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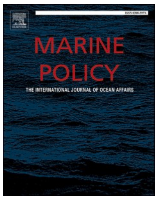

Full length article

Seaweed blue carbon: Ready? Or Not?

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ABSTRACT

There is an urgent need to achieve the United Nations Sustainable Development Goals (SDGs). At the same time, greenhouse gasses (GHGs) that contribute to global warming must be reduced to avoid even more severe climate disruption. Macroalgal (seaweed) systems can help the world achieve the SDGs by producing food, other valuable products, livelihoods, and a number of ecological benefits. Seaweed systems may also be drawing down atmospheric carbon dioxide, an important GHG, under some conditions. However, the net impacts of seaweed systems on GHGs ("blue carbon") depends on many context-specific, complex biogeochemical processes and have thus far been difficult to quantify. We engaged experts in a system mapping exercise to support decision-making in the context of the high levels of uncertainty associated with seaweed blue carbon. The conservation and restoration of seaweed stands appears to be a low-regrets intervention that would produce many benefits, including some carbon sequestration under some conditions, with low risk. Increasing the productivity of seaweed farms may have a similar benefit and risk profile. A large expansion of seaweed farming coupled with sinking the seaweed biomass could significantly increase carbon sequestration, but with relatively large social, economic, and ecological risks. Certain products made from seaweed that sequester carbon, replace GHG-intensive products, or suppress GHG emissions could enhance the climate and socioeconomic benefits of seaweed systems while also improving prospects for quantifying and verifying them. More research and interventions will likely be necessary for such products to scale. A portfolio of seaweed systems would probably be necessary to realize the variety of benefits that these systems are capable of generating.

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1. Introduction

There is an urgent need to produce more food, livelihoods, and revenue to achieve ambitious United Nations Sustainable Development Goals (SDGs) that include ending poverty and hunger [128,25]. At the same time, there is an urgent need to slow the rate of climate change to avoid even more severe climate change impacts [62]. This will require not only dramatic reductions in emissions of gasses that drive climate change (“greenhouse gasses” or GHGs), but also the active removal of GHGs from the atmosphere [62].

Natural stands of macroalgae (seaweed) and seaweed farms are already contributing to the achievement of several SDGs. They produce food and other products, livelihoods, and economic development as well as many ecological benefits such as habitat for marine organisms, nutrient pollution removal, and the local alleviation of ocean acidification [20,63,69,90]. Many species of seaweed grow rapidly and some are relatively easy to cultivate [40,50,7,78,90]. Seaweed systems may also be capable of sequestering carbon under some conditions [27,40,44,60,74]. Seaweed systems may provide these benefits with lower land, water, and other inputs relative to terrestrial food production and certain types of land-based carbon drawdown strategies [77].

Much of the recent interest in seaweed systems as natural climate solutions (i.e., natural or managed ecosystem processes that mitigate climate change by reducing atmospheric GHG concentrations) is based on the fact that some seaweeds are among the most productive organisms on the planet, and thus absorb carbon (C) very rapidly [98,94,95]. However, the climate mitigation value of seaweeds is not solely determined by the amount of carbon taken up and fixed in the algal biomass, but also by the rate of exudation, grazing, microbial activity, carbon transport to sediments or deep water, release of other greenhouse gasses such as methane [107,48,67], inputs of carbon to the system, and the balance between all of the heterotrophic and autotrophic processes within a seaweed system [37,42,74]. These factors, and hence C sequestration by seaweed systems, are species- and context-specific.

Carbon drawdown (i.e., removal of atmospheric carbon dioxide, CO_2) by seaweeds also depends on many context-specific factors. Seaweeds take up dissolved C from seawater and convert it to organic compounds and biomass [95] via photosynthesis. The dissolved C removed by seaweed is slowly replaced by atmospheric CO_2 [89], resulting in a flux of CO_2 from the atmosphere into the ocean at rates that depend on several context-dependent oceanographic factors [126,133]. One study, Ikawa and Oeschel [61], adduces evidence of C flux from the atmosphere into surface waters, perhaps induced by a kelp bed 1.5 km away. However, several factors make it difficult to infer whether the seaweed beds were causing these fluxes. It has been challenging to measure fluxes of CO_2 from the atmosphere to the ocean directly and to attribute these fluxes to C uptake by seaweeds [58,8]. Many factors that affect the equilibrium of atmospheric and oceanic CO_2 (e.g., water temperature, C absorption by phytoplankton, influx of CO_2 via upwelling, remineralization of CO_2 by the food web, etc.) can make attribution of C drawdown by seaweed difficult or even result in fluxes of CO_2 from the ocean to the atmosphere [42].

Because C sequestration by seaweed systems is so complex (Fig. 1), estimates of how much of the C that is absorbed by seaweeds, removed from the atmosphere, and sequestered (i.e. stored for centuries or millennia) are highly uncertain. Indeed, Gallagher et al. [42] conclude that under many conditions, natural, well-established seaweed stands release more C than they sequester. When CO_2 absorption by seaweeds is sufficient to overcome CO_2 release via remineralization of both C fixed by the seaweeds and allochthonous C, seaweed systems can sequester more C than they release [42], but methane emissions from seaweed systems can offset sequestration under some conditions [107]. Hurd et al. [58] describe many of the factors that influence carbon sequestration by seaweed systems. One approach to measuring the climate mitigation service of seaweeds may be to measure the air-sea flux of CO_2 in carefully controlled field experiments that reduce complexity by normalizing for important variables affecting C sequestration, such as advective import and export of carbon and net ecosystem productivity. Accounting for emissions of methane and other GHGs will also be critically important [107].

Currently, most harvested seaweed is consumed as food, made into animal feed, or used to make colloids [117]. These products are valuable but do not result in carbon (C) sequestration on timescales relevant for climate change mitigation due to their relatively short turnover times [11]. Using seaweed as food may reduce GHG emissions to the extent that it replaces GHG-intensive foods, but GHG emissions associated with processing seaweed into some types of food could reduce or even obviate that benefit [72]. Efforts to understand the major sources of these emissions (e.g., [138]) and reduce them (e.g., [143]) are underway.

While many uncertainties remain, products made from seaweed are being developed that could generate added economic value and result in reduced GHG emissions. These include biofuels del Río et al. [43,28], bioplastics [145], seaweed-based fertilizers and biostimulants [35], and feed supplements that may reduce methane emissions from cattle [135,81,84]. Still other seaweed uses may result in new carbon sequestration or GHG reduction pathways. These uses may include seaweed-based construction materials [118,31], durable bioplastics [31], and the application of soil amendments made from seaweed to reduce GHG emissions [105]. It is important to note that the effects of seaweed products on atmospheric GHG concentrations are uncertain: ascertaining these effects will require comprehensive analysis of the inputs, processes, and net GHG emissions associated with each type of product or use. The cost-effectiveness of making such products also remains unclear. Using seaweed to make such products may allow for the verification and quantification of climate benefits through Life Cycle Analysis [51] or other analytical methods that fully account for GHG sources and sinks.

It is possible to envision many types of interventions that could increase the amount of food, economic development, and climate benefits from seaweed systems. Informed decisions as to which interventions should be encouraged through policy development and investment will require evaluations of climate benefits, other social, economic, and ecological benefits, and the social and ecological risks associated with each intervention. Toward that end, we reviewed literature to evaluate what is known about carbon stocks and flows associated with natural seaweed stands and seaweed farms, and used a participatory system mapping process (https://www.simfo.org/) to identify types of interventions and conditions that could result in reductions of atmospheric GHG concentrations mediated by seaweed systems, and to evaluate these interventions with respect to their readiness for implementation. We used the following search terms to drive the literature review: "seaweed carbon sequestration", "seaweed farming", "carbon sequestration", "macroalgae", "carbon", "seaweed stands", "natural seaweed beds", "seaweed replacements", "emissions", "biogas", "biochar", "blue carbon", "life cycle assessment", "fertilizer". To prepare system maps, we first prepared base carbon stock and flow diagrams based on the literature review. We then convened a series of 3 workshops in which 29 experts from academic institutions, US government agencies, private foundations, the seaweed farming industry, and NGOs were first asked to enhance the carbon stock and flow map with additional stocks and flows. These experts represented a range of disciplines, including phycologists, seaweed farm experts, marine ecologists, social scientists, and economists. Next, the experts were asked to elucidate the drivers which add to or dissipate the carbon stocks, as well as the uncertainties associated with quantifying these drivers, stocks, and flows. Kumu notation software (https://www.kumu.io) was used to track expert input onto the system map.

The resulting system map (a simplified version of which is depicted in Fig. 1) depicts some of the complexity of any seaweed system, while also showing where the system could be modified to facilitate the development of strategies aimed at enhancing carbon sequestration or avoiding GHG emissions using seaweed.

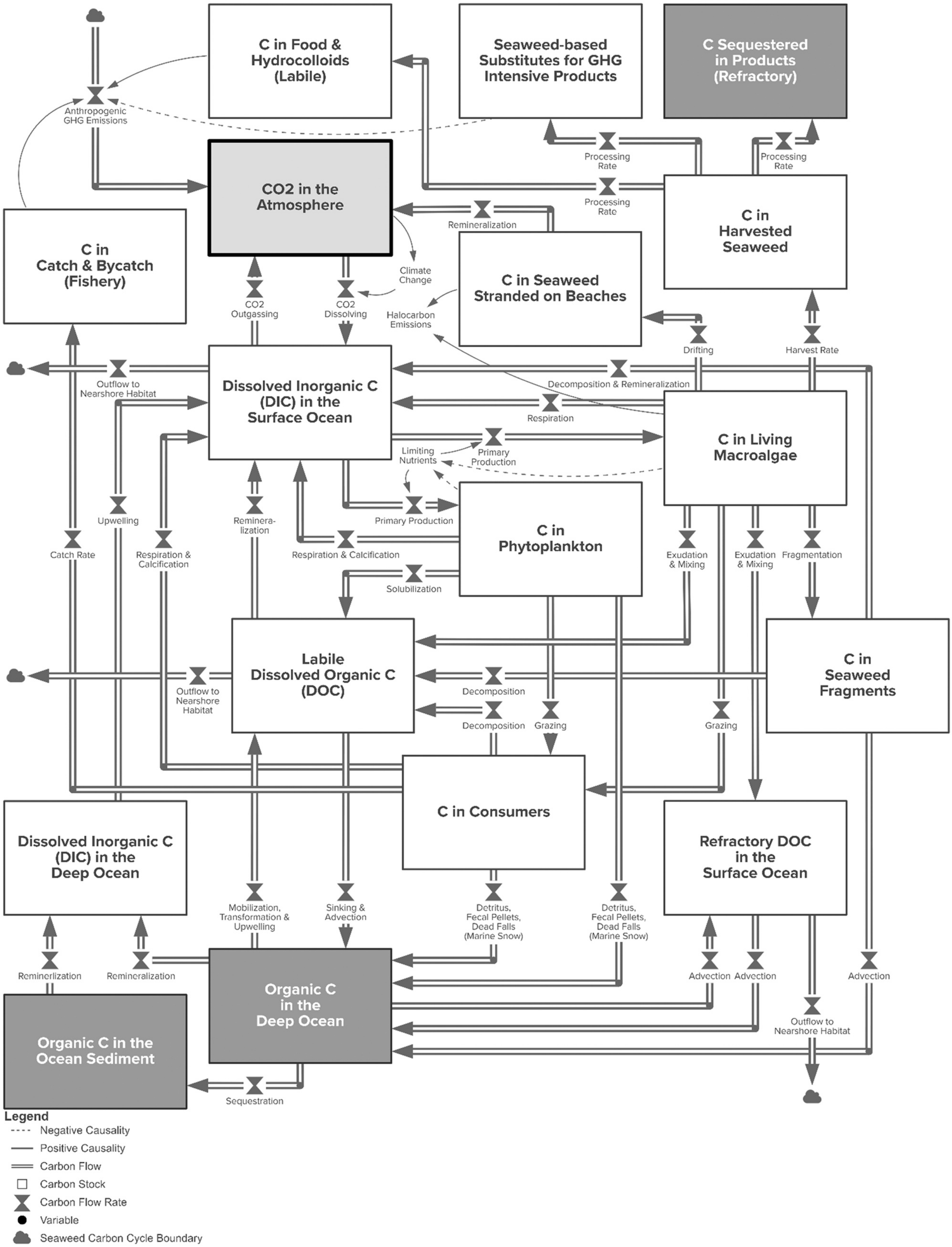

Fig. 1. Simplified map of carbon stocks and flows through a generalized seaweed system. Boxes represent carbon stocks, gray boxes represent carbon burial, double lines represent flows of carbon, inverted triangles represent flow rates, solid arrows represent positive feedback (an increase in one variable results in an increase in another), and dashed arrows represent negative feedback (an increase in one variable results in a decrease in another).

The system mapping process included both the biophysical and human dimensions of seaweed socioecological systems, making it possible for the experts to qualitatively evaluate the co-benefits and risks associated with interventions aimed at increasing climate benefits. Finally, based on the outputs of the mapping exercise and literature review, we characterized the benefits and risks of three interventions aimed at enhancing carbon sequestration and avoided GHG emissions associated with seaweed systems: (1) conserving and restoring natural seaweed stands; (2) increasing the productivity of seaweed farms; and (3) expanding seaweed farming along with developing markets for seaweed-based products that sequester C, replace GHG-intensive products, or directly reduce GHG emissions.

2. Carbon sequestration by natural seaweed stands

While natural stands of seaweeds generally fix C rapidly, much of this C is converted into biomass and dissolved organic carbon (DOC), resulting in relatively rapid remineralization back into CO_2 [125]; hence, only a portion can be sequestered on a timescale of centuries or millennia. Some of the biomass is grazed, resulting in remineralization via respiration [34] as well as some C deposition via defecation [101]. Prevailing currents and circulation can also transport biomass onto beaches. Krumhansl and Scheibling [75] estimate that as much as 82% of kelp productivity is lost to processes such as grazing, fragmentation, incremental erosion, and periodic loss of holdfasts and thalli. A portion of the DOC exuded by seaweeds is also remineralized to CO_2 in surface waters via microbial decomposition (i.e., labile DOC), with the rest being resistant to decomposition (i.e., refractory DOC) [124,136,74]. Some of the fragments that break off seaweeds also enter the food web and are remineralized, while some are deposited in sediments or advected to deep water (along with refractory DOC) which likely results in C sequestration [112,74]. Recent evidence suggests that certain molecules exuded in great abundance by brown algae are highly refractory but difficult to measure and not routinely screened (e.g., fucoidan) and may therefore represent a large pool of sequestered carbon that has not been accounted for [15,95].

Seaweed stands are subject to seasonal variations in sporulation and grazing pressure, along with occasional large losses of biomass (e.g., during storms or ice scouring), which can influence the amount of fixed C that is sequestered [125]. Of course, the source of recruits and the type of substrate at a site will influence species composition as well as the size and density of the stand, which also influence C uptake. Many of the factors that influence C uptake and sequestration by seaweed stands are associated with the species of seaweed (e.g., kelp vs encrusting species, climatic zone (e.g., temperate, tropical, subtropical) [37], geology (e.g., the nature and extent of substrate suitable for seaweed attachment and of sedimentary basins), prevailing winds, and oceanography (e.g., advection to deep water, current speeds affecting sedimentation rates, storm events, etc.).

The status of a naturally-occurring seaweed ecosystem as a C sink or source is determined by the balance between C uptake, storage, and loss which is in turn mediated by many biogeochemical processes that include photosynthesis, calcification, microbial uptake of DOC exuded by seaweeds, and the import and export of both dissolved and particulate C [42]. Different types of seaweed process C differently, with implications for the overall rate of sequestration. For example, calcifying algae both photosynthesize and calcify, and the net results on pCO_2 levels depend on a number of factors [8]. Calcifying algae can also grow on seaweed, complicating the estimation of carbon sequestration by a seaweed bed. Depending on the ratio of calcification to photosynthetic C fixation, this could offset a major fraction of the effects of autotrophy. This offset could be as much as 60% for pelagic *Sargassum* [8] and $>$ 100% (i.e., net heterotrophy) for seaweeds associated with coral reefs. Gallagher et al. [42] point out the importance of accounting for the input of allochthonous carbon subsidies from surrounding coastal waters and rivers, as these inputs can also offset autotrophy in the seaweed system. The degree to which C is sequestered and even the direction of C flux (from the atmosphere to the ocean or vice-versa) is also influenced by the scale of analysis [42]. Large system boundaries that include C exchange with other parts of the ocean, or which include areas of very high respiration, may cause the system to be a net source of C. More studies of air-sea C flux in different kinds of seaweed stands and farms under different environmental conditions compared with reference sites would be useful for determining the conditions under which seaweed systems are C sinks.

The role of pelagic seaweed in C sequestration is less well understood than for coastal seaweed beds. Accumulations of pelagic seaweeds can become quite large due to ocean gyres and eddies that concentrate floating species like *Sargassum spp*. These seaweeds can form very large floating masses up to 588 km^2 in area and 500 cm thick [26,74]. It has been estimated that about 10% of the production of pelagic *Sargassum spp.* in the Atlantic sinks to the seafloor in deep water as fragments, and there are also massive episodic injections of pelagic seaweed biomass into deep water during storms [74]. Both the chronic and episodic advection of this biomass presumably result in some C sequestration. There is considerable uncertainty over the amount of C stored in pelagic seaweed aggregations, and few estimates. One exception is that of Hu et al. [55] who suggest that *Sargassum* in the North Atlantic alone could potentially store up to 0.013 GT CO_2.

Seaweed aggregations can sometimes have adverse impacts on tourism and other activities as the biomass starts to decompose after reaching shallow waters and beaches [26], resulting in undesirable odors and other nuisance factors, as well as some release of C (and methane, if landfilled) to the atmosphere. To sequester more of the carbon stored in this seaweed biomass, it would be necessary to harvest the seaweed and direct the biomass into a GHG reduction pathway, such as sinking [74] or products that sequester C, replace GHG-intensive products, or suppress GHG emissions. However, any of these pathways could pose ecological risks if they result in large scale harvesting, as pelagic seaweeds are important habitats for many species, both at sea and after the biomass strands on beaches [99,17]. These seaweeds are also an important source of fixed carbon and nutrients to coastal ecosystems, including beaches (SAFMC 2002); hence, removal of pelagic seaweeds could reduce these ecosystem services.

The rate of C sequestration by natural seaweed systems remains uncertain, as does the global C stock represented by seaweed. While the area of standing stocks of natural seaweed beds has been estimated to be 6.06–7.22 million km^2 with a net primary production of 4.84 GT CO_2 yr^{-1} [33], the amount of C present within seaweed stands is highly uncertain, ranging from 0.028 to 9.35 GT [58]. Seaweed species vary markedly in C content and areal density, hence additional data and models accounting for these differences are needed for a more accurate estimate of C stocks in natural seaweed stands. Taking some but not all of the factors that influence C sequestration into account, Krause-Jensen and Duarte [74] roughly estimated global C sequestration by seaweeds to be between 61 and 173 Tg C/yr (0.22–0.62 GT CO_2 yr^{-1}) based on the amount of C export sequestered, noting that the large range indicates the need for fuller accounting of the processes that affect carbon sequestration [74].

The context-specific factors that influence C fluxes through seaweed stands must be better understood to accurately quantify C sequestration. It will also be necessary to understand and accurately quantify C sequestration of the current system relative to that of a baseline or alternative stable state. These states can be less or more autotrophic [42] than the current state of the seaweed system and may export C at different rates [30]. The processes that determine C sequestration by seaweeds are all likely to vary with dominant species, bed density, wild harvest intensity, nutrient availability, grazing intensity, season, and other factors. They will also likely vary with environmental conditions such as whether the seaweed is subjected to high current and wave energy, steepness of the gradation of the bottom to depth, sediment conditions, and other factors [89].

The potential for seaweed conservation and restoration for increasing carbon sequestration by natural seaweed beds depends in part on the degree to which seaweed beds have declined. Natural seaweed populations have declined very steeply in certain regions due to climate change, fishing pressure, excessive sedimentation, and other factors. For example, a 93% decline in kelp cover was observed off the California coast in the last 20 years (Rodgers-Bennett and Catton 2019). Kelp forests appear to have declined about two and four times faster than coral reefs and tropical forests, respectively [36]. However, these declines may be offset by increases in other areas, resulting in a relatively small global average decline rate of 1 or 2% [76]. If the average decline rate is indeed small, then even though restoration efforts would result in an expansion of seaweed cover, this might equate to relatively low additional C sequestration potential (compared with additional C sequestration if decline rates are high). On the other hand, the potential for additional C sequestration via seaweed stand restoration could be high for specific stands, depending on the availability of suitable habitat and the extent of seaweed biomass loss. Restoration of seaweed stands that have been lost offers an opportunity to store additional C into seaweed biomass for as long as the biomass can be maintained, minus the C transferred to the food web. However, because many factors affect biomass levels in seaweed beds, biomass levels can be highly variable [106], increasing the vulnerability of the C stored in biomass to remineralization.

Conservation and restoration efforts aimed at increasing C sequestration by natural seaweed stands could be challenging because of context-specific differences in the factors that limit seaweed productivity and longevity of storage, including climate change, depletion of predators of grazing species, sediment input, disease, and other factors. A recent meta-analysis of seaweed restoration studies suggests a relatively high rate of success [34], however many of these have been small in scale and the results perhaps do not reflect failures that are unreported in the literature. Eger et al. [34] report on some large-scale restoration successes as well. The Nature Conservancy offers useful guidance on how to develop kelp forest restoration plans [46]. Shifts in seaweed distribution due to climate change and other factors pose another challenge to seaweed conservation and restoration efforts [137]. Moreover, C sequestration by natural seaweed stands is challenging to quantify because many processes that occur within and outside of the stands influence it.

Based on these considerations, we conclude that while it is unclear how significant natural seaweed systems are as C sinks, conservation of seaweed stands would generate many co-benefits such as biodiversity enhancement [121,5,69] and present relatively few social or ecological risks. Emerging restoration models may be capable of delivering social and economic benefits to small-scale fishers and of maintaining seaweed biomass. For example, in the Urchinomics model, fishers are paid to harvest "empty" urchins from urchin barrens, which are then fed in cultivation systems to enable them to be sold into premium markets [129,130].

3. Carbon sequestration by seaweed farms

The potential for C sequestration by natural seaweed beds is constrained by factors such as natural productivity limits, dependence on certain types of substrate and water depths, biofouling, losses of C to DOC exudation and grazing, and the rate of natural advection of refractory DOC and fragments to sediments and deep waters [29], among others. Moreover, C sequestration by natural seaweed beds also depends on allochthonous C inputs and respiratory losses [42].

Seaweed farming can, in concept at least, reduce some of these constraints on C sequestration by seaweed. Farming methods that increase productivity and locating farms near advective flows to deep water and depositional basins, for example, could result in increased C sequestration. There is some evidence that seaweed farms drive deficits in pCO_2 [140], suggesting that CO_2 uptake by seaweeds and other autotrophs exceeds CO_2 release rates via respiration and other processes under some conditions; however, the complex chemistry of CO_2 in seawater makes this inference uncertain. Because net ecosystem production rates of seaweed farms may not be significantly higher than those of natural stands, and because the degree of system autotrophy or heterotrophy appears to be highly variable in both natural stands and in farms [109], the conversion of harvested seaweed into products that store C, directly reduce CH_4 or N_2O emissions, or replace GHG-intensive products may prove to be key for increasing climate mitigation by seaweed systems.

Farmed seaweeds can be highly productive. Some farmed seaweeds, such as the kelps *Macrocystis, Saccharina,* and *Laminaria,* have very high rates of productivity and C fixation on the order of $\geq$ 3000 g C m^{-2} $year^{-1}$. Several other species have productivity rates of about 1000 g C m^{-2} $year^{-1}$ [22]. Productivity and resilience can be increased by farming practices that optimize spacing, choice of species or cultivars, timing of seeding and harvesting, and other operational aspects [18,114,127]. Several breeding programs are ongoing with the kelp *Saccharina* and *Macrocystis* with the goal of enhancing productivity by 20–30% (WHOI 2022; [59]). It is important to note that some measures aimed at increasing productivity may have adverse impacts on net C sequestration. For example, nutrient limitation could be overcome via artificial upwelling [73], however, this could entail added expense and energy inputs [89] and may introduce another C loss factor, since generating an upwelling could liberate deep ocean dissolved CO_2 [31,73].

Limitations on seaweed production imposed by the need for suitable habitat can also be overcome by farming seaweeds, by providing artificial habitat for spore settlement and grow-out. In theory, seaweed can be grown anywhere in the ocean where sufficient light and nutrients are available. Froehlich et al. [40] estimated that about 48 million km^2 of ocean area may be suitable for seaweed farming, based primarily on light and nutrient availability. Using a dynamic kelp growth model, Strong-Wright and Taylor [116] found favorable conditions for growth of *Saccharina latissima* across a large area of the Atlantic Ocean north of 40 N. A new study suggests that about 0.3% of ocean area (~1 million km^2) could be profitably farmed if seaweed was used for food [27]. These estimates are hypothetical, as nutrient availability may limit seaweed production (e.g., [96]), seaweed growth may be vulnerable to climate change impacts, and offshore waters may prove in other ways to be unsuitable for seaweed farming. In addition, seaweed farming will be constrained by economic feasibility and other factors; seaweed farming outside Asia and some other low-income regions is still constrained by economic and trade conditions. Hence, the extent of potential farmable ocean area remains poorly understood. The National Oceanic and Atmospheric Administration's effort to identify Aquaculture Opportunity Areas represents a significant refinement in the identification of areas that are suitable for ocean farming but is restricted to a few regions within the US EEZ [103,87] and still requires ground-truthing. Despite the high uncertainty, it seems clear that only a small fraction of the suitable ocean area is currently being used for seaweed farms, which cover only about 1600 km^2 currently [32,40], suggesting high potential for expansion.

The quantity of C sequestered by new seaweed farms is likely to vary dramatically depending on siting, operations, and the ways in which the yield is used ([14], Arenzo-Soltero et al., 2022; [39]). DeAngelo et al. [27] found that net cost of seaweed farming per ton of CO_2e is sensitive to transportation distances, capital inputs, seeded line, and other factors. Hence, the range of C sequestration that may be possible as a result of expanded seaweed farming will likely be very large, even once sufficient data are available on rates of C absorption, remineralization, and storage to estimate C sequestration from seaweed farms. At very large scales, nutrient availability, impacts on open ocean ecosystems [13], and conflicts with other claims on marine space could constrain offshore seaweed farming [32]. Farming seaweed in waters that are enriched in nutrients as a result of agricultural runoff or atmospheric deposition may also reduce nutrient competition, but this could compromise the perceived quality of the seaweed harvest and could have an impact on certain product certifications and labels important for marketing and associated price premiums (e.g., “organic” labeling). In addition, the environmental benefits of seaweed farming are transient where seaweed farming is seasonal (e.g., [142]).

Seaweed farm yield can be processed into a variety of products, with varying potentials to enhance the climate benefits of seaweed. This also creates an opportunity to facilitate verification and quantification of the net effects of seaweed farms on GHGs through life cycle analysis [51]. Such products could also improve the cost-effectiveness of seaweed as blue carbon. DeAngelo et al. [27] used coupled dynamic seaweed growth and technoeconomic models to estimate the costs of global seaweed production and related climate benefits. According to these authors, under the most optimistic assumptions, sinking farmed seaweed to the deep sea to sequester a gigaton of CO_2 per year could cost US$480 per tCO_2 on average, while using farmed seaweed for products that result in a reduction of a gigaton of CO_2-equivalent GHG emissions annually could return a profit of $50 per tCO_2-eq. The amount of C stored and the duration of C storage in products currently made from seaweed is probably relatively small, as the vast majority of seaweed is used in ways (food, hydrocolloids, and other products) that result in the rapid cycling of fixed C back to the atmosphere [11], resulting in limited C sequestration. However, new products such as mortar and building materials made from seaweed [100,118,82,88] would increase the duration of C storage. Moreover, growing demand for substitutes for GHG-intensive foods and other products such as fuel and plastic creates some scope for reducing future GHG emissions via new types of products made from seaweed [125,32] or via ruminant feed supplements [132].

Because many of the constraints to C sequestration in natural seaweed stands can be overcome by farming seaweeds, seaweed farming appears to have considerable potential for enhancing C sequestration and for reducing GHG emissions. The 2021 study board on ocean CDR convened by the U.S. National Academies of Science, Engineering and Medicine (NASEM) estimated that farming a 100 m wide continuous belt of ocean along 63% of global coastline (about 73,000 km^2) could sequester about 0.1 Gt CO_2 yr^{-1} if all the biomass were sunk directly into the deep ocean [89]. This would represent a 45-fold increase from the current areal extent of seaweed farming (1600 km^2; [32]) but would represent only about 0.2% of the total suitable farmable area estimated by Froehlich et al. [40] or about 7% of the area that could be farmed profitably as estimated by DeAngelo et al. [27]. This estimate rests on several simplifying assumptions: (1) 8% of DOC exuded by the seaweed is refractory and becomes sequestered; (2) 20% of the biomass is lost to breakage, grazing, and other factors; (3) yield will approximate that of a natural kelp forest (1 kg dry weight m^{-2}); and (4) 1.5 harvests will be completed each year. It is unclear how much of this sequestered fraction would be offset by the consumption of allochthonous organic carbon by the organisms and microbes associated with the seaweed [42].

Growing large amounts of seaweed in open ocean waters in order to achieve the scale required to sequester a significant amount of atmospheric C would likely have a range of ecological effects [13]. Because seaweeds have relatively large nutrient requirements and store nutrients far longer than phytoplankton, and because many open ocean waters are low in nutrients, open ocean seaweed farms could compete for nutrients with naturally occurring phytoplankton communities [4]. This nutrient competition would be expected to have a variety of effects on open ocean communities that are important components of the ocean’s biological pump, which exports C from surface waters to depth, resulting in C sequestration [13]. As an illustration of the potential scale of such effects, a recent study estimates that by 2026, seaweed farms could potentially use all of the anthropogenic nutrient runoff in China [141]. There is concern that shading and the highly efficient uptake of nutrients by large-scale seaweed farming could reduce phytoplankton productivity in some areas, with adverse impacts on marine food webs [13,18]. Differences in the types of DOCs exuded by seaweeds and phytoplankton and the release of halocarbons and volatile organic compounds while seaweeds are at the surface can also impact open ocean ecosystems and the climate system if offshore seaweed farming expands [13,8]. While emissions of some types of halocarbons (DMS) may reduce radiative forcing [148,8], other types could increase radiative forcing or have adverse impacts on stratospheric ozone [122,68]. However, the impacts on warming in either direction are likely to be small, as the majority of the halocarbons emitted by seaweeds have low residence times in the atmosphere [68,85]. The effects of halocarbon emissions from seaweed remain uncertain [68].

While the climate and ecological effects of large-scale seaweed farming are not yet well documented, a recent study of a fairly large *Sargassum* farming operation (ca. 1000 ha producing 7000–9000 dry tons of seaweed per year) in the East China sea suggests that waters within the farm had elevated pH and reduced inorganic N levels relative to adjacent and offshore control areas [123], suggesting some degree of ocean acidification remediation and reduction of eutrophication potential. Phytoplankton abundance was lower and diversity was higher within the farm, suggesting light and nutrient limitation induced by the seaweed farm as well as possible inhibition of certain dominant phytoplankton species [123]. The inhibition of bloom-forming phytoplankton species may be restricted to only part of the year [142].

Seaweed farming currently involves some fossil fuel use, resulting in GHG emissions. Operating processes (e.g., harvesting) and value-add processes (e.g., drying) could be optimized to reduce or prevent emissions, for example via conversion to fuel efficient or zero emission boats, changes in flushing rates, the use of low energy intensive drying methods [115,69], or reducing the GHG footprint of other aspects of seaweed processing [110,113,14,2]. If these sources of GHG emissions can be reduced, and if seaweed farm yield is used to make products that sequester C, replace GHG-intensive products, or directly suppress GHG emissions, seaweed farms have the potential to contribute to the mitigation of climate disruption while generating a number of other social, economic, and ecological benefits.

4. Implications of seaweed-based products and uses

There is a widespread perception that sinking seaweed may result in a C sequestration pathway that is easier to measure than the natural sequestration pathway. Hence, there has been considerable interest in sinking seaweed on the part of scientists, entrepreneurs, and investors [10,120,32,40] particularly with regard to seaweed farming in offshore waters. However, measuring and verifying C sequestration via this pathway may prove challenging, due to the complex dynamics of C in marine systems. Some studies raise concerns about the cost-effectiveness of this pathway given that none of the value inherent in seaweed as a product can be realized [102]. This pathway obviates the many valuable food and economic benefits conferred by seaweed, limiting contributions to UN Sustainable Development Goals. Moreover, adding large amounts of seaweed biomass to deep waters could result in adverse ecological effects in ways that are similar to modeled impacts of other ocean-based CDR pathways that result in the export of atmospheric carbon to deep ocean waters and sediments [13].

An alternative to sinking seaweed may be to create products from seaweed that store C, thus decoupling sequestration from ocean biogeochemical processes, perhaps making monitoring and verification less challenging, while capturing social, economic, and ecological value of seaweed and reducing impacts on ocean ecosystems. A variety of compounds can be made from seaweed, with potential applications to durable construction materials [118], binding agents for mortar and concrete [118,82,88] and other building materials [100]. It remains to be seen whether the durations of carbon storage in such products are long enough to be relevant for reducing radiative forcing, and whether the production of such products results in net reductions in GHG emissions.

Carbon sequestration is not the only way seaweed farm products could help stabilize the climate system. Reductions in GHG emissions could be realized to the extent that seaweed-based products are substituted for products made from petroleum or by using GHG-intensive processes. Moreover, uses of seaweed that result in reduced emissions of more powerful GHGs like nitrous oxide (N_2O), or those that both trap more heat and have shorter atmospheric lifetimes relative to CO_2 such as methane (CH_4), may present options for maximizing the effects of seaweed systems on mitigating climate change that can be quantified and verified. Conversion of seaweed to biofuel could reduce GHG emissions to the extent it is substituted for fossil fuels or as a feedstock in a bioenergy with C capture and storage (BECCS) system [57]. Seaweed has been used successfully to make single-use bioplastic wrapping, as well as more durable bioplastics [93] which could result in reduced GHG emissions to the extent they are substituted for GHG-intensive plastic wrap and other plastic products [79].

Some seaweed products and uses may result in reduced GHG emissions in other ways. Application of seaweed-based soil conditioners could potentially spare the release of GHG such as N_2O associated with chemical fertilizer production and use [111] while increasing crop yields [105,144,23] and crop and soil quality [35,49]. Use of seaweed-based soil conditioners may indirectly influence the production of N_2O by changing soil chemistry, especially in slightly acidic soils, although more research is needed [122]. This application may be limited by the relatively small concentrations of macronutrients present in seaweed biomass [106]. Moreover, there is some evidence that biochar made from seaweed can reduce CH_4 emissions from rice paddies [105], (Huang et al., 2019) and reduce N_2O emissions in a variety of agricultural soils to offset atmospheric warming [52]. However, the net climate benefit of these pathways are uncertain due to GHG emissions associated with making and using these products and other factors [1,105], and concerns remain about the effects of seaweed additives on crop yield, with yield increasing in some cases and decreasing in others.

Animal husbandry operations can be large sources of GHGs, due both to ruminant enteric methane emissions and to microbial decomposition of organic carbon and nitrogen in animal waste to CH_4 and N_2O. There is evidence that inclusion of small amounts of certain types of seaweed (e.g., *Asparagopsis taxiformis or armata*) to cattle feed can reduce methane emissions [132,70,81,84]. The efficacy, health and safety impacts of this pathway are under active investigation.

5. Additional benefits associated with carbon sequestration by seaweed

Seaweed can generate a number of benefits for marine ecosystems, in addition to the climate change mitigation benefits described above. It is important to note that some of these benefits are so significant that they could rightly constitute the main benefits of seaweed farming, with climate change mitigation as a secondary benefit, especially in contexts in which the climate benefits are small or highly uncertain. Here, we summarize some of these additional benefits that could be generated by natural seaweed beds and seaweed farms.

Seaweed farms and natural seaweed stands appear to have the capacity to ameliorate certain types of water quality problems. Rapid uptake of CO_2 via seaweed photosynthesis, which removes dissolved inorganic carbon and increases seawater pH, can remediate ocean acidification locally [86,140]; however, the strength of this beneficial effect is likely to depend on the specific geographic and biogeochemical context. For example, photosynthesis by seaweeds growing in habitats that are low in biogenic carbonate minerals (e.g., coral sands or shell sediments) may facilitate calcification by shellfish and other calcifying organisms by locally increasing the saturation state of aragonite, resulting in CO_2 release. Moreover, the effects of CO_2 uptake by seaweeds on pH may be limited not only in areal extent but also to certain depth strata and are difficult to distinguish from the effects of phytoplankton CO_2 uptake [54]. Because many seaweed species take up nutrients rapidly and, in some cases, can deplete nutrients to very low levels [97], seaweed stands and farms can mitigate nutrient pollution [141].

Seaweed systems can also contribute to biodiversity [121] and habitat provisioning [77] if they are sited and managed properly. Siting seaweed farms near natural seaweed stands may enhance these ecological benefits, e.g., via the movement of organisms from the farm. Seaweeds may also improve habitat quality by facilitating the settlement of fine sediments originating from soil erosion [65] and by removing heavy metals and nutrient pollution [147,65].

In addition to these ecological benefits, seaweeds can generate several social and economic benefits. These include job creation, which can be especially important in coastal communities that are highly dependent on fisheries and need to reduce harvests temporarily in order to allow fish stocks to recover to sustainable levels [144] and therefore diversify economies. Seaweeds may also enhance fisheries production under certain conditions (e.g., where habitat is limiting fish productivity or habitat connectivity) by improving habitat conditions and by attracting aggregations of target species [104,121]. Seaweeds can be the basis for circular marine bioeconomies which recycle waste products and generate multiple benefits [146].

Clearly, seaweeds are capable of generating many benefits, but the degree to which they generate them depends on harvesting intensity as well as siting and other factors. Moreover, trade-offs exist between many of these benefits. Some types of natural seaweed beds that are not harvested could, in concept, provide consistent biodiversity and habitat provisioning benefits but generate fewer social and economic benefits than harvested beds. Rotational trimming to increase social and economic benefits might reduce the ecosystem benefits somewhat, while frequent harvests of large fractions of the standing biomass could dramatically reduce them. Natural seaweed beds can also remove nutrient and heavy metal pollution and ameliorate ocean acidification consistently if they are not harvested; however, this would limit the food and economic value of the seaweed stand.

There are also trade-offs between carbon sequestration by seaweed systems and other benefits. For example, managing a seaweed farm to maximize carbon sequestration by sinking seaweed biomass into deep ocean waters would reduce or eliminate other benefits such as food production, and may pose ecological risks to deep sea ecosystems [89]. Conversely, producing food, hydrocolloids, and other valuable products (with short lifetimes) from seaweed would likely result in less carbon sequestration due to the short life cycle of the C in these products. Wild harvesting seaweeds intensively to generate products that store C or replace GHG-intensive products would likely reduce in situ benefits such as amelioration of ocean acidity [18], habitat provisioning [18,77], and fishery enhancement [9].

6. Interventions to increase carbon sequestration by seaweed, and their potential social and economic effects

To develop guidance on which natural climate solutions to incentivize and invest in, it is useful to describe and evaluate the interventions that would be required to reduce atmospheric GHG concentrations or radiative forcing via these solutions with respect to their benefits, costs, and risks. In this section we describe three interventions for implementing seaweed-based carbon sequestration and/or GHG reduction. We also characterize the potential to contribute to climate stabilization, and ecological and socioeconomic benefits, risks, and uncertainties associated with climate mitigation potential that could be associated with each intervention (summarized in Table 1). It is important to note that at the scale of individual projects, many other context-specific factors must be considered, including C sequestration or emissions from the system prior to the project and the potential for future climate impacts to render particular pathways inviable.

Table 1
Summary of the benefits, risks, and climate mitigation uncertainties of the three interventions studied.

Conservation & restoration	Benefits: • Water quality improvement • Ecotourism and fishery enhancements through providing nursery habitat and as attractive dive locations • High levels of habitat and biodiversity provisioning • Local amelioration of ocean acidification • Carbon sequestration under some conditions through restoration of seaweed beds • Reduced GHG emissions through replacement of high emitting products with those made of harvested seaweed Risks: • Potential short-term decreases in fishery revenues if a seaweed stand is overgrazed and the predators regulating grazing pressure need to recover from fishing pressure • Genetic bottlenecks if restoration is based on a highly inbred strain, or only a few such strains; bottlenecks are difficult to identify due to the paucity of seaweed genetic diversity studies • Warming, changes in nutrient availability, increased prevalence of pests and pathogens, and other impacts associated with climate change. • Climate Mitigation Uncertainties: • Probability of recovery given context-specific drivers of seaweed bed loss and recovery • Variability in seaweed system net productivity • Fraction of carbon absorbed that is sequestered • Climate mitigation benefits of storing carbon temporarily in seaweed biomass • Environmental factors that affect air-sea carbon flux (i.e., whether atmospheric carbon is absorbed by seawater within which the seaweed stand occurs, or whether carbon is released from the seawater into the atmosphere) • Effects of halocarbon emissions from seaweed on radiative forcing
Increased seaweed farm productivity	Benefits: • Additional seaweed habitat and biodiversity provisioning • Some enhanced amelioration of ocean acidification • Excess nutrient removal, depending on scale, siting and operations • Increased yields for seaweed farms Risks: • Small-holders could be impacted by reductions of seaweed prices through increased supply • Higher productivity seaweed farms located in nutrient-poor water could reduce phytoplankton production • Sequestering C by sinking seaweed would increase the advection of organic C into deep water, which could alter food webs, species composition, and oxygen levels via microbial decomposition and respiration • Increased risk of spreading and impact of pest organisms associated with seaweed farming and genetic impact on wild seaweed stands • Warming, changes in nutrient availability, increased prevalence of pests and pathogens, and other impacts associated with climate change. • Climate Mitigation Uncertainties: • Environmental factors that affect net air-sea carbon flux • Variability in seaweed system net productivity • Climate mitigation benefit given different use scenarios for seaweed yield and life cycle impacts of seaweed farming and products • Effects of halocarbon emissions from seaweed on radiative forcing
Expanded seaweed farming with new products	Benefits: • High potential for reducing GHG concentrations, which could scale with increasing use of suitable farming area • Habitat and biodiversity provisioning from offshore farms • Expanded seaweed farming could result in larger scale amelioration of ocean acidification, although this requires more research Risks: • Hazards to navigation, fishing, and other uses of offshore water • Small-holders could be impacted by reductions of seaweed prices through increased supply • Higher risk of wildlife entanglement • Higher operational costs in offshore areas due to increased distance from port and harsh environmental conditions • Sinking seaweed would increase the advection of organic C into deep water, which could alter food webs, species composition, and oxygen levels via microbial decomposition and respiration • Risk of GHG emissions like halocarbons and allelopathic exudates from certain farmed seaweed species; the magnitude of this risk remains uncertain • Increased risk of spreading and impact of pest organisms associated with seaweed farming and genetic impact on wild seaweed stands • Warming, changes in nutrient availability, increased prevalence of pests and pathogens, and other impacts associated with climate change. • Climate Mitigation Uncertainties: • Climate mitigation potential given different seaweed yield use scenarios and life cycle impacts of farming and products • Climate mitigation potential given ocean area that can be farmed profitably, without adverse impacts on other uses of marine space or on ecosystem structure or function • Environmental factors that affect net air-sea carbon flux • Effects of halocarbon emissions from seaweed on radiative forcing

6.1. Intervention 1: conserve existing seaweed beds and restore beds that have declined

This would likely involve research to ascertain context-specific factors causing declines and/or limiting restoration potential, followed by context-specific threat reduction activities (e.g., harvesting grazing organisms whose populations have exploded due to lack of predation; regulations to reduce fishing pressure on predators of grazing species; reduction of pollution, etc.).

These activities could require policy and regulatory reform, increased funding, or new policies and regulations. Implementing entities and specific restoration actions would vary depending on the nature of the threats. For example, if overfishing of predators and subsequent increases in grazer abundance is a major factor limiting seaweed restoration at a site, fishery management agencies could reduce fishing pressure on the predatory species. If, on the other hand, excessive turbidity related to deforestation or agricultural practices were determined to be major factors limiting seaweed restoration, entities with jurisdiction over these practices would need to be engaged, affecting different sets of stakeholders. Programs to build capacity among small-scale seaweed harvesters and connect harvest operations with markets could result in a more equitable distribution of the benefits of conservation and restoration of seaweed stands. Specific interventions would occur in nearshore tropical and temperate waters with sufficient light, nutrient, and substrate availability to support seaweed growth. Carbon removal via seaweed bed restoration within exclusive economic zones (EEZs) that is sufficiently well documented could be credited in

Nationally Determined Contribution (NDC) accounts.

Potential for climate mitigation: Conservation of existing seaweed beds would probably not result in additional C sequestration, but afforestation of seaweed beds that have declined could have this effect under some conditions. The quantity of C sequestration that would result remains highly uncertain, but it has been estimated that if large scale seaweed afforestation in suitable habitats were to occur, these ecosystems might sequester about 0.634 GT CO_2 yr^{-1} [74]. It is important to note that Gallagher et al. [42] estimate that, using the same parameters for seaweed NPP but extending the sequestration measurements to include the effects of other ecological processes (e.g., allochthonous C inputs, heterotrophy, etc.), natural seaweed ecosystems are on average a carbon source, rather than a carbon sink. The fact that many factors influence C sequestration by seaweed via natural processes of C export and burial puts a premium on decoupling pathways for using seaweed to sequester C and reduce GHG emissions from the ocean. For example, use of larger fractions of harvest from natural seaweed beds to make refractory products that store C for decades or to make products such as bioplastics, biofuels, or fertilizers that result in avoided GHG emissions would enhance the role of natural seaweed beds in climate stabilization, but the potential would likely be relatively low due to tradeoffs between harvesting and the provision of ecosystem services.

Social and economic effects. This intervention could benefit fisheries and ecotourism, as seaweed beds can be important nurseries for sport and commercial target species and many are attractive dive tourism locations [119,12,34]. However, it could also have negative impacts on short-term fishery revenues in contexts which require reductions in fishing pressure to restore predator populations capable of regulating grazing pressure, if that is what is needed to restore a seaweed stand.

Ecological benefits: High levels of habitat and biodiversity provisioning, local amelioration of ocean acidification, water quality improvement, and fishery enhancement.

Ecological risks: We do not anticipate large adverse ecological impacts from the conservation and restoration of natural seaweed stands. There may be risk of genetic bottlenecks if restoration is based on one or few highly inbred strains [129].

Climate risk: Natural seaweed beds are vulnerable to warming, changes in nutrient availability, and other factors associated with climate change ([108,6,71]; Román et al., 2020; [83]). Pests and pathogens that affect seaweeds may also become more prevalent with climate change [134,56].

6.2. *Intervention 2: increase productivity and climate benefits of existing seaweed farms*

The productivity and climate benefits of existing seaweed farms could be increased by identifying and addressing factors that constrain productivity, such as disease, strain selection, pollution, capacity, and financing. There could also be pathways to address constraints to the development of farms that optimize for carbon sequestration, such as the quantification of carbon sequestration, research to address other aspects of a high-quality carbon credit [19], and the enhancement of markets for certain types of seaweed products and uses. Because many factors influence C sequestration by seaweed farms, increased productivity may result in increased C sequestration via the natural sequestration pathway only under certain environmental and operating conditions. This intervention could be undertaken largely by seaweed farmers, processors, blue carbon accrediting entities, and buyers, and supported by NGOs and government agencies which could provide extension services and oversight to ensure that efforts to increase productivity do not harm public trust resources or the interests of other stakeholders. In the near term, this intervention would be largely limited to farms located in nearshore tropical and temperate waters, as that is where the vast majority of seaweed farms are currently sited. To evaluate this intervention at the project scale, it will be important to carefully define “farming”, as different types of seaweed harvesting occur along a spectrum of input, from zero to some effort to increase productivity to very intensive efforts involving specialized infrastructure [131,56]. The definition of farming along this spectrum has important implications for who can access C financing related to a C project involving efforts to increase seaweed productivity, particularly for indigenous and historically marginalized communities.

Potential for C sequestration: Potential productivity increases in current seaweed farms would vary depending on local conditions, including nutrient availability, water flow, temperature, and other factors. They would also likely depend on local technical capacity. Duarte et al. [31] assume an average yield of 16 t DW ha^{-1} when estimating potential C sequestration by seaweed and note that this is nearly 10-fold lower than maximum productivity reached under intensified farming conditions. Froelich et al. (2019) use an estimate of 20 t DW ha^{-1} and also note that this is uncertain due to variability in productivity at the farm level. These considerations suggest that potential productivity increases could be large. This in turn could result in proportionally larger amounts of C storage in farmed seaweed biomass; however, the rates of several processes that influence C sequestration could change with increasing productivity, including DOC exudation rate, the fraction of the DOC that is refractory, and fragmentation rate.

Ecological benefits: Additional seaweed habitat and biodiversity, with some enhanced amelioration of ocean acidification and habitat/biodiversity provisioning as well as excess nutrient removal, depending on siting and operations.

Social and economic effects: Increased productivity of seaweed farms could benefit small-holders who currently dominate seaweed farming operations, as well as operators of offshore farms. This intervention, if highly successful, could also reduce seaweed prices by increasing supply unless demand increases more rapidly, impacting mostly small-holders who currently dominate production.

Ecological risks: Higher productivity seaweed farms located in nutrient-poor water could reduce phytoplankton production. Sequestering C by sinking seaweed into deep waters would increase the advection of organic C into deep water which could alter food webs, species composition, and oxygen levels via microbial decomposition and respiration. These risks could potentially be mitigated by sinking unusable portions of the harvest, rather than the entire harvest; however, this will require more research. In addition, biosecurity management actions should be undertaken to lower the risks such as spreading diseases, epiphytes, and the introduction of undesirable non-native organisms [24].

Climate risk: Seaweed farms are vulnerable to warming, changes in nutrient availability, increased frequency and severity of storms, and other factors associated with climate change [16,56,64]. This will likely change the distribution of suitable farming sites for some species. Pests and pathogens that affect seaweeds may also become more prevalent with climate change [134]. Fertilization and pest control will increase the risks of adverse ecological impact.

6.3. *Intervention 3: expand seaweed farming*

Most of the expansion of seaweed farming is expected to occur in offshore waters both within and beyond national jurisdictions. New governance systems will be necessary for offshore seaweed aquaculture. Here, governance systems are defined as systems capable of controlling the development and impact of industrial activity. This definition includes management activities such as goal setting, performance standard, regulations, monitoring, and implementation of accountability measures. Some nations are developing governance systems for offshore aquaculture, but governance is largely absent as very few commercial ventures currently exist. Research into the social and ecological risks that could be associated with offshore seaweed farms would be required to set performance standards, accountability measures, and other elements of an effective offshore governance system. Any governance system would also have to reduce barriers to expansion without compromising social, economic, and ecological goals. For example, the complexity and cost of aquaculture permitting in US waters is widely recognized as a significant barrier to industry expansion. Solutions may include the establishment of aquaculture enterprise zones where farmers could take advantage of government subsidized research to prepare permit applications or operate under an umbrella permit supported by several farms, performance standards, and accountability measures to mitigate risks of adverse social, economic, and ecological impacts. National plans of action and the incorporation of seaweed C sequestration into NDC accounts could also be elements of this intervention that incentivize the expansion of types of seaweed farming that sequester more C than other types.

This intervention would also include an effort to develop seaweed farms with high C sequestration capacity and promote enabling conditions, e.g., by quantifying C sequestration by different types of seaweed farms, doing research to address other aspects of a high-quality carbon credit [19], and enhancing markets for and investment in products and uses of seaweed that sequester carbon and/or result in reduced GHG emissions. Life Cycle Assessments will be necessary to account for GHG sources and reductions to quantify the net effects of seaweed products.

Sites and therefore jurisdictions for expansion are uncertain and would depend on many factors, including light and nutrient availability, proximity to shoreside support facilities and markets, areas where risk of interactions with marine wildlife is high, and others. Siting will also depend on existing claims on marine space and the need to minimize adverse ecological impacts, e.g., reductions in phytoplankton production resulting from nutrient uptake by farms. While these considerations will limit the potential farmable area of the ocean, this is still likely to be quite large. For example, in the US Caribbean and Florida, 80% of the total area within 10–100 m depth is potentially available for seaweed farming or does not appear to have any conflicts with navigation, natural resources, oceanographic conditions, etc. (NOAA OceanReports [91]). For sugar kelp, *Saccharina latissima*, in Alaska and New England, that number drops to about 20% of the total area available. But for Alaska in particular, a considerable amount of farmable area remains (over 3.5 million ha) [91]. The large and fragmentary nature of these areas (or intentional siting for this purpose) could mitigate adverse impacts caused by nutrient uptake by the farms. However, this could also result in higher costs and GHG emissions.

Potential for C sequestration: NASEM [89] estimate that farming about 72,900 km^2 of seaweed and injecting the biomass into the deep ocean could sequester 0.1 GT CO_2 yr^{-1}. This could scale with increasing use of the suitable farming area of the ocean, barring other limiting factors such as negative impact on phytoplankton productivity, open ocean ecosystems, congestion at sea, etc. Variations in the fraction of the yield that is sunk will of course alter the potential for C sequestration as well as co-benefits and risks. Overall climate change mitigation would increase to the extent that seaweed products capable of storing carbon, replacing GHG-intensive products, or suppressing GHG emissions scale if GHG emissions associated with making, transporting or using such products do not offset their climate mitigation benefits.

Co-benefits: Because floating objects and seaweed are known to attract marine life, it seems likely that this intervention could result in substantial amounts of habitat and biodiversity provisioning. Large scale seaweed farming could also result in larger scale amelioration of ocean acidification, although this requires more research.

Social and economic effects: This intervention may primarily benefit entrepreneurs with access to capital and technical expertise, perhaps to the detriment of small-holders as a result of competition in some markets. Larger scale seaweed farming could also pose hazards to navigation, fishing, and other uses of offshore waters. This intervention, if highly successful, could also reduce seaweed prices by increasing supply, impacting mostly small-holders who currently dominate production.

Ecological risks: More seaweed farms could generate multiple risks, including nutrient depletion, disease transmission, and wildlife entanglement [41]. Sequestering 1 GT CO_2 yr^{-1} via sinking seaweed into deep waters (~2000 m) would increase the injection of organic C into deep water by about 25%, a very significant increase [89] that could alter food webs, species composition, and oxygen levels via microbial decomposition and respiration. There is also a potential risk of GHG emissions like halocarbons and allelopathic exudates from certain farmed seaweed species, although the magnitude of these risks is unknown.

Climate risk: same as for intervention 2.

7. Conclusions

The literature and our systems mapping exercise indicate that the major processes that influence carbon sequestration by seaweeds are fairly well understood conceptually, but significant data gaps exist. Estimates of the amount of carbon being sequestered by seaweeds currently depend on extrapolations of the rates of C uptake, C pool size in seaweed biomass, DOC exudation, microbial mineralization, losses to grazing and senescence, and advection of C fixed by seaweeds to sediments or deep waters from limited studies of only a few species in a few locations; moreover data on these rates and pools are not often collected simultaneously or over long periods of time. More empirical, parallel studies of these rates and pools with more species under different environmental conditions would be needed to improve global estimates of seaweed carbon sequestration. It seems likely that the rate of CO_2 drawdown resulting from C uptake by seaweeds will also vary due to CO_2 concentration differentials between the ocean and the atmosphere in different parts of the ocean and at different times of the year [125,58]. More measurements of air-sea CO_2 flux will be necessary to improve estimates of CO_2 drawdown rates associated with seaweed systems. Improved estimates of the amount of marine space that could be farmed for seaweed profitably along with analysis of different product portfolio scenarios and life cycle assessment would also help clarify the global potential for seaweed systems to sequester C and result in reduced GHG emissions [51].

Quantifying C sequestration by specific seaweed farms with respect to the creation of high-quality C credits [19] will require many new data streams on C sequestration magnitude, duration, and vulnerability as well as on net impacts on GHG emissions and information on social and ecological impacts. These data will need to be context specific, as these variables will depend on oceanographic and climatic conditions at the farm site, harvest frequency and timing, fraction of biomass harvested, seaweed density, farmed species, product disposition, GHG emissions associated with seaweed production and processing, and impacts of the farm on other sources and sinks of GHGs. Such data are largely lacking; however, several research efforts are underway to fill these data gaps [47,66,108].

Natural seaweed stands and seaweed farms already produce many social, economic, and ecological benefits, including food and hydrocolloids, livelihoods and supplemental incomes for people and communities with limited economic opportunities, biodiversity provisioning, local amelioration of ocean acidification, shoreline protection, and some C depending on context-specific conditions [104,54,80]. However, there are tradeoffs inherent in the generation of these benefits. For example, farms that use seaweed to make food products or hydrocolloids would be expected to sequester less C than farms that bury seaweed biomass in the sea or on land. On the other hand, farms that maximize carbon sequestration would probably generate less food and other valuable products and co-benefits. Some farms can probably be optimized to produce many of these benefits simultaneously, perhaps through a cascading biorefinery approach [139,143,53]. However, a portfolio of farms producing different types of products and uses with different harvest cycles would probably be required to realize all the benefits that seaweeds are capable of providing at scale.

There are several ways in which C sequestration and avoided GHG emissions associated with seaweeds could be enhanced, including the three evaluated here: Conservation and restoration of existing seaweed stands, increasing productivity of seaweed farms, and expansion of seaweed farming to offshore waters with expanded markets for products that enhance C sequestration (e.g. construction materials), replace GHG-intensive products (e.g., biofuels and bioplastics), or suppress GHG emissions (e.g., ruminant feeds supplements if these prove to be safe and effective).

Conservation and restoration of natural seaweed stands appears to be a low-regrets strategy that will be important for avoiding C loss from the ocean to the atmosphere and for conserving and expanding the many benefits that seaweed generates, with few risks. This intervention would not likely result in a large increase in additional carbon sequestration because the areal extent of such efforts is constrained by available nearshore habitat. Moreover, it would probably be difficult to verify and quantify the amount of additional C sequestered because many factors influence this. However, this intervention would likely result in a large number of substantial co-benefits, including food production, fishery enhancement, biodiversity provisioning, and increased socio-ecological resilience with low risk of adverse social, economic, or ecological impact. Acceleration of C sequestration by seaweeds via this intervention would require research to identify context-specific threats to natural seaweed stands and specific areas where threats are amenable to localized threat reduction actions such as the reduction of fishing pressure or pollution and appropriate substrate [38]. Seaweed afforestation can also be expanded to suitable habitats that have not traditionally had seaweed or have not had stands for > 20 years (e.g., TBF 2022). However, in this context, the driving factors for the absence of seaweed must be established if seaweed restoration is to be successful. Moreover, restoration could require some degree of ecosystem modification, e.g., grazer control or the use of seaweed strains that are resilient to climate change.

There is also scope for increasing carbon sequestration by increasing the productivity of current seaweed farms through improved strain selection and other practices. While the potential for increasing seaweed farm productivity appears to be high, it is unclear how much additional C sequestration would result because of the complex biogeochemistry of C in the ocean. This intervention could result in additional C sequestration for existing farms and generate many co-benefits with little risk. However, C sequestration would be constrained by the relatively small area that is currently farmed (estimated to be about 1600 km^2; [32]) plus some increment to account for the business-as-usual growth rate in the number and extent of seaweed farms. Additional productivity in the near-term would likely drive the production of carbon-labile products such as food and hydrocolloids with little sequestration value, given current market structure. This would also constrain the amount of additional C that could be sequestered and the degree to which GHG emissions could be reduced via the replacement of GHG-intensive products with products made from seaweed. Enhancement of climate benefits via this intervention would require more research on high yield strains for many more species, as well as research on how to improve cultivation methods and remove constraints on productivity such as disease. Capacity building would also be required to mainstream practices that improve farm productivity, particularly in tropical regions where temperatures are already high. New policies and a robust C offset market would probably be necessary to encourage the development of products and uses that could leverage increased seaweed productivity to result in increased C sequestration and/or reduce GHG emissions.

Expansion of seaweed farming into offshore waters and scaling certain types of products made from seaweed is perhaps the most promising way to increase the climate benefits of growing seaweeds. However, this could entail significant risks to open ocean ecosystems, which are important components of the ocean's biological carbon pump that sequesters CO_2 [13]. Offshore seaweed farming is becoming feasible given rapid advances in infrastructure, farm operations, and monitoring. Farmable area is constrained by rough seas, light and nutrient availability, as well as by the need for proximity to shore-side support infrastructure, claims on marine space, and the need to avoid negative social and ecological impacts. While estimates of farmable area are uncertain, recent research that takes some of these factors into account, like NOAA's Aquaculture Opportunity Areas initiative, suggest that farmable area in US waters (where there is little seaweed farming currently) is likely large relative to the area currently farmed [103,87,92]. Further advances in how to safely sequester seaweed C, in offshore farming infrastructure (including the integration of seaweed farms on existing offshore platforms), and in understanding the fate of C absorbed by seaweed grown in different types of farms will likely be necessary to make this intervention viable NASEM [89]. While it may be possible to improve estimates of the C sequestration potential of different types of farms, many of the uncertainties that remain can only be reduced by building highly monitored farms in diverse ocean settings that are optimized for C sequestration NASEM [89] or by decoupling the main sequestration pathway from ocean ecosystems (e.g., by injecting C fixed by seaweed into geological formations [3] or converting seaweeds into products that store C, replace GHG-intensive products, or directly suppress GHG emissions).

As is the case for nearshore seaweed farming, there will be tradeoffs between benefits that offshore seaweed farms could generate. In the near term, seaweed yield from offshore farms would likely flow into food production, hydrocolloid production, and perhaps into some newer high value products such as nutraceuticals given current markets [21]. This would constrain carbon sequestration in the absence of interventions to incentivize sequestration, such as policy directives, government funding, and high integrity markets for carbon offsets based on seaweed carbon sequestration. In concept, it may be possible to develop seaweed farms that are optimized to minimize tradeoffs (e.g., farms that are trimmed rotationally to generate seaweed products that reduce GHG emissions and sinking unusable portions of the harvest, while keeping enough standing biomass in the water to generate ecosystem services). However, a portfolio of seaweed farms optimized to achieve a variety of goals may be a more viable way to minimize tradeoffs and realize more of the benefits that seaweed farming is capable of generating. Net effects of such farms on GHG emissions could be quantified with Life Cycle Analysis [51].

Seaweeds are, in concept, capable of significant climate change mitigation. While the natural C sequestration pathway for seaweed systems is constrained in several ways, products made from seaweed have the potential to result in increased C sequestration and reduced GHG emissions. However, these benefits depend on a number of variables, many of which are context-dependent. Moreover, more research will be needed to project the potential social, economic, and ecological impacts of interventions aimed at generating these benefits. To make rational decisions regarding such interventions, it will be necessary to more accurately quantify the amount of C that can be sequestered and the degree to which GHG emissions can be reduced by seaweed systems (including products) operating under different conditions, to characterize the co-benefits associated with each intervention, and to characterize risk and risk mitigation strategies so that these considerations can be weighed. For these reasons the expert group of the International Maritime Organization (IMO) stated that they could not make authoritative statements about the likelihood that individual geoengineering approaches can mitigate climate change, and with what risk levels [45]. Based on the system mapping exercise described here, the conservation and restoration of natural seaweed beds and efforts to increase seaweed farm productivity and resilience appear to be low-regrets climate mitigation strategies that can be redoubled now to generate many social, economic, and ecological benefits despite the large uncertainties surrounding their climate mitigation potential. The climate benefits of expanded seaweed farming and the scaling of products made from seaweed that are capable of replacing GHG-intensive products require more scenario development and life cycle assessment to project.

CRediT authorship contribution statement

Rod Fujita: Conceptualization, Methodology, Writing – original draft, Revision. **Simona Augyte**: Research, Writing, Investigation. **Jennifer Bender**: Review, Investigation. **Poppy Brittingham**: Review, Investigation, Editing. **Alejandro H. Buschmann**: Review, Investigation, Editing. **Max Chalfin**: Review, Investigation. **Jamie Collins**: Review, Investigation**.** **Kristen A. Davis**: Review, Investigation. **John Barry Gallagher**: Review, Investigation, Editing. **Rebecca Gentry**: Review, Investigation. **Rebecca L. Gruby**: Review, Investigation, Editing. **Kristin Kleisner**: Review, Investigation. **Monica Moritsch**: Review, Investigation, Editing. **Nichole Price**: Review, Investigation, Editing. **Loretta Roberson**: Review, Investigation, Editing. **John Taylor**: Review, Investigation. **Charles Yarish**: Review, Investigation.

Data availability

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

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