Report

Current Biology

Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting

Highlights

- ca. 48 million km^2 of the oceans are suitable for seaweed aquaculture (SA)
- Offsetting the aquaculture sector requires 14%–25% of current farmed seaweeds
- Production scale and cost are too limiting to sequester global agricultural CO_2eq
- SA could help buffer eutrophic, hypoxic, or acidic waters in at least 77 countries

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In Brief

Carbon offsetting is a contentious but growing market for mitigating climate change. Aquatic farming of seaweeds is a growing sector that may provide a new form of offsetting in the oceans. Froehlich et al. find large-scale global mitigation through CO_2eq sequestration unlikely but local to regional applications more feasible.

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Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting

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SUMMARY

Carbon offsetting—receiving credit for reducing, avoiding, or sequestering carbon—has become part of the portfolio of solutions to mitigate carbon emissions, and thus climate change, through policy and voluntary markets, primarily by land-based re- or afforestation and preservation [1, 2]. However, land is limiting, creating interest in a rapidly growing aquatic farming sector of seaweed aquaculture [3–5]. Synthesizing data from scientific literature, we assess the extent and cost of scaling seaweed aquaculture to provide sufficient CO_2eq sequestration for several climate change mitigation scenarios, with a focus on the food sector—a major source of greenhouse gases [6]. Given known ecological constraints (nutrients and temperature), we found a substantial suitable area (ca. 48 million km^2) for seaweed farming, which is largely unfarmed. Within its own industry, seaweed could create a carbon-neutral aquaculture sector with just 14% (mean = 25%) of current seaweed production (0.001% of suitable area). At a much larger scale, we find seaweed culturing extremely unlikely to offset global agriculture, in part due to production growth and cost constraints. Yet offsetting agriculture appears more feasible at a regional level, especially areas with strong climate policy, such as California (0.065% of suitable area). Importantly, seaweed farming can provide other benefits to coastlines affected by eutrophic, hypoxic, and/or acidic conditions [7, 8], creating opportunities for seaweed farming to act as "charismatic carbon" that serves multiple purposes. Seaweed offsetting is not the sole solution to climate change, but it provides an invaluable new tool for a more sustainable future.

RESULTS AND DISCUSSION

Mitigating anthropogenic greenhouse gas (GHG) emissions remains a complex and likely existential challenge in our efforts to combat climate change. The 2018 Global Carbon Budget report shows an increase in CO_2 emissions over the past 2 years, reversing the previously promising flat 3-year trend [9]. The release of the Fourth National Climate Assessment by the U.S. Global Change Research Program highlights the urgency and cost of impacts already being felt due to our changing climate [10]. Although sobering, global action to reduce the human carbon footprint is continuing to gain momentum at individual (e.g., solar panels), regional (e.g., the California Climate Action Plan), and global (e.g., 2015 Paris Climate Agreement) scales [1]. A suite of strategies are proposed and being implemented to combat climate change, including one of the most commonly cited: carbon offsetting (i.e., credit to reduce, avoid, or sequester carbon) [1, 2]. In fact, carbon markets are now the largest of environmental or emissions trading markets in the world [11]. Protecting existing carbon stocks is critical to avoiding substantial additional carbon emissions, but meaningful mitigation requires sequestering carbon from past and ongoing emissions. However, there are inherent limitations to restorative practices in offsetting; most notably, available space or habitat on land (e.g., forests) [12] and water (e.g., wild seaweed beds) [13, 14]. However, new sectors are emerging that may have substantial potential to help bolster our ability to counter emissions, one of the most promising being aquaculture (i.e., aquatic farming).

The aquaculture of finfish, crustacea, shellfish, and seaweed is one of the fastest growing food sectors on the planet, with seaweed aquaculture demonstrating the fastest growth (8% per year) [15]. Currently, seaweeds are cultured primarily for food, medicine, cosmetics, and bioenergy, with little large-scale strategic use of seaweed farming for explicit carbon offsetting [7]—biofuel being the closest precursor to such an industry [16]. However, interest in using seaweed aquaculture to combat GHG emissions is increasing [3–5]. While there is disagreement about if or how wild macroalgae meet the criteria of the Blue Carbon framework, there is mounting evidence for seaweeds' role in sequestering carbon, particularly as it relates to farmed production [5, 17–19].

Recent scientific evidence suggests that wild seaweeds may sequester significant amounts of carbon in the oceans by the organic matter (dissolved and particulate) being exported to the deep ocean (>1,000 m), where it is essentially buried [13, 20]. While actual burial can occur in more nearshore sediments, the larger seaweed carbon sink (ca. 90%) occurs through

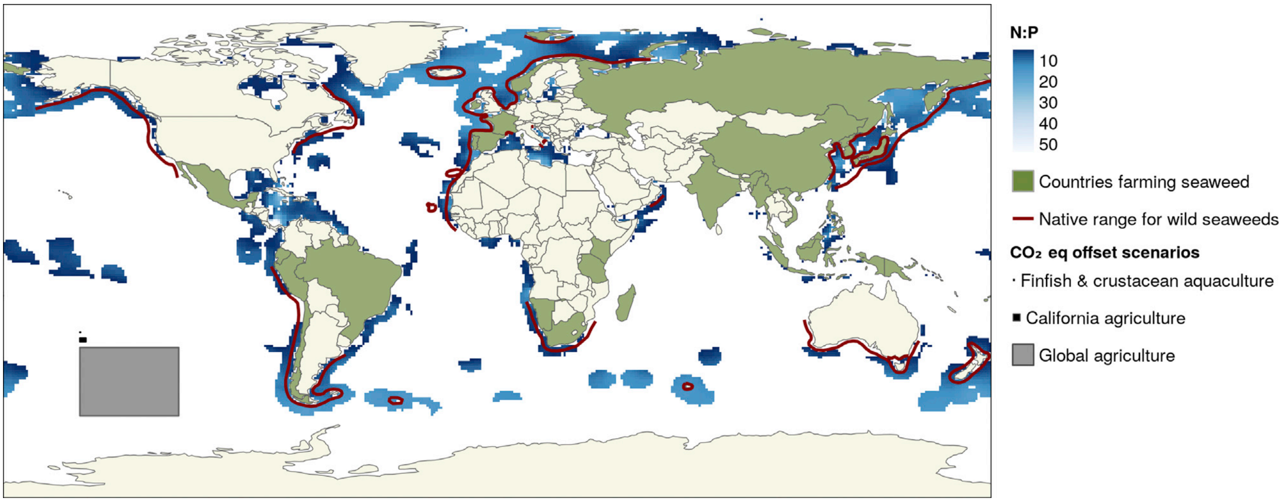

Figure 1. Ecological Suitability Map for Seaweed Aquaculture

The nutrient ratio range (N:P of 4:1 to 80:1) is depicted in the gradient of blue (30:1 mean optima); known native range of the most dominant seaweed genera adapted from Teagle et al. [22] is depicted in red, and current seaweed producing countries [15] are depicted in green. The areas (square kilometers; km^2) required to offset CO_2eq for the three scenarios are depicted by the gray and black boxes in the bottom left corner of the map and identified in the key. Aquaculture refers to (median) finfish and crustacean production. Global agriculture relates to direct emissions only.
See also Tables S1 and S2.

export via the "biological pump" of the ocean [5, 17]. When we describe the potential of seaweed aquaculture sequestration, we assume the development of technology that would facilitate and potentially optimize the offshore export process, specifically depositing seaweed in the deep ocean where the material is mineralized to remain for hundreds to thousands of years; possibly millions, if subducted (i.e., geological timescale) [21]. Under this assumption, the potential to offset GHG emissions with current levels of seaweed aquaculture is still limited; if all farmed seaweeds (33 different species and groups; Table S1) were sequestered through export facilitation, rather than harvested for direct human use, it would only remove ca. 2 million tonnes of CO_2 (1% of potential wild seaweed sequestration) [4]. This discrepancy in possible "carbon savings" from wild versus farmed seaweeds is due to extent. Current aquaculture (as of 2016) only accounts for approximately 0.05% (range = 0.03%–0.14%) of the area occupied by wild populations (ca. 1.9 thousand km^2 farmed seaweeds versus 3.5 million km^2 wild seaweeds) [4, 13]. Thus, the question motivating our research is whether there is realistic potential to scale seaweed aquaculture for the purpose of carbon offsetting and, if so, where.

Here, we specifically explore the potential and practicality of seaweed aquaculture as a new mode of carbon offsetting, with a focus on food sector emissions to explore the potential to offset themselves. First, we map potential suitable marine waters for culturing seaweed species based on documented wild ranges of seaweeds (indicator of native regions) [22], temperature ranges for growth (thermal ecotones) [23], nutrient availability (N:P ratio) [24], and countries currently producing seaweeds (metric of knowledge and infrastructure) [15]. We then assess three potential scenarios of offsetting, chosen to represent different policy objectives and scales of action, to determine the level (tonnes of production) and extent (square kilometers in suitable locations) it would take to achieve a level of carbon neutrality for (1) its own sector, the global finfish and crustacean aquaculture industry; (2) a much higher emissions food sector, global agriculture; and, to explore a policy-relevant scale, (3) agriculture emissions from an economy with strong climate action policy, the State of California, USA. We also compare regions of seaweed suitability and highly impacted coastal sites (eutrophic, hypoxic, and acidic) to explore locations for "charismatic carbon" potential, where actions provide benefits beyond offsetting. Lastly, we assess the economic feasibility of these scenarios by calculating the potential costs of seaweed sequestration (USD per tonne of CO_2eq), given current production methods and culturing of certain species.

Based on average nutrient levels and temperature suitability for a suite of seaweed species [23–25] (see Method Details in STAR Methods), we find a total area of approximately 48 million km^2 ecologically available for seaweed production (Figure 1). Notably, known native ranges of dominant seaweed genera map closely to the average nutrient ranges [22], as expected, but differ substantially from seaweed-aquaculture-producing countries (Figure 1). Specifically, 132 countries have likely suitable nutrient levels, but only 37 are currently producing. Notably, several large GHG emitters, such as the United States, have no measurable seaweed aquaculture production. Thus, there is clear scope for scaling seaweed aquaculture to offset carbon emissions, but an array of economic, social, and political barriers likely exist, as they do for the aquaculture sector in general [26]. Nonetheless, an important first question is whether farming seaweeds can offset emissions from its own sector, global aquaculture, to set the stage for recognition and possible movement in the industry to be carbon conscious.

Aquaculture now accounts for ca. 50% of seafood production (freshwater and marine) and is rapidly growing [15]. Finfish and crustacean production results in some of the largest emissions

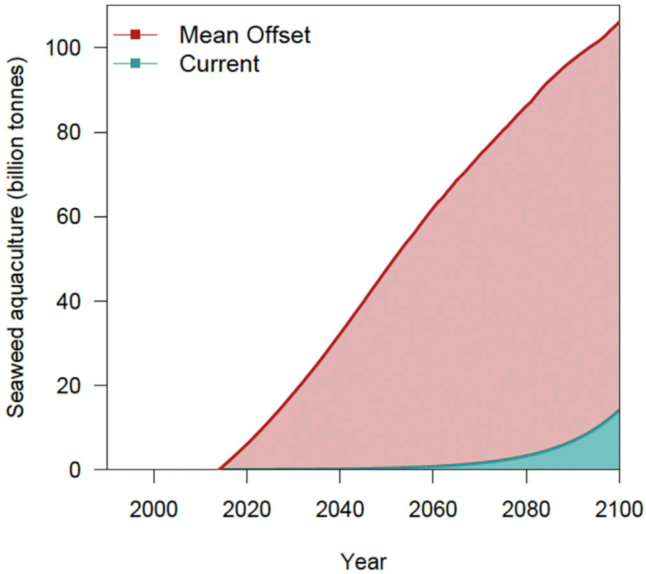

Figure 2. Comparative Trajectory of Seaweed Aquaculture, in Tonnes
Seaweed production under current exponential growth trends (aqua) versus the average amount needed (red) to incrementally increase (0.15% CO_2eq sequestration per year) offsetting the agricultural sector (12% of direct global emissions) by 2100, under current global climate policies.
See also Table S2.

in the aquaculture sector [27], with an estimated 303 thousand tonnes of CO_2eq of annual emission based on the median across farms (mean = 526 thousand tonnes of CO_2eq). Based on the average sequestration ability of seaweeds (1.11 thousand tonnes of CO_2eq per year per square kilometer; see Method Details), it would take a remarkably small area, just 273 km^2 (474 km^2 if using mean emission values), for the industry to be carbon neutral. This area equates to about 14% (mean emissions = 25%) of all current cultured seaweed production, an area approximately the size of Palau, or 0.001% of the ecologically suitable ocean (Figure 1), offering an achievable opportunity to promote policies and incentives to create a carbon-neutral industry in the near term. For example, locally integrated multitrophic aquaculture (IMTA)—growing seaweeds alongside aquatic animal production—could become an "offset pre-requisite" for finfish or crustacean farms and permitting in some regions around the world [28, 29]. Alternatively, seaweed sequestration companies could increase their scale and sell carbon offsets for emitters (similar to forest offsetting). Notably, the potential for seaweed offsetting to scale up is substantial if offshore aquaculture is implemented, especially compared to land-based offsetting, where space is limiting [7, 16].

Given the potential for seaweed farming to provide net carbon neutrality for the aquaculture industry, we next explored an ambitious mitigation strategy: the potential for seaweed farming to offset global agriculture. Directly, agriculture (excluding GHG flux from land use and forestry; see Method Details) has consistently contributed about 12% of global emissions annually for the past 30 years (5.1 billion tonnes of CO_2eq per year; ca. 50% of the agricultural total) [6]. To mitigate this fraction of emissions by the end of the century, seaweed farming would need to ramp up from the current 1.9 thousand km^2 to 7.3 million km^2, representing 15% of the ocean that is possibly suitable for seaweed aquaculture or approximately two times the area of wild species (Figure 1)—not a realistic or, perhaps, desirable prospect. Moreover, the current exponential rate of seaweed aquaculture expansion (8% per year) still could not achieve carbon neutrality (Figure 2), even when considering only half of global agricultural emissions (i.e., direct). Thus, seaweed offsetting is not a "silver bullet" to meet the Paris Agreement pledge levels before the end of the century. While seaweed sequestration potential may be high in many regions, the global reduction of carbon emissions, especially to stay below 2°C, still rests on cleaner sources of energy and protection of our expansive, but threatened, carbon sinks, including wild blue carbon biogenic regions [30]. However, targeted industrial-scale expansion of seaweed offset farms in regions, such as Asia—where potential is high, farming already occurs (Figure 1), and mariculture sequestration is gaining interest (e.g., [31])—could help make substantial strides toward these ambitious goals as well as provide other local ecosystem services [7, 8].

The potential for seaweed farming to serve as a global mitigation solution by itself is limited but may still be a viable option for forward-looking countries or economies with bold targets for combating carbon emissions while simultaneously supporting Blue Growth initiatives. Notably, California—the fifth largest economy in the world, including its agricultural sector—is continuing a commitment to act on climate change, including the 2015 Senate Bill 1383 to regulate climate pollutants, like methane, a potent (30× CO_2 capacity to trap heat) [27, 32] and common by-product of livestock production [33]. California agricultural emissions were estimated at 34.4 million tonnes of CO_2eq in 2016 (8% of total California emissions) [34], but the entire sector could be carbon neutral with 3.8% of West Coast Exclusive Economic Zones (EEZs), or 0.065% of all suitable global waters (Figure 1). Taking advantage of this capacity fits well within the larger current California Climate Action Plan to significantly reduce GHG by 2030 through the "Natural and Working Lands" strategy (https://www.climatechange.ca.gov/) and subsequent "Ocean Resiliency Act" bill (SB-69) being drafted. Seaweed offsetting also aligns with broader U.S. federal legislation, such as the Green New Deal [35]. Importantly, such practices in California or other coastal waters would need to be managed to coexist with current ocean uses and protections [8, 36].

Carbon offsetting is not without controversy, e.g., [37], but aligning Blue Growth for food with mitigating global climate change provides new avenues for innovation and climate-conscious growth of an already rapidly expanding sector. Here, we focus on seaweed aquaculture for offsetting global carbon emissions through sequestration, but local benefits from seaweed production can also be derived. New research is demonstrating the ability of seaweeds to buffer some of the other impacts of anthropogenic pollution, including ocean acidification and low-oxygen events (hypoxia) [7, 8]. Notably, there are approximately 250 known eutrophic locations around the world where seaweed offsetting could help mitigate this anthropogenic stressor, and over 500 sites of hypoxic events that could also benefit from improved water quality (oxygen and reduced nutrient loads; Figure 3) [38]. Additionally, sub-polar and temperate regions, in particular, are already feeling the

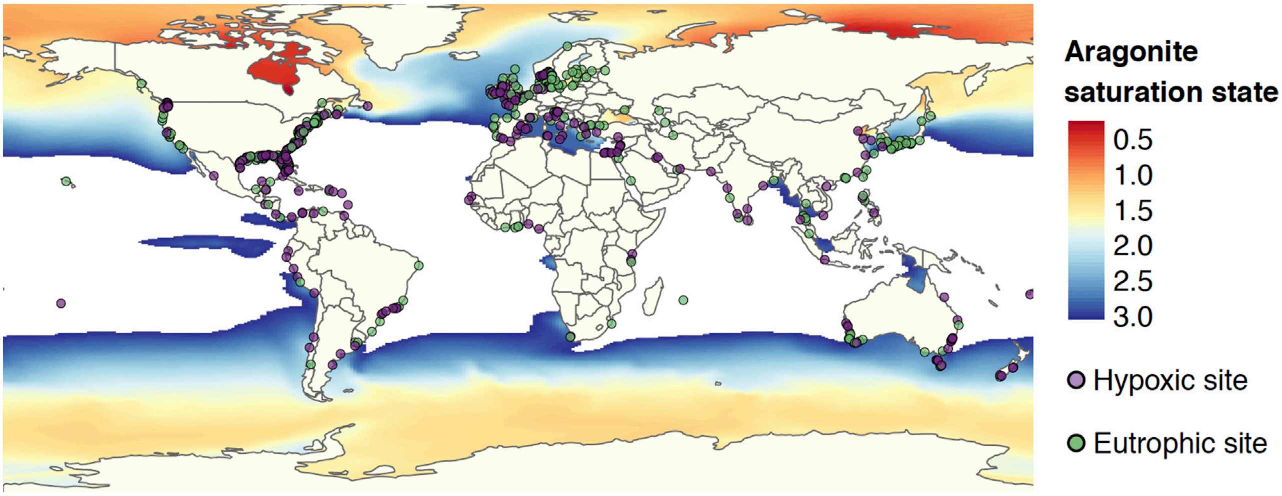

Figure 3. Potential for "Charismatic Carbon" Siting based on Coastal Systems with Eutrophic, Hypoxic, and/or Acidified Waters
Hypoxia is considered dissolved oxygen levels less than 2 mgL^{-1}. Acidification is represented here by estimated aragonite saturation (Ω) less than 3.0.

stress of ocean acidification, an increasing threat to wild and farmed aquatic species (Figure 3) [39, 40]. Of countries with suitable seaweed area, we find that 77 have potentially stressful acidic conditions (aragonite saturation, $\Omega, < 3$), 27 report hypoxic and eutrophic waters, and 24 countries have all three, including the United States, India, and Brazil (Figure 3). This and other potential co-benefits (e.g., habitat for wild fish and invertebrates) [7] of seaweed aquaculture may provide even more "charismatic carbon" incentive for its development [41]. Ultimately, the future of Blue Growth may benefit from becoming "greener," with a concerted exploration and investment in seaweed offsetting.

Of course, offsetting still costs money to implement [2]. Because seaweed offsetting is not a current, ubiquitous practice, the technology and exact cost to grow and sink production biomass offshore is largely unknown. However, limited evidence suggests that current seaweed farming costs (seaweed farm median = \$543, minimum = \$71 USD per tonne of CO_2; Table 1) may be at the higher end of equivalent land-based offsetting, with some terrestrial estimates of \$31.84–\$383.62 per tonne of CO_2 (see Method Details) [2, 44]. Exact costs will depend on species grown, oceanographic conditions, and available technology. For instance, one of the fastest growing species in the world, *Macrocystis pyrifera*, could contribute approximately 27% more production per hectare [42, 44] than the average species, and maximizing seaweed carbon content could potentially reduce costs by 38% (see Method Details; Table S3).

Because commercial-scale seaweed farming is relatively nascent compared to many of the land-based strategies and technologies, and production explicitly for the purpose of offsetting is minute, growth in the sector could drive prices down. Expanding other markets—such as the use of certain seaweed strains in livestock feed, where inclusion in cow diets

Table 1. Summary Table of Cost Estimates for Sequestering a Tonne of CO_2 through Seaweed Farming

Source	Species and Use	Region	Description	Cost Ranges, in USD per Tonne of CO_2
[42]	*Macrocystis pyrifera* (kelp), abalone feed	south of Chile	harvest rates and cost values modeled using data from a pilot study; estimates provided for 3 scenarios (10-, 30-, and 50-ha plots)	\$178–\$472
[43]	*Kappaphycus*, carrageenan	Indonesia, Philippines, Tanzania, India, Soloman Islands, Mexico	costs provided for six countries with varying size farms and, in some cases, three harvest systems (floating versus off-bottom)	\$71–\$770
[44]	*Macrocystis pyrifera* (kelp), abalone feed	south of Chile	actual harvest data; two harvests per year; cost decreases with larger areas, but data were only provided for 10-ha area; cost would be lower with larger farm area	\$1,459
[45]	*Euchema spp*, carrageenan	"generalized" tropical environment	"indicative" cost estimates for 150-m × 150-m farm	\$613
[46]	*Laminaria digitate*	Ireland	evaluated cost for four scenarios with different hatchery and "grow-out" options	\$14,222–\$27,222
[47]	Not specified, but assumes a yield of 20 dry tonnes ha^{-1}	North Sea	evaluated high and low-cost investment scenarios	\$1,291–\$1,924

See Tables S2–S8 for detailed methods and assumptions. Estimates do not correct for inflation.

may significantly (75%–99%) reduce ruminant methane production [48–50]—as well as offshore production for biofuel [16], could further accelerate economies of scale. That said, climate change and increases in CO_2 will challenge some farmed seaweed species' growth and survival [3, 14], limiting the upper bounds of sequestration while potentially promoting growth in others [51, 52]. Thus, the average seaweed snapshot that we provide will likely change in the future, a critical next step in understanding the offsetting potential across species and spatial scales.

Scaling up seaweed aquaculture is also not without potential negative consequences, especially under poor siting and management practices. Ocean cultivation of seaweeds means interactions with wild organisms and ecosystems, including, but not limited to, the potential of diverting nutrients away from wild food webs, changing local hydrodynamics, possible entanglements, and disease risk [53]. In addition, halocarbons resulting from macroalgae growth may be a negative atmospheric by-product that could affect ozone or UV flux, but so far, the short-lived (<6-month-old) molecules from algae sources (wild or farmed) appear to have little to no measurable climate influence, though research should continue [5]. The ecological framing presented here only begins to assess the limitations and opportunities associated with seaweed farming but, hopefully, acts as a catalyst for studying the potential of such an industry more earnestly from an ecological to engineering perspective, as well as considerations for necessary management to minimize negative impacts.

Ultimately, seaweed offsetting can likely play only a relatively small role in reversing GHG emissions to mitigate climate change, but its potential is on par with those of many other options being considered or pursued, yet it has essentially been ignored to date. Our work highlights the potential for an industry that has yet to be realized but could be part of the climate mitigation portfolio, especially when it comes to making aquaculture more sustainable more quickly. The urgency of climate mitigation demands use of every possible tool available.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- LEAD CONTACT AND MATERIALS AVAILABILITY
- METHOD DETAILS
  - Current status of seaweed distribution and harvest
  - Suitability Map
- QUANTIFICATION AND STATISTICAL ANALYSIS
  - Offsetting scenarios
  - Eutrophic, hypoxic, and acidified regions
  - Costs of farming
- DATA AND CODE AVAILABILITY

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.cub.2019.07.041.

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AUTHOR CONTRIBUTIONS

H.E.F. and B.S.H. conceived the idea. H.E.F., J.C.A., and M.F. collected data and conducted analyses. H.E.F., B.S.H., J.C.A., and M.F. wrote the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Coding platform	[54]	N/A
Native seaweed ranges	[22, 24, 25]	N/A
Production data	[12]	N/A
Phosphate & nitrate	[55]	N/A
Sea surface temperature	[56]	N/A
Aquaculture emissions	[27]	N/A
Future agricultural emissions	[3]	N/A
California emissions	[34]	N/A
Seaweed sequestration values	[15, 57]	N/A
Eutrophic and hypoxic regions	[58]	N/A
Ocean acidification	[59]	N/A
Cost of farming	Table 1	N/A

LEAD CONTACT AND MATERIALS AVAILABILITY

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Dr. Halley E. Froehlich (hefroehlich@ucsb.edu). This study did not generate new unique reagents.

METHOD DETAILS

We explore the potential of seaweed aquaculture to offset carbon emission through sequestration now and in the future. Using current global oceanographic, biological, and production data, we first mapped the potential ecologically suitable range of areas for a suite of seaweed species (N = 33; Table S1). We then assessed how that area compared to the spatial extent needed and regional opportunities to offset three different levels of carbon emissions, with a focus toward creating a carbon neutral food sector. Next, we evaluated cost estimates of sequestration given current seaweed production and ranges of comparable land-based offsetting. We also highlight the benefits and possible production challenges of growing certain species. Lastly, we compared locations around the globe where seaweed aquaculture could provide additional benefits to offsetting (i.e., ‘charismatic carbon’), specifically coastal systems affected by eutrophication, hypoxia, and ocean acidification [38]. All analyses were performed in R v3.5.0 [54].

Current status of seaweed distribution and harvest

As no spatially explicit maps exist for current ranges of all seaweeds, we manually drew range maps for the dominant genera of native seaweed ranges based on Teagle et al. [22] using the R packages *mapview* and *mapedit*. The native ranges provide a ground-truth for our models of seaweed suitability (see below). The United Nations Food and Agriculture Organization’s (FAO) data on global production of aquatic plants were used to identify countries that have produced measurable amounts of farmed marine ‘aquatic plants’ within the last five years (2012-2016) [15].

Suitability Map

To model suitability, we used multiple open-source datasets to identify feasible, non-species-specific seaweed growing areas within national jurisdictions (Exclusive Economic Zones) based on nutrient availability and ocean temperature. We assume light attenuation is not limiting for photosynthetic species (green macroalgae) because farming is unlikely to occur below the photic zone in any particular region. Similarly, we assume for more exposed regions, offshore technology coming online now for multiple species, including seaweeds [16, 60], would be applied.

For nutrients, we used spatial data from the National Oceanic and Atmospheric Administration (NOAA) World Ocean Atlas (2013) for phosphate (P) and nitrate (N; μmol/L) to calculate the average N:P ratio for the top 10 meters of surface water [55]. While seasonal levels and upwelling regions of absolute nutrient content do vary some over time and space, the ratio appears most relevant for seaweed aquaculture [24]. Cells with N:P values outside the range 4:1 to 80:1 were removed. Harrison & Hurd [24] found 30:1 is optimal for average seaweed growth, but note the typical range extends from 10:1 to 80:1. We used a lower limit of 4:1 because areas with known native seaweeds (e.g., Pacific coast of N. America) were not initially captured with the N:P layer using a range minimum of 10:1. This is likely due to coarse spatial data resolution (1 degree cells) and variability in nutrient level not captured by the available averaged data. As a result, we reduce the minimum range (4:1) closer to lower values reported by Atkinson [25] in order to capture areas with native seaweeds [22]. We depict the full range of suitable nutrient values because 'optimal' is species specific. Thus, a given seaweed species will have a much smaller suitable extent than the multispecies results presented here.

We further restrict the potential area by temperature ranges suitable for growth (0 – 35°C; optimal mean ± SD = 26.3 ± 3.9°C) [23], based on the average sea surface temperature over the last decade (range = −1.9 – 30°C) from NOAA's Coral Reef Temperature Anomaly Database (CoRTAD) v6 [56]. Based on assumed constraints from cost and political feasibility, we also removed all cells outside of delineated Exclusive Economic Zones (EEZs) to limit areas to those within a given country's waters. With the emergent industry of offshore aquaculture [60], the resulting area is likely the upper limit of suitable extent and acts as a general baseline for our comparative offsetting scenarios.

QUANTIFICATION AND STATISTICAL ANALYSIS

Offsetting scenarios

Duarte et al. [4] provided sequestration potential of all standing seaweed aquaculture and calculated the global potential for all seaweed (on average) to mitigate climate change. Using the same data on seaweed sequestration from Duarte et al. and Sondak et al. [4, 57], we expand this approach to include specific scenarios and carbon levels now and in the future. We specifically assume a conversion of dry to wet weight of 0.10, the portion of mean carbon content of dry seaweed at 0.248 (noting a range between 20%–40%), the molecular weight conversion of C to CO_2 per unit of weight of dry matter of 3.67, and a typical dry weight yield of 1,455 tonnes per km^2. These values result in an average sequestration potential of 1,324 tonnes of CO_2 per km^2 of seaweed (upper and lower carbon content % = 2,126 and 1,068 tonnes of CO_2 per km^2, respectively). However, we take it one step further by accounting for the average reduction in sequestration (16%) potential due to CO_2eq produced from seaweed farming itself, based on the reported values from Fry et al. [61] and Pechsiri et al. [62]; this results in an adjusted mean sequestration potential of 1,110 tonnes of CO_2 per km^2. For higher comparative offsetting potential (versus the average), we use *Macrocystis pyrifera* yield, one of the fastest growing organisms – not just seaweed – on the planet, assuming an estimate of 2,000 tonnes of dry weight per km^2 [7]. It should be emphasized, while we use average values from the literature, a meta-analysis of seaweed Life Cycle Assessments (LCAs) would greatly improve the certainty of these estimates and extent of variability at the species and farm level.

Using the average seaweed production and sequestration estimates, we then compared three net-neutral seaweed carbon-offsetting scenarios from a food-systems perspective: (1) global finfish and crustacean aquaculture, (2) direct global agricultural emissions (excludes land use and forestry flux, see below for details), and (3) California agricultural emissions. Estimates (median and mean) for finfish and crustacean aquaculture emissions were calculated from the most recent and comprehensive synthesis of farm level LCAs from Poore and Nemecek [27], combined with total FAO aquaculture (edible) production (freshwater and marine) [15]. The second scenario is based on future emission projections from the Global Climate Tracker data portal [6], with a particular focus on past and projected contribution from agriculture [6]. We focus on direct emission and not the additional GHG flux of 4.3-5.5 $GtCO_2$eq per year from land use and land-use change activities (e.g., forestry) [63], demonstrating even offsetting half of agricultural GHG is unlikely at the global scale. Concentrating on outputs from the 'Current Climate Policies' high and low mitigation trajectories (projected warming 3.1-3.7°C by 2100), we calculated the average extent (km^2) and yield (wet weight tonnes) of increasing seaweed carbon sequestration 0.15% per year in order to reach 12% CO_2 sequestration by the end of the century. We then compared that to the current exponential rate (8% per year; $R^2 = 0.99$) of increase of global seaweed production to 2100:

$$y = 2E{-}63e^{0.0733x} \qquad \text{(Equation 1)}$$

where y is seaweed production (wet tonnes) and x is time (year). This demonstrates the level of increase in tonnage needed for a global climate mitigation strategy compared to current trends. The third and final scenario is based on the most recent (2016) estimates of CO_2eq emission from the California agricultural sector (34.4 million tonnes of California's total 429.4 million total GHG emissions), reported by the California Air and Resource Board [34]. We then identified current and proposed legislation and policy at the state and national level were such seaweed offsetting could be incorporated.

Eutrophic, hypoxic, and acidified regions

'Charismatic carbon' is the concept that certain types of offsetting can offer co-benefits, in addition to carbon sequestration [41]. Prioritizing sequestering carbon from sources that also provide habitat for wild species and/or other ecosystem services can potentially support a higher standard and thus price for certification [41]. Here we highlight three dominant stressors to coastal systems that could be reduced by seaweed production: eutrophication, hypoxia, and ocean acidification [7, 8]. All three oceanographic disturbances appear to be increasing in extent, duration, and magnitude globally, linked to anthropogenic activities, including GHG emissions [38, 64, 65]. Ocean acidification is based on estimated aragonite saturation (Ω) less than 3.0, an approximate threshold when carbonate shelled organisms can become stressed, potentially impacting growth and survival [59]. Hypoxic and eutrophic locations are taken from Diaz et al. [58] and Ω modeled from Feely et al. [59]. Notably, strategic placement of seaweed production in highly nutrified waters could potentially reduce risk of diverting energy away from the wild ecosystem and instead improve water quality [17]. With these layers, we quantified the number of countries with impacted coastal waters, but which also have suitable waters for seaweed aquaculture to demonstrate the scale of global potential.

Costs of farming

Through a non-exhaustive review of the most recent literature (post-2010), we find six scientific articles and reports estimating the cost of using current seaweed aquaculture to sequester CO_2. Information on farm size, yield, harvest costs, and sequestration are compiled for each study and USD cost per tonne of CO_2 reported (Tables 1 and S2–S8 for details). Variation in costs can arise due to several factors, including seaweed species, region, farm size, and rearing/harvest methods. There are also differences among the economic models themselves, such as how investment costs are handled. These aspects are similar to land-based offsetting, which report a range of estimated costs of $31.84–$383.62 tonne per CO_2 (includes opportunity costs of land) [2]. The seaweed studies captured here may overestimate the cost of carbon sequestration since evaluations are based on species and methods developed for non-sequestration purposes (e.g., food, cosmetics). Other species or strains of seaweed may be better suited for sequestering CO_2, and improved farming methods over time would lower overall costs. Our calculation for some of these studies may further overestimate cost due to fairly conservative values of converting tonnes of seaweed wet weight to tonnes of CO_2 sequestered (Table S2). For example, maximization of seaweed carbon content of (40%) decreases costs by ca. 38%. This provides just one example of potential efficiency cost savings (Table S3).

DATA AND CODE AVAILABILITY

All data are publicly available. The code and outputs generated during this study are available on the GitHub Cart-sci/seaweed repository: https://github.com/CART-sci/seaweed.