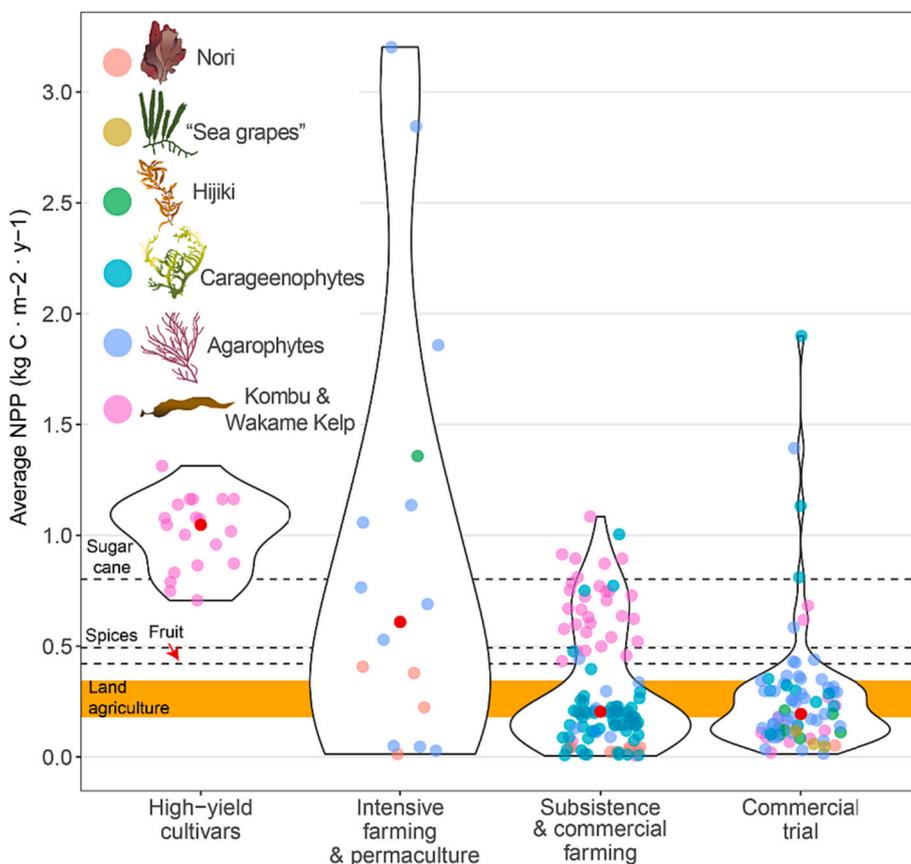


Fig. 3. Carbon fixation rates (net primary productivity, NPP) of the main seaweed aquaculture crops based on their cultivation method. Dashed lines indicate the mean NPP of a few selected highly productive land crops, whilst a yellow rectangle shows the NPP range of most land crops (data from FAO in Goudriaan et al., 2001). Red dots indicate mean values.

approach to increase seaweed carbon uptake rates in areas where nutrients are limiting in China (Fan et al., 2019).

On the other hand, increases in sequestration efficiency may be achieved by increasing the amount of fixed carbon that gets transported and stored in long-term carbon reservoirs. For instance, strategically placing farms in areas with high sedimentation rates (e.g., fjords) that could potentially increase the amount of carbon buried under farms

(Smith et al., 2015), or in offshore deeper waters or nearby hydrodynamic or geomorphological features that serve as conduits to the deep sea (e.g., strong offshore currents, canyons; van der Mheen et al., 2024), may be a way to enhance carbon sequestration. Offshore farming presents however numerous technical and economic challenges that remain mostly unresolved to date (Bak et al., 2020; Coleman et al., 2022).

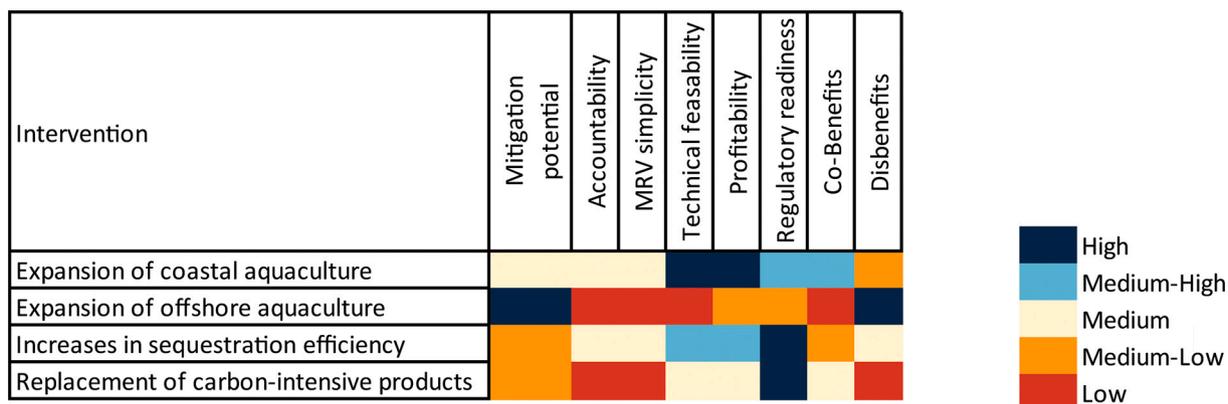


Fig. 4. Assessment of seaweed farming interventions that can potentially contribute to climate change. Scores are based in the calculations presented here and available literature. All criteria refer to current status of knowledge. ‘Mitigation potential’ refers to the overall magnitude of potential mitigation. ‘Accountability’ refers to whether interventions would fit within existing carbon accounting methodologies and frameworks. ‘MRV simplicity’ refers to the complexity to monitor, report and verify GHGs fluxes of each intervention to create credible mitigation. ‘Technical feasibility’ refers to the viability of upscaling the intervention. ‘Profitability’ refers to potential revenues generated based on current market prices. ‘Regulatory readiness’ refers the complexity and cost of obtaining permits to farm within national and international jurisdictions. ‘Co-benefits’ refers to any non-mitigation benefits arising from the intervention (e.g., biodiversity, social uplifting). ‘Disbenefits’ refers to any potential negative impacts resulting from the intervention.

6. Conclusions

Several potential pathways through which seaweed farming can contribute to CDR have been established. These can be broadly divided into carbon removal at sea before biomass is harvested, or the long-term storage of carbon in seaweed products like biochar. Additionally, seaweed products made from the harvested biomass may contribute greenhouse gas emissions avoidance and climate change mitigation if they substitute more carbon-intensive footprints (Fig. 4). Burial of unharvested biomass in the vicinity of farms under suitable sedimentary conditions appears to be the best documented carbon removal pathway, and the one which can be reliably accounted for in existing carbon accounting frameworks. More research is needed, however, to solidify the evidence base linking farming operations to permanent carbon removal. Although seaweed farming has one of the lowest emissions and environmental impacts of any aquaculture product, our first-order estimate suggests that currently farming emissions likely offset any potential CDR capacity. Using renewables to supply hatchery electricity, or using recycled materials for farming operations, have been identified as key ways to reduce farming emissions, and should be prioritized to enhance the sustainability of seaweed products. Overall, however, even if these are adopted in the short or mid-term future, it appears that seaweed farming does not yet have the scale to contribute to carbon removal at a rate necessary to meaningfully affect atmospheric CO₂ concentrations at the global level. Still, seaweed farming may lead to CDR at localized scales and can already deliver products with a low-carbon footprint. As such, this industry represents a key pathway towards a more sustainable future, and economically incentivizing the industry can help optimize its multiple benefits. Operationalizing the potential of seaweed farming to contribute to CDR will require the decarbonization of supply chains, developing robust models to trace and verify the fate of seaweed carbon, directing harvested biomass to long-term carbon storage products, and expanding farming outside traditional cultivation areas.

CRedit authorship contribution statement

Albert Pessarrodona: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Jennifer Howard:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **Emily Pidgeon:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **Thomas Wernberg:** Funding acquisition, Supervision, Validation, Writing – review & editing. **Karen Filbee-Dexter:** Funding acquisition, Methodology, Writing – review & editing.

Declaration of competing interest

Karen Filbee-Dexter reports financial support was provided by Australian Research Council. Thomas Wernberg reports financial support was provided by Australian Research Council.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.170525>.

References

- Akhand, A., Watanabe, K., Chanda, A., Tokoro, T., Chakraborty, K., Moki, H., Tanaya, T., Ghosh, J., Kuwae, T., 2021. Lateral carbon fluxes and CO₂ evasion from a subtropical mangrove-seagrass-coral continuum. *Sci. Total Environ.* 752, 142190 <https://doi.org/10.1016/j.scitotenv.2020.142190>.
- Alpert, S.B., Spencer, D.F., Hidy, G., 1992. Biospheric options for mitigating atmospheric carbon dioxide levels. *Energy Convers. Manag.* 33, 729–736. [https://doi.org/10.1016/0196-8904\(92\)90078-B](https://doi.org/10.1016/0196-8904(92)90078-B).
- Alvarado-Morales, M., Boldrin, A., Karakashev, D.B., Holdt, S.L., Angelidaki, I., Astrup, T., 2013. Life cycle assessment of biofuel production from brown seaweed in Nordic conditions. *Bioresour. Technol.* 129, 92–99. <https://doi.org/10.1016/j.biortech.2012.11.029>.
- Arzeno-Soltero, I.B., Frieder, C., Saenz, B.T., Long, M.C., DeAngelo, J., Davis, S.J., Davis, K.A., 2022. Biophysical Potential and Uncertainties of Global Seaweed Farming. *EarthArXiv*.
- Bach, L.T., Tamsitt, V., Gower, J., Hurd, C.L., Raven, J.A., Boyd, P.W., 2021. Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum belt. *Nat. Commun.* 12, 2556. <https://doi.org/10.1038/s41467-021-22837-2>.
- Bach, L.T., Ho, D.T., Boyd, P.W., Tyka, M.D., 2023. Toward a Consensus Framework to Evaluate Air – Sea CO₂ Equilibration for Marine CO₂ Removal. <https://doi.org/10.1002/ao2.10330>.
- Bak, U.G., Mols-Mortensen, A., Gregersen, O., 2018. Production method and cost of commercial-scale offshore cultivation of kelp in the Faroe Islands using multiple partial harvesting. *Algal Res.* 33, 36–47. <https://doi.org/10.1016/j.algal.2018.05.001>.
- Bak, U.G., Gregersen, O., Infante, J., 2020. Technical challenges for offshore cultivation of kelp species: lessons learned and future directions. *Bot. Mar.* 63, 341–353. <https://doi.org/10.1515/bot-2019-0005>.
- Boderskov, T., Rasmussen, M.B., Bruhn, A., 2023. Upscaling cultivation of *Saccharina latissima* on net or line systems; comparing biomass yields and nutrient extraction potentials. *Front. Mar. Sci.* 10, 1–18. <https://doi.org/10.3389/fmars.2023.992179>.
- Boyd, P.W., Bach, L.T., Hurd, C.L., Paine, E., Raven, J.A., Tamsitt, V., 2022. Potential negative effects of ocean afforestation on offshore ecosystems. *Nat. Ecol. Evol.* <https://doi.org/10.1038/s41559-022-01722-1>.
- Braeckman, U., Pasotti, F., Vázquez, S., Zacher, K., Hoffmann, R., Elvert, M., Marchant, H., Buckner, C., Quartino, M.L., Mác Cormack, W., Soetaert, K., Wenzhöfer, F., Vanreusel, A., 2019. Degradation of macroalgal detritus in shallow coastal Antarctic sediments. *Limnol. Oceanogr.* 64, 1423–1441. <https://doi.org/10.1002/lno.11125>.
- Brey, T., Müller-Wiegmann, C., Zittier, Z.M.C., Hagen, W., 2010. Body composition in aquatic organisms - a global data bank of relationships between mass, elemental composition and energy content. *J. Sea Res.* 64, 334–340. <https://doi.org/10.1016/j.seares.2010.05.002>.
- Broch, O.J., Alver, M.O., Bekkby, T., Gundersen, H., Forbord, S., Handå, A., Skjermo, J., Hancke, K., 2019. The kelp cultivation potential in coastal and offshore regions of Norway. *Front. Mar. Sci.* 5, 1–15. <https://doi.org/10.3389/fmars.2018.00529>.
- Broch, O.J., Hancke, K., Ellingsen, I.H., 2022. Dispersal and deposition of detritus from kelp cultivation. *Front. Mar. Sci.* 9, 840531 <https://doi.org/10.3389/fmars.2022.840531>.
- Buck, B.H., Buchholz, C.M., 2004. The offshore-ring: a new system design for the open ocean aquaculture of macroalgae. *J. Appl. Phycol.* 16, 355–368. <https://doi.org/10.1023/B:JAPH.0000047947.96231.ea>.
- Buck-Wiese, H., Andskog, M.A., Nguyen, N.P., Bligh, M., 2022. Fucoid brown algae inject fucoidan carbon into the ocean. *Proc. Natl. Acad. Sci.* 120, e2210561119 [doi: 10.1073/pnas](https://doi.org/10.1073/pnas).
- Cai, L., Fang, J., Liang, X., 2003. Natural sedimentation in large-scale aquaculture areas of Sunco Bay, north China Sea. *J. Fish. Sci. China* 10, 305–310.
- Campbell, I., Macleod, A., Sahlmann, C., Neves, L., Funderud, J., Øverland, M., Hughes, A.D., Stanley, M., 2019. The environmental risks associated with the development of seaweed farming in Europe - prioritizing key knowledge gaps. *Front. Mar. Sci.* 6 <https://doi.org/10.3389/fmars.2019.00107>.
- Chen, S., Xu, K., Ji, D., Wang, W., Xu, Y., Chen, C., Xie, C., 2020a. Release of dissolved and particulate organic matter by marine macroalgae and its biogeochemical implications. *Algal Res.* 52, 102096 <https://doi.org/10.1016/j.algal.2020.102096>.
- Chen, S., Xu, K., Wang, W., Xu, Y., Chen, C., Xie, C., Ji, D., 2020b. Growth and contents of C, N, and P of kelp (*Saccharina japonica*) cultured in Nanri Island, China and its effects on particulate and dissolved organic matter of seawater. *J. Fish. China* 44, 1306–1316. <https://doi.org/10.11964/jfc.20190811917>.
- Chung, I.K., Beardall, J., Mehta, S., Sahoo, D., Stojkovic, S., 2011. Using marine macroalgae for carbon sequestration: a critical appraisal. *J. Appl. Phycol.* 23, 877–886. <https://doi.org/10.1007/s10811-010-9604-9>.
- Chung, I.K., Oak, J.H., Lee, J.A., Shin, J.A., Kim, J.G., Park, K.S., 2013. Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean Project Overview. *ICES J. Mar. Sci.* 70, 1038–1044. <https://doi.org/10.1093/icesjms/fss206>.
- Coleman, S., Dewhurst, T., Fredriksson, D.W., St. Gelais, A.T., Cole, K.L., MacNicol, M., Lauffer, E., Brady, D.C., 2022. Quantifying baseline costs and cataloging potential

- optimization strategies for kelp aquaculture carbon dioxide removal. *Front. Mar. Sci.* 9, 966304 <https://doi.org/10.3389/fmars.2022.966304>.
- Collins, N., Kumar Mediboyina, M., Cerca, M., Vance, C., Murphy, F., 2022. Economic and environmental sustainability analysis of seaweed farming: monetizing carbon offsets of a brown algae cultivation system in Ireland. *Bioresour. Technol.* 346, 126637 <https://doi.org/10.1016/j.biortech.2021.126637>.
- Czyrnek-Delètre, M.M., Rocca, S., Agostini, A., Giuntoli, J., Murphy, J.D., 2017. Life cycle assessment of seaweed biomethane, generated from seaweed sourced from integrated multi-trophic aquaculture in temperate oceanic climates. *Appl. Energy* 196, 34–50. <https://doi.org/10.1016/j.apenergy.2017.03.129>.
- DeAngelo, J., Saenz, B., Arzeno-Soltero, I., Frieder, C., Long, M., Hamman, J., Davis, K., Davis, S., 2022. Economic and Biophysical Limits to Seaweed-based Climate Solutions, 3094. *EarthArXiv*.
- DeAngelo, J., Saenz, B.T., Arzeno-Soltero, I.B., Frieder, C.A., Long, M.C., Hamman, J., Davis, K.A., Davis, S.J., 2023. Economic and biophysical limits to seaweed farming for climate change mitigation. *Nat. Plants* 9, 45–57. <https://doi.org/10.1038/s41477-022-01305-9>.
- Dolliver, J., Connor, N.E.O., 2022. Estimating growth, loss and potential carbon sequestration of farmed kelp: a case study of *Saccharina latissima* at Strangford Lough, Northern Ireland ABSTRACT. *Appl. Phycol.* 3, 324–339. <https://doi.org/10.1080/26388081.2022.2081934>.
- Duarte Moreno, H., Reuter, H., Kase, A., Teichberg, M., 2021. Seaweed farming and land-use impacts on seagrass meadows in the region of Rote Island, Indonesia. *Estuar. Coast. Shelf Sci.* 263 <https://doi.org/10.1016/j.ecss.2021.107635>.
- Duarte, C.M., Wu, J., Xiao, X., Bruhn, A., Krause-Jensen, D., 2017. Can seaweed farming play a role in climate change mitigation and adaptation? *Front. Mar. Sci.* 4, 100. <https://doi.org/10.3389/fmars.2017.00100>.
- Duarte, C.M., Bruhn, A., Krause-Jensen, D., 2022. A seaweed aquaculture imperative to meet global sustainability targets. *Nat. Sustain.* 5, 185–193. <https://doi.org/10.1038/s41893-021-00773-9>.
- Erlania, Nyoman Radiarta, 2015. The use of seaweeds aquaculture for carbon sequestration: a strategy for climate change mitigation. *J. Geodesy Geomatics Eng.* 2, 109–115. <https://doi.org/10.17265/2332-8223/2015.06.006>.
- Fan, W., Zhao, R., Yao, Z., Xiao, C., Pan, Y., Chen, Y., Jiao, N., Zhang, Y., 2019. Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture using artificial upwelling. *Water (Basel)* 11. <https://doi.org/10.3390/w11091754>.
- Fang, T., Cui, J., Ou, Y., Dai, J., Wang, M., Liu, Q., Yang, Q., 1983. Breeding of the new variety “Danhai No. 1” of *Laminaria japonica* by using a female haploid clone of the kelp. *J. Shandong Coll. Oceanol.* 13, 63–71.
- Fang, J., Zhang, J., Xiao, T., Huang, D., Liu, S., 2016. Integrated multi-trophic aquaculture (IMTA) in Sanggou Bay, China. *Aquac. Environ. Interact.* 8, 201–205. <https://doi.org/10.3354/aei00179>.
- FAO, 2018. FAO 2011–2021. Fisheries and aquaculture software. FishStatJ - Software for Fishery and Aquaculture Statistical Time Series. In: FAO Fisheries Division [online].
- Feng, X., Li, H., Zhang, Z., Xiong, T., Shi, X., 2022. Microbial-mediated contribution of kelp detritus to different forms of oceanic carbon sequestration. *Ecol. Indic.* 142, 109186 <https://doi.org/10.1016/j.ecolind.2022.109186>.
- Ferdouse, F., Løvstad Holdt, S., Smith, R., Muriá, P., Yang, Z., 2018. The Global Status of Seaweed Production, Trade and Utilization (FAO Globefish Research Programme).
- Firman, Z., Tri, H., Jeverson, R., Hafizh, P., Muhammad, S., Hada, P.A.M., 2023. Economic feasibility analysis of macroalgae farming-based carbon dioxide removal. *J. Sustain. Sci. Manag.* 18, 137–145. <https://doi.org/10.46754/jssm.2023.08.009>.
- Fossberg, J., Forbord, S., Broch, O.J., Malzahh, A.M., Jansen, H., Handå, A., Forde, H., Bergvik, M., Fledrum, A.L., Skjermo, J., Olsen, Y., 2018. The potential for upscaling kelp (*Saccharina latissima*) cultivation in salmon-driven integrated multi-trophic aquaculture (IMTA). *Front. Mar. Sci.* 9, 1–12. <https://doi.org/10.3389/fmars.2018.00418>.
- Frigstad, H., Gundersen, H., Andersen, G.S., Borgersen, G., Kville, K.O., Krause-Jensen, D., Boström, C., Bekkby, T., D’Auriac, M.A., Ruus, A., Thormar, J., Asdal, K., Hancke, K., 2021. Blue Carbon – Climate Adaptation, CO₂ Uptake and Sequestration of Carbon in Nordic Blue Forests.
- Froehlich, H.E., Afflerbach, J.C., Frazier, M., Halpern, B.S., 2019. Blue growth potential to mitigate climate change through seaweed offsetting. *Curr. Biol.* 29, 1–7. <https://doi.org/10.1016/j.cub.2019.07.041>.
- Ganesan, M., Thirupathi, S., Jha, B., 2006. Mariculture of *Hypnea musciformis* (Wulfen) Lamouroux in South east coast of India. *Aquaculture* 256, 201–211. <https://doi.org/10.1016/j.aquaculture.2006.01.039>.
- Gao, Y., Zhang, Y., Du, M., Lin, F., Jiang, W., Li, W., Li, F., Lv, X., Fang, J., Jiang, Z., 2021. Dissolved organic carbon from cultured kelp *Saccharina japonica*: production, bioavailability, and bacterial degradation rates. *Aquac. Environ. Interact.* 13, 101–110. <https://doi.org/10.3354/aei00393>.
- Gao, G., Gao, L., Jiang, M., Jian, A., He, L., 2022. The potential of seaweed cultivation to achieve carbon neutrality and mitigate deoxygenation and eutrophication. *Environ. Res. Lett.* 17 <https://doi.org/10.1088/1748-9326/ac3fd9>.
- Geden, O., Affairs, S., Minx, J.C., Change, C., 2023. The State of Carbon Dioxide Removal.
- Ghosh, A., Vijay Anand, K.G., Seth, A., 2015. Life cycle impact assessment of seaweed based biostimulant production from onshore cultivated *Kappaphycus alvarezii* (Doty) Doty ex Silva-is it environmentally sustainable? *Algal Res.* 12, 513–521. <https://doi.org/10.1016/j.algal.2015.10.015>.
- GitarSKIY, M.L., 2019. The refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. *Fundam. Appl. Climatol.* 2, 5–13. <https://doi.org/10.21513/0207-2564-2019-2-05-13>.
- Goudriaan, J., Groot, J.J., Rob., Uithol, W.J., 2001. Productivity of agro-ecosystems. In: Roy, J., Saugier, B., Mooney, H.A. (Eds.), *Terrestrial Global Productivity*. Academic Press, San Diego, pp. 301–313.
- Han, T., Shi, R., Qi, Z., Huang, H., Gong, X., 2021. Impacts of large-scale aquaculture activities on the seawater carbonate system and air-sea CO₂ flux in a subtropical mariculture bay, southern China. *Aquac. Environ. Interact.* 13, 199–210. <https://doi.org/10.3354/aei00400>.
- Hancke, K., Broch, O.J., Olsen, Y., Bekkby, T., Hansen, P.K., Fieler, R., Attard, K.M., Borgersen, G., Christie, H.C., 2021. Environmental impacts of kelp cultivation and recommendations for a management strategy [in Norwegian with English abstract]. <https://niva.brage.unit.no/niva-xmlui/handle/11250/2731345>.
- Hasselström, L., Thomas, J.B.E., 2022. A critical review of the life cycle climate impact in seaweed value chains to support carbon accounting and blue carbon financing. *Clean. Environ. Syst.* 6 <https://doi.org/10.1016/j.cesys.2022.100093>.
- Hatch Innovation Services, 2022. A practical guide to global seaweed farming [WWW Document]. URL: <https://seaweedinsights.com/global-production/>.
- Hill, R., Bellgrove, A., Macreadie, P.I., Petrou, K., Beardall, J., Steven, A., Ralph, P.J., 2015. Can macroalgae contribute to blue carbon? An Australian perspective. *Limnol. Oceanogr.* 60, 1689–1706. <https://doi.org/10.1002/lno.10128>.
- Howard, J., Sutton-Grier, A.E., Smart, L.S., Lopes, C.C., Hamilton, J., Kleypas, J., Simpson, S., McGowan, J., Pessarrodona, A., Alleyway, H.K., Landis, E., 2023. Blue carbon pathways for climate mitigation: known, emerging and unlikely. *Mar. Policy* 156, 105788. <https://doi.org/10.1016/j.marpol.2023.105788>.
- Hu, Z.M., Shan, T.F., Zhang, J., Zhang, Q.S., Critchley, A.T., Choi, H.G., Yotsukura, N., Liu, F.L., Duan, D.L., 2021. Kelp aquaculture in China: a retrospective and future prospects. *Rev. Aquac.* 1–28 <https://doi.org/10.1111/raq.12524>.
- Hurd, C.L., Law, C.S., Bach, L.T., Britton, D., Hovenden, M., Paine, E.R., Raven, J.A., Tamsitt, V., Boyd, P.W., 2022. Forensic carbon accounting: assessing the role of seaweeds for carbon sequestration. *J. Phycol.* 58, 347–363. <https://doi.org/10.1111/jpy.13249>.
- Hwang, E.K., Yotsukura, N., Pang, S.J., Su, L., Shan, T.F., 2019. Seaweed breeding programs and progress in eastern Asian countries. *Phycologia* 58, 484–495. <https://doi.org/10.1080/00318884.2019.1639436>.
- Hwang, E.K., Choi, H.G., Kim, J.K., 2020. Seaweed resources of Korea. *Bot. Mar.* 63, 395–405. <https://doi.org/10.1515/bot-2020-0007>.
- IPCC, 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA. <https://doi.org/10.1017/9781009325844>.
- IPCC Task Force on National Greenhouse Gas Inventories, 2014. Methodological Guidance on Lands with Wet and Drained Soils, and Constructed Wetlands for Wastewater Treatment, 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.
- Jiang, Z., Fang, J., Mao, Y., Han, T., Wang, G., 2013. Influence of seaweed aquaculture on marine inorganic carbon dynamics and sea-air CO₂ flux. *J. World Aquacult. Soc.* 44, 133–140. <https://doi.org/10.1111/jwas.12000>.
- Jones, D.C., Ito, T., Takano, Y., Hsu, W.C., 2014. Spatial and seasonal variability of the air-sea equilibration timescale of carbon dioxide. *Glob. Biogeochem. Cycles* 28, 1163–1178. <https://doi.org/10.1002/2014GB004813>.
- Jones, A.R., Alleyway, H.K., McAfee, D., Reis-Santos, P., Theuerkauf, S.J., Jones, R.C., 2022. Climate-friendly seafood: the potential for emissions reduction and carbon capture in marine aquaculture. *Bioscience*. <https://doi.org/10.1093/biosci/biab126>.
- Jung, K.A., Seong-Rin, L., Kim, Y., Park, J.M., 2017. Opportunity and challenge of seaweed bioethanol based on life cycle CO₂ assessment. *Environ. Prog. Sustain. Energy* 36, 200–206. <https://doi.org/10.1002/ep>.
- Kamby, C.S.B., Campbell, I., Sondak, C.F.A., Nor, A.R.M., Lim, P.E., Cottier-Cook, E.J., 2020. An analysis of the current status and future of biosecurity frameworks for the Indonesian seaweed industry. *J. Appl. Phycol.* 32, 2147–2160. <https://doi.org/10.1007/s10811-019-02020-3>.
- Kelly, E.L.A., Cannon, A.L., Smith, J.E., 2020. Environmental impacts and implications of tropical carrageenophyte seaweed farming. *Conserv. Biol.* 34, 326–337. <https://doi.org/10.1111/cobi.13462>.
- Keng, F.S.L., Phang, S.M., Abd Rahman, N., Leedham Elvidge, E.C., Malin, G., Sturges, W.T., 2020. The emission of volatile halocarbons by seaweeds and their response towards environmental changes. *J. Appl. Phycol.* 32, 1377–1394. <https://doi.org/10.1007/s10811-019-02026-x>.
- KKP, 2018. Annual Report of the Ministry of Marine Affairs and Fisheries (Kementerian Kelautan dan Perikanan, KKP) of the Republic of Indonesia. Laporan Tahunan Kementerian Kelautan dan Perikanan Tahun.
- Krause-Jensen, D., Duarte, C.M., 2016. Substantial role of macroalgae in marine carbon sequestration. *Nat. Geosci.* 9, 737–742. <https://doi.org/10.1038/ngeo2790>.
- Langford, A., Waldron, S., Sulphahri, Saleh, H., 2021. Monitoring the COVID-19-affected Indonesian seaweed industry using remote sensing data. *Mar. Policy* 127, 104431. <https://doi.org/10.1016/j.marpol.2021.104431>.
- Langford, A., Zhang, J., Waldron, S., Julianto, B., Siradjuddin, I., Neish, I., Nuryartono, N., 2022. Price analysis of the Indonesian carrageenan seaweed industry. *Aquaculture* 550, 737828. <https://doi.org/10.1016/j.aquaculture.2021.737828>.
- Laurens, L.M.L., Lane, M., Nelson, R.S., 2020. Sustainable seaweed biotechnology solutions for carbon capture, composition, and deconstruction. *Trends Biotechnol.* 38, 1232–1244. <https://doi.org/10.1016/j.tibtech.2020.03.015>.
- Leedham, E.C., Hughes, C., Keng, F.S.L., Phang, S.M., Malin, G., Sturges, W.T., 2013. Emission of atmospherically significant halocarbons by naturally occurring and farmed tropical macroalgae. *Biogeosciences* 10, 3615–3633. <https://doi.org/10.5194/bg-10-3615-2013>.
- Lelahy, Y., Ingle, K.N., Golberg, A., 2016. Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability. *Algal Res.* 17, 150–160. <https://doi.org/10.1016/j.algal.2016.03.031>.

- Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M., 2014. An overview of current status of carbon dioxide capture and storage technologies. *Renew. Sust. Energ. Rev.* 39, 426–443. <https://doi.org/10.1016/j.rser.2014.07.093>.
- Li, X., Cong, Y., Yang, G., Shi, Y., Qu, S., Li, Z., Wang, G., Zhang, Z., Luo, S., Dai, H., Xie, J., Jiang, G., Liu, J., Wang, T., 2007. Trait evaluation and trial cultivation of Dongfang No. 2, the hybrid of a male gametophyte clone of *Laminaria longissima* (Laminariales, Phaeophyta) and a female one of *L. japonica*. *J. Appl. Phycol.* 19, 139–151. <https://doi.org/10.1007/s10811-006-9120-0>.
- Li, X., Liu, J., Cong, Y., Qu, S., Zhang, Z., Dai, H., Luo, S., Han, X., Huang, S., Wang, Q., Liang, G., Sun, J., Jin, Y., Wang, D., Yang, G., 2008. Breeding and trial cultivation of Dongfang No. 3, a hybrid of *Laminaria* gametophyte clones with a more than intraspecific but less than interspecific relationship. *Aquaculture* 280, 76–80. <https://doi.org/10.1016/j.aquaculture.2008.05.005>.
- Li, H., Zhang, Y., Liang, Y., Chen, J., Zhu, Y., Zhao, Y., Jiao, N., 2018. Impacts of maricultural activities on characteristics of dissolved organic carbon and nutrients in a typical raft-culture area of the Yellow Sea, North China. *Mar. Pollut. Bull.* 137, 456–464. <https://doi.org/10.1016/j.marpolbul.2018.10.048>.
- Li, H., Zhang, Z., Xiong, T., Tang, K., He, C., Shi, Q., Jiao, N., Zhang, Y., 2022. Carbon sequestration in the form of recalcitrant dissolved organic carbon in a seaweed (kelp) farming environment. *Environ. Sci. Technol.* 56, 9112–9122. <https://doi.org/10.1021/acs.est.2c01535>.
- Li, J., Bergman, K., Thomas, J.B.E., Gao, Y., Gröndahl, F., 2023. Life cycle assessment of a large commercial kelp farm in Shandong, China. *Sci. Total Environ.* 903 <https://doi.org/10.1016/j.scitotenv.2023.166861>.
- Lian, Y., Wang, R., Zheng, J., Chen, W., Chang, L., Li, C., Yim, S.C., 2023. Carbon sequestration assessment and analysis in the whole life cycle of seaweed. *Environ. Res. Lett.* 18, 074013 <https://doi.org/10.1088/1748-9326/acdae9>.
- Liu, D., Bai, J., Song, S., Zhang, J., Sun, P., Li, Y., Han, G., 2007. The impact of sewage discharge on the macroalgae community in the Yellow Sea coastal area around Qingdao, China. *Water Air Soil Pollut. Focus* 7, 683–692. <https://doi.org/10.1007/s11267-007-9121-2>.
- Liu, F., Sun, X., Wang, F., Wang, W., Liang, Z., Lin, Z., Dong, Z., 2014. Breeding, economic traits evaluation, and commercial cultivation of a new *Saccharina* variety “Huangguan No. 1”. *Aquac. Int.* 22, 1665–1675. <https://doi.org/10.1007/s10499-014-9772-8>.
- Liu, S., Huang, J., Yang, Q., Yang, S., Yang, G., Sun, Y., 2015. Burial fluxes and source apportionment of carbon in culture areas of Sanggou Bay over the past 200 years. *Acta Oceanol. Sin.* 34, 23–30. <https://doi.org/10.1007/s13131-015-0724-6>.
- Liu, X., Dunne, J.P., Stock, C.A., Harrison, M.J., Adcroft, A., Resplandy, L., 2019. Simulating water residence time in the coastal ocean: a global perspective. *Geophys. Res. Lett.* 46, 13910–13919. <https://doi.org/10.1029/2019GL085097>.
- Liu, J., Chen, Y., Wang, Y., Du, M., Wu, Z., 2023. Greenhouse gases emissions and dissolved carbon export affected by submarine groundwater discharge in a maricultural bay, Hainan Island, China. *Sci. Total Environ.* 857, 159665 <https://doi.org/10.1016/j.scitotenv.2022.159665>.
- Lovelock, C.E., Adame, M.F., Bradley, J., Dittmann, S., Hagger, V., Hickey, S.M., Hutley, L.B., Jones, A., Kelleway, J.J., Lavery, P.S., Macreadie, P.I., Maher, D.T., McGinley, S., McGlashan, A., Perry, S., Mosley, L., Rogers, K., Sippo, J.Z., 2022a. An Australian blue carbon method to estimate climate change mitigation benefits of coastal wetland restoration. *Restor. Ecol.*, e13739 <https://doi.org/10.1111/rec.13739>.
- Lovelock, C.E., Adame, M.F., Butler, D.W., Kelleway, J.J., Dittmann, S., Fest, B., King, K.J., Macreadie, P.I., Mitchell, K., Newnham, M., Ola, A., Owers, C.J., Welti, N., 2022b. Modeled approaches to estimating blue carbon accumulation with mangrove restoration to support a blue carbon accounting method for Australia. *Limnol. Oceanogr.* 67, S50–S60. <https://doi.org/10.1002/lno.12014>.
- Mahmood, T., Fang, J., Jiang, Z., Ying, W., Zhang, J., 2017. Seasonal distribution, sources and sink of dissolved organic carbon in integrated aquaculture system in coastal waters. *Aquac. Int.* 25, 71–85. <https://doi.org/10.1007/s10499-016-0014-0>.
- McHugh, D.J., 2003. *A Guide to the Seaweed Industry*, FAO Fisheries Technical Paper no. 441.
- Mithoo-Singh, P.K., Keng, F.S.L., Phang, S.M., Elvidge, E.C.L., Sturges, W.T., Malin, G., Rahman, N.A., 2017. Halocarbon emissions by selected tropical seaweeds: species-specific and compoundspecific responses under changing pH. *PeerJ* 2017, 1–22. <https://doi.org/10.7717/peerj.2918>.
- NASEM, 2021. *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*. The National Academies Press, Washington DC. <https://doi.org/10.17226/26278>.
- Needelman, B.A., Emmer, I.M., Emmett-Mattox, S., Crooks, S., Megonigal, J.P., Myers, D., Oreska, M.P.J., McGlathery, K., 2018. The science and policy of the verified carbon standard methodology for tidal wetland and seagrass restoration. *Estuar. Coasts* 41, 2159–2171. <https://doi.org/10.1007/s12237-018-0429-0>.
- Nilsson, A.E., Bergman, K., Gomez Barrio, L.P., Cabral, E.M., Tiwari, B.K., 2022. Life cycle assessment of a seaweed-based biorefinery concept for production of food, materials, and energy. *Algal Res.* 65 <https://doi.org/10.1016/j.algal.2022.102725>.
- N’Yeurt, A.D.R., Chynoweth, D.P., Capron, M.E., Stewart, J.R., Hasan, M.A., 2012. Negative carbon via ocean afforestation. *Process. Saf. Environ. Prot.* 90, 467–474. <https://doi.org/10.1016/j.psep.2012.10.008>.
- Ocean Visions, 2022. *Answering Critical Questions About Sinking Macroalgae for Carbon Dioxide Removal: A Research Framework to Investigate Sequestration Efficacy and Environmental Impacts*.
- O’dell, A.R., 2022. *Scotland’s Blue Carbon: The Contribution From Seaweed Detritus*. University of the Highlands and Islands.
- Orr, J.C., Sarmiento, J.L., 1992. Potential of marine macroalgae as a sink for CO₂: constraints from a 3-D general circulation model of the global ocean. *Water Air Soil Pollut.* 64, 405–421. <https://doi.org/10.1007/BF00477113>.
- Ortega, A., Gerdali, N.R., Alam, I., Kamau, A.A., Acinas, S.G., Logares, R., Gasol, J.M., Massana, R., Krause-Jensen, D., Duarte, C.M., 2019. Important contribution of macroalgae to oceanic carbon sequestration. *Nat. Geosci.* 12, 748–754. <https://doi.org/10.1038/s41561-019-0421-8>.
- Paine, E.R., Boyd, P.W., Strzepek, R.F., Ellwood, M., Brewer, E.A., Diaz-Pulido, G., Schmid, M., Hurd, C.L., 2023. Iron limitation of kelp growth may prevent ocean afforestation. *Commun. Biol.* 6, 1–9. <https://doi.org/10.1038/s42003-023-04962-4>.
- Pan, Z., Gao, Q.-F., Dong, S.-L., Wang, F., Li, H.-D., Zhao, K., Jiang, X.-Y., 2019. Effects of abalone (*Haliotis discus hannai* Ino) and kelp (*Saccharina japonica*) mariculture on sources, distribution, and preservation of sedimentary organic carbon in Allian Bay, China: identified by coupling stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) with C/N ratio. *Mar. Pollut. Bull.* 141, 387–397.
- Pan, Z., Tan, Y.M., Gao, Q.F., Dong, S.L., Fang, X.D., Yan, J.L., 2021. A 120-year record of burial fluxes and source apportionment of sedimentary organic carbon in Allian Bay, China: implication for the influence of mariculture activities, and regional environment changes. *Aquaculture* 535, 736421. <https://doi.org/10.1016/j.aquaculture.2021.736421>.
- Perkins, A.K., Santos, I.R., Rose, A.L., Schulz, K.G., Hans-Peter Grossart, B.D.E., Kelaher, Brendan P., J.M.O., 2022. Production of dissolved carbon and alkalinity during macroalgal wrack degradation on beaches: a mesocosm experiment with implications for blue carbon. *Biogeochemistry* 160, 159–175. <https://doi.org/10.1007/s10533-022-00946-4>.
- Pessarrodona, A., Assis, J., Filbee-Dexter, K., Burrows, M.T., Gattuso, J.-P., Duarte, C.M., Krause-Jensen, D., Moore, P.J., Smale, D.A., Wernberg, T., 2022. Global seaweed productivity. *Sci. Adv.* 8, 2465.
- Pessarrodona, A., Franco-santos, R.M., Wright, L.S., Vanderklift, M.A., Howard, J., Pidgeon, E., Wernberg, T., Filbee-dexter, K., 2023. Carbon sequestration and climate change mitigation using macroalgae: a state of knowledge review. *Biol. Rev.* <https://doi.org/10.1111/brv.12990>.
- Phang, S.M., Keng, F.S.L., Paramjeet-Kaur, M.S., Lim, Y.K., Rahman, N.A., Leedham, E.C., Robinson, A.D., Harris, N.R.P., Pyle, J.A., Sturges, W.T., 2015. Can seaweed farming in the tropics contribute to climate change through emission of short-lived halocarbons? *Malays. J. Sci.* 34, 8–19. <https://doi.org/10.22452/mjs.vol34no1.2>.
- Poore, J., Nemecek, T., 2018. Reducing food’s environmental impacts through producers and consumers. *Science* 992, 987–992. <https://doi.org/10.1126/SCIENCE.AAQ0216>.
- Pratama, I., Albasri, H., 2021. cult- Indonesia. *Aquat. Living Resour.* 34 <https://doi.org/10.1051/alr/2021015>.
- Queirós, A.M., Stephens, N., Widdicombe, S., Tait, K., McCoy, S.J., Ingels, J., Ains, R., Beesley, A., Carnovale, G., Cazenave, P., Dashfield, S., Hua, E., Jones, M., McNeill, C.L., Nunes, J., Parry, H., Pascoe, C., Widdicombe, C., Smyth, T., Atkinson, A., Krause-Jensen, D., Somerfield, P.J., Rühl, S., Ains, R., Beesley, A., Carnovale, G., Cazenave, P., Dashfield, S., Hua, E., Jones, M., Lindeque, P., McNeill, C.L., Nunes, J., Parry, H., Pascoe, C., Widdicombe, C., Smyth, T., Atkinson, A., Krause-Jensen, D., Somerfield, P.J., 2019. Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean. *Ecol. Monogr.*, e01366 <https://doi.org/10.1002/ecm.1366>.
- Reis, R.P., Castelar, B., Moura, A.L., Kirk, R., 2009. Invasive potential of *Kappaphycus alvarezii* off the south coast of Rio de Janeiro state, Brazil: a contribution to environmentally secure cultivation in the tropics. *Bot. Mar.* 52, 283–289. <https://doi.org/10.1515/BOT.2009.002>.
- Reithmaier, G.M.S., Johnston, S.G., Junginger, T., Goddard, M.M., Sanders, C.J., Hutley, L.B., O, D.T., Maher, D.T., 2021. Alkalinity production coupled to pyrite formation represents an unaccounted blue carbon sink. *Glob. Biogeochem. Cycles* 35, e2020GB006785. <https://doi.org/10.1029/2020GB006785>.
- Ren, L., Zhang, J., Fang, J., Tang, Q., Zhang, M., Du, M., 2014. Impact of shellfish biopesticides and rotten seaweed on the sediments of Allian Bay, China. *Aquac. Int.* 811–819 <https://doi.org/10.1007/s10499-013-9709-7>.
- Ricart, A.M., Krause-Jensen, D., Hancke, K., Price, N.N., Masqué, P., Duarte, C.M., 2022. Sinking seaweed in the deep ocean for carbon neutrality is ahead of science and beyond the ethics. *Environ. Res. Lett.* 17, 081003 <https://doi.org/10.1088/1748-9326/ac82ff>.
- Ridoutt, B., Lehnert, S.A., Denman, S., Charmley, E., Kinley, R., Dominik, S., 2022. Potential GHG emission benefits of *Asparagopsis taxiformis* feed supplement in Australian beef cattle feedlots. *J. Clean. Prod.* 337 <https://doi.org/10.1016/j.jclepro.2022.130499>.
- Ritschard, R.L., 1992. Marine algae as a CO₂ sink. *Water Air Soil Pollut.* 64, 289–303. <https://doi.org/10.1007/BF00477107>.
- Rosentretre, J.A., Maher, D.T., Erler, D.V., Murray, R.H., Eyre, B.D., 2018. Methane emissions partially offset “blue carbon” burial in mangroves. *Sci. Adv.* 4, eaao4985 <https://doi.org/10.1126/sciadv.aao4985>.
- Rosentretre, J.A., Al-Haj, A.N., Fulweiler, R.W., Williamson, P., 2021. Methane and nitrous oxide emissions complicate coastal blue carbon assessments. *Glob. Biogeochem. Cycles* 35, 1–8. <https://doi.org/10.1029/2020GB006858>.
- Roth, F., Broman, E., Sun, X., Bonaglia, S., Nascimento, F., Prytherch, J., Brücher, V., Lundevall Zara, M., Brunberg, M., Geibel, M.C., Humborg, C., Norkko, A., 2023. Methane emissions offset atmospheric carbon dioxide uptake in coastal macroalgae, mixed vegetation and sediment ecosystems. *Nat. Commun.* 14, 42. <https://doi.org/10.1038/s41467-022-35673-9>.
- Seghetta, M., Hou, X., Bastianoni, S., Bjerre, A.B., Thomsen, M., 2016. Life cycle assessment of macroalgal biorefinery for the production of ethanol, proteins and fertilizers – a step towards a regenerative bioeconomy. *J. Clean. Prod.* 137, 1158–1169. <https://doi.org/10.1016/j.jclepro.2016.07.195>.
- Seghetta, M., Romeo, D., D’Este, M., Alvarado-Morales, M., Angelidaki, I., Bastianoni, S., Thomsen, M., 2017. Seaweed as innovative feedstock for energy and feed –

- evaluating the impacts through a life cycle assessment. *J. Clean. Prod.* 150, 1–15. <https://doi.org/10.1016/j.jclepro.2017.02.022>.
- Siegel, D.A., Devries, T., Doney, S.C., Bell, T., 2021. Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. *Environ. Res. Lett.* 16, 104003 <https://doi.org/10.1088/1748-9326/ac0be0>.
- Singh, I., Anand, K.G.V., Solomon, S., Shukla, S.K., Rai, R., Zodape, S.T., Ghosh, A., 2018. Can we not mitigate climate change using seaweed based biostimulant: a case study with sugarcane cultivation in India. *J. Clean. Prod.* 204, 992–1003. <https://doi.org/10.1016/j.jclepro.2018.09.070>.
- Smith, R.W., Bianchi, T.S., Allison, M., Savage, C., Galy, V., 2015. High rates of organic carbon burial in fjord sediments globally. *Nat. Geosci.* 8, 450–453. <https://doi.org/10.1038/NGEO2421>.
- Sobuj, M.K.A., Mostofa, M.G., Islam, Z., Rabby, A.F., Rahman, T., Sonia, S.S., Hasan, S.J., Rahman, S., 2023. Floating raft culture of *Gracilariopsis longissima* for optimum biomass yield performance on the coast of Cox's Bazar, Bangladesh. *Sci. Rep.* 13, 1–10. <https://doi.org/10.1038/s41598-023-28675-0>.
- Sondak, C.F.A., Ang, P.O., Beardall, J., Bellgrove, A., Boo, S.M., Gerung, G.S., Hepburn, C.D., Hong, D.D., Hu, Z., Kawai, H., Largo, D., Lee, J.A., Lim, P.E., Mayakun, J., Nelson, W.A., Oak, J.H., Phang, S.M., Sahoo, D., Peerapornpis, Y., Yang, Y., Chung, I.K., 2017. Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). *J. Appl. Phycol.* 29, 2363–2373. <https://doi.org/10.1007/s10811-016-1022-1>.
- Spencer, D.F., 1991. Open ocean macroalgal farms for CO₂ mitigation and energy production, in: Proceedings of LEA Conference on Technology Responses to Global Environmental Challenges. pp. 6–8.
- Sui, J., Zhang, J., Ren, S.J., Lin, F., 2019. Organic carbon in the surface sediments from the intensive mariculture zone of Sanggou Bay: distribution, seasonal variations and sources. *J. Ocean Univ. China* 18, 985–996. <https://doi.org/10.1007/s11802-019-3768-y>.
- Sun, J., Norouzi, O., Mašek, O., 2022. A state-of-the-art review on algae pyrolysis for bioenergy and biochar production. *Bioresour. Technol.* 346 <https://doi.org/10.1016/j.biortech.2021.126258>.
- Sutton-Grier, A., Howard, J., 2018. Coastal wetlands are the best marine carbon sink for climate mitigation. *Front. Ecol. Environ.* 16, 73–74. <https://doi.org/10.1002/fee.1766>.
- Thomas, J.B.E., Sodré Ribeiro, M., Potting, J., Cervin, G., Nylund, G.M., Olsson, J., Albers, E., Undeland, I., Pavia, H., Gröndahl, F., 2021. A comparative environmental life cycle assessment of hatchery, cultivation, and preservation of the kelp *Saccharina latissima*. *ICES J. Mar. Sci.* 78, 451–467. <https://doi.org/10.1093/icesjms/fsaa112>.
- UNFCCC, 2022. Common Metrics [WWW Document]. URL. <https://unfccc.int/process-and-meetings/transparency-and-reporting/methods-for-climate-change-transparency-common-metrics>.
- United States Department of Energy, 2017. MARINER Program [WWW Document]. <https://arpa-e.energy.gov/technologies/programs/mariner>.
- Van Dam, B.R., Crosswell, J.R., Paerl, H.W., 2018. Flood-driven CO₂ emissions from adjacent North Carolina estuaries during Hurricane Joaquin (2015). *Mar. Chem.* 207, 1–12. <https://doi.org/10.1016/j.marchem.2018.10.001>.
- van der Mheen, M., Wernberg, T., Pattiaratchi, C., et al., 2024. Substantial kelp detritus exported beyond the continental shelf by dense shelf water transport. *Sci. Rep.* 14, 839. <https://doi.org/10.1038/s41598-023-51003-5>.
- Vanderklift, M.A., Herr, D., Lovelock, C.E., Murdiyarsa, D., Raw, J.L., Steven, A.D.L., 2022. A guide to international climate mitigation policy and finance frameworks relevant to the protection and restoration of blue carbon ecosystems. *Front. Mar. Sci.* 9, 872064 <https://doi.org/10.3389/fmars.2022.872064>.
- Vijn, S., Compant, D.P., Dutta, N., Foukis, A., Hess, M., Hristov, A.N., Kalscheur, K.F., Kebreab, E., Nuzhdin, S.V., Price, N.N., Sun, Y., Tricarico, J.M., Turzillo, A., Weisbjerg, M.R., Yarish, C., Kurt, T.D., 2020. Key considerations for the use of seaweed to reduce enteric methane emissions from cattle. *Front. Vet. Sci.* 7, 1–9. <https://doi.org/10.3389/fvets.2020.597430>.
- Visch, W., Nylund, G.M., Pavia, H., 2020. Growth and biofouling in kelp aquaculture (*Saccharina latissima*): the effect of location and wave exposure. *J. Appl. Phycol.* 32, 3199–3209. <https://doi.org/10.1007/s10811-020-02201-5>.
- Wang, Y., Yang, W., Cai, Y., Fang, Z., Zhao, X., Zhang, Q., Yuan, H., Lin, N., Zou, C., Zheng, M., 2023a. Macroalgae culture-induced carbon sink in a large cultivation area of China. *Environ. Sci. Pollut. Res.* 30, 107693–107702. <https://doi.org/10.1007/s11356-023-29985-6>.
- Wang, Y., Yang, W., Zhao, X., Zhang, Q., Chen, H., Fang, Z., Zheng, M., 2023b. Changes in the carbon source and storage in a cultivation area of macro-algae in Southeast China. *Mar. Pollut. Bull.* 188 <https://doi.org/10.1016/j.marpolbul.2023.114680>.
- Webb, R.M., Silverman-Roati, K., Gerrard, M.B., 2021. Removing Carbon Dioxide Through Ocean Alkalinity Enhancement and Seaweed Cultivation: Legal Challenges and Opportunities.
- Wen, Y., Wang, S., Shi, Z., Jin, Y., Thomas, J.B., Azzi, E.S., Franzén, D., Gröndahl, F., Martin, A., Tang, C., Mu, W., Jönsson, P.G., Yang, W., 2022. Pyrolysis of engineered beach-cast seaweed: performances and life cycle assessment. *Water Res.* 222 <https://doi.org/10.1016/j.watres.2022.118875>.
- Wu, H., Kim, J.K., Huo, Y., Zhang, J., He, P., 2017. Nutrient removal ability of seaweeds on *Pyropia yezoensis* aquaculture rafts in China's radial sandbanks. *Aquat. Bot.* 137, 72–79. <https://doi.org/10.1016/j.aquabot.2016.11.011>.
- Wu, J., Zhang, H., Pan, Y., Krause-Jensen, D., He, Z., Fan, W., Serrano, O., Rivkin, R.B., Zheng, Y., Gu, J., Zhang, X., Zhang, Z., Zhao, P., Qiu, W., Chen, G., Duarte, C.M., 2020. Opportunities for blue carbon strategies in China. *Ocean Coast. Manag.* 194, 105241 <https://doi.org/10.1016/j.ocecoaman.2020.105241>.
- Wu, J., Keller, D.P., Oschlies, A., 2023. Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an earth system modeling study. *Earth Syst. Dyn.* 14, 185–221. <https://doi.org/10.5194/esd-14-185-2023>.
- Xiao, X., Agustí, S., Yu, Y., Huang, Y., Chen, W., Hu, J., Li, C., Li, K., Wei, F., Lu, Y., Xu, C., Chen, Z., Liu, S., Zeng, J., Wu, J., Duarte, C.M., 2021. Seaweed farms provide refugia from ocean acidification. *Sci. Total Environ.* 776, 145192 <https://doi.org/10.1016/j.scitotenv.2021.145192>.
- Xiong, T., Li, H., Hu, Y., Zhai, W., Dong, Z., Zhang, Z., Liu, Y., Zhang, J., Lu, L., Chang, L., Xue, L., Wei, Q., Jiao, N., Zhang, Y., 2024. Seaweed farming environments do not always function as CO₂ sink under synergistic influence of macroalgae and microorganisms. *Agric. Ecosyst. Environ.* 361 <https://doi.org/10.1016/j.agee.2023.108824>.
- Yong, W.T.L., Thien, V.Y., Rupert, R., Rodrigues, K.F., 2022. Seaweed: a potential climate change solution. *Renew. Sust. Energ. Rev.* <https://doi.org/10.1016/j.rser.2022.112222>.
- Yoshikawa, T., Takeuchi, I., Furuya, K., 2001. Active erosion of *Undaria pinnatifida* Suringar (laminariales, phaeophyceae) mass-cultured in Otsuchi Bay in northeastern Japan. *J. Exp. Mar. Biol. Ecol.* 266, 51–65. [https://doi.org/10.1016/S0022-0981\(01\)00346-X](https://doi.org/10.1016/S0022-0981(01)00346-X).
- Zamroni, A., Yamao, M., 2011a. Coastal resource management: fishermen's perception of seaweed farming in Indonesia. *World Acad. Sci. Eng. Technol.* 60, 32–38.
- Zamroni, A., Yamao, M., 2011b. Coastal resource management: fishermen's perception of seaweed farming in Indonesia. *World Acad. Sci. Eng. Technol.* 60, 32–38.
- Zemke-White, W.L., 2003. Environmental Impacts of Seaweed Farming in the Tropics.
- Zeng, D., Huang, D., Qiao, X., He, Y., Zhang, T., 2015. Effect of suspended kelp culture on water exchange as estimated by in situ current measurement in Sanggou Bay, China. *J. Mar. Syst.* 149, 14–24. <https://doi.org/10.1016/j.jmarsys.2015.04.002>.
- Zhai, W., 2018. Exploring seasonal acidification in the Yellow Sea. *Sci. China Earth Sci.* 61, 647–658. <https://doi.org/10.1007/s11430-017-9151-4>.
- Zhang, Q.S., Tang, X.X., Cong, Y.Z., Qu, S.C., Luo, S.J., Yang, G.P., 2007. Breeding of an elite *Laminaria* variety 90-1 through inter-specific gametophyte crossing. *J. Appl. Phycol.* 19, 303–311. <https://doi.org/10.1007/s10811-006-9137-4>.
- Zhang, J., Fang, J., Wang, W., Du, M., Gao, Y., Zhang, M., 2012. Growth and loss of mariculture kelp *Saccharina japonica* in Sungo Bay, China. *J. Appl. Phycol.* 24, 1209–1216. <https://doi.org/10.1007/s10811-011-9762-4>.
- Zhang, Y.Y., Zhang, J.H., Liang, Y.T., Li, H.M., Li, G., Chen, X., Zhao, P., Jiang, Z.J., Zou, D.H., Liu, X.Y., Liu, J.H., 2017. Carbon sequestration processes and mechanisms in coastal mariculture environments in China. *Sci. China Earth Sci.* 60, 2097–2107. <https://doi.org/10.1007/s11430-017-9148-7>.
- Zhang, M., Qin, H., Wang, Z., Li, B., Ma, Y., 2022a. The interaction between DOC released by cultured kelp (*Saccharina japonica*) and the bacterial community reveals the potential for increasing marine carbon sequestration by macroalgae culture. *Front. Mar. Sci.* 9, 1–12. <https://doi.org/10.3389/fmars.2022.985548>.
- Zhang, X., Boderskov, T., Bruhn, A., Thomsen, M., 2022b. Blue growth and bioextraction potentials of Danish *Saccharina latissima* aquaculture — a model of eco-industrial production systems mitigating marine eutrophication and climate change. *Algal Res.* 64 <https://doi.org/10.1016/j.algal.2022.102686>.
- Zhang, M., Qin, H., Ma, Y., Qi, Y., Zhao, Y., Wang, Z., Li, B., 2023. Carbon sequestration from refractory dissolved organic carbon produced by biodegradation of *Saccharina japonica*. *Mar. Environ. Res.* 183, 105803 <https://doi.org/10.1016/j.marenvres.2022.105803>.
- Zuniga-Jara, S., Marín-Riffo, M.C., Bulboa-Contador, C., 2016. Bioeconomic analysis of giant kelp *Macrocystis pyrifera* cultivation (Laminariales; Phaeophyceae) in northern Chile. *J. Appl. Phycol.* 28, 405–416. <https://doi.org/10.1007/s10811-015-0581-x>.