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Economic and biophysical limits to seaweed-based climate solutions

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Net-zero greenhouse gas emissions targets are driving interest in opportunities for biomass-based negative emissions and bioenergy, including from marine sources such as seaweed. Yet the biophysical and economic limits to farming seaweed at scales relevant to the global carbon budget have not been assessed in detail. We use coupled seaweed growth and technoeconomic models to estimate the costs of global seaweed production and related climate benefits, systematically testing the relative importance of model parameters. Under our most optimistic assumptions, sinking farmed seaweed to the deep sea to sequester a gigaton of CO_2 per year costs as little as \$560/tCO_2 on average, while using farmed seaweed for products that avoid a gigaton of CO_2-equivalent greenhouse gas (GHG) emissions annually could return a profit of \$30/tCO_2-eq. However, these costs depend on low farming costs, high seaweed yields, and assumptions that almost all carbon in seaweed is removed from the atmosphere and seaweed products can displace products with substantial embodied non-CO_2 GHG emissions. Moreover, the gigaton-scale climate benefits we model would require farming vary large areas (>100,000 km^2)—a >40-fold increase in the area currently farmed. Our results therefore suggest that seaweed-based climate benefits may be feasible, but targeted research and demonstrations are needed to further reduce economic and biophysical uncertainties.

[209 words]

Reaching net-zero CO_2 emissions will entail drastically reducing fossil fuel emissions and offsetting any residual emissions by removing carbon from the atmosphere (i.e. negative emissions)[1-5]. Biomass-based technologies may help on both fronts, by supplying carbon-neutral alternatives to fossil fuels[6,7] and providing negative emissions via enhancement of natural sinks[8] and/or bioenergy with carbon capture and storage[9]. However, numerous studies have questioned whether terrestrial biomass can provide either energy or negative emissions at the scales required in many climate mitigation scenarios, often owing to limited land and water resources[10-12]. This has driven surging interest in ocean-based carbon dioxide removal, including via cultivated macroalgae (seaweed), which would not require inputs of land or freshwater and might have environmental co-benefits (e.g., [13-21]). Seaweed products might also help to lower greenhouse gas emissions, for example by reducing methane emissions from ruminants[22], and replacing fossil fuels[23] and emissions-intensive agricultural products[24].

Seaweed has been successfully farmed in some places for centuries, and used for food, animal feed, and in more modern times, cosmetics, medicine, fertilizer, and biofuels[25-28]. Production of seaweed for food increased 6% per year 2000-2018[29] and harvest totaled ~1 million tons of carbon worldwide in 2018[29]. In comparison, climate scenarios that limit warming to 1.5°

or 2˚C generally require more than 1 gigaton of carbon (i.e. >3.67 Gt CO_2) to be removed annually from the atmosphere in the year CO_2 emissions reach net-zero[3]. To contribute to such climate goals, seaweed farming must therefore expand tremendously, and in turn contend with large uncertainties in the productivity of different types of seaweed in different places, the net costs of farming, the magnitude of emissions avoided or carbon sequestered, and the potential for undesirable ecological impacts. Recent studies of seaweed farming have examined localized opportunities and dynamics in particular regions[15,16,30], made rough estimates of the global potential[13,14,31,32], and modeled the Earth system response to gigaton-scale production[19]. Yet the productivity, costs, and potential climate benefits of such farming are spatially heterogeneous and scale-dependent, and the key sensitivities and trade-offs important to investors and decision makers have not been comprehensively evaluated. Here, we use coupled biophysical and technoeconomic models to systematically assess the economic costs and potential climate benefits of seaweed farming, testing their sensitivity across large ranges in individual variables and comparing different product pathways.

Details of our analytic approach are described in the *Methods*. In summary, we use outputs from a newly-developed biophysical model (G-MACMODS)[33] to estimate potential harvest of four different seaweed types (tropical red, tropical brown, temperate red, and temperate brown; Supplementary Fig. 1) at a resolution of 1/12° (~9 km at the equator) globally. Nutrients are a key constraint on seaweed growth. G-MACMODS assumes that nitrogen is the limiting nutrient and we model two idealized scenarios: an "ambient" nutrient scenario that computes growth based on observed, climatological surface nitrate concentrations, and a "flux-limited" scenario that computes growth rate based on ambient nitrate concentrations, but limits algal biomass increases so as not to exceed the magnitude of local upward nitrate flux as estimated by a high-resolution simulation of the Community Earth System Model[34]. Based on the simulated yields, we then calculate spatially-explicit costs per ton of seaweed harvested and either costs per ton of GHG emissions avoided (when used as food, feed, or for biofuels) or costs per ton of carbon removed from the atmosphere as a carbon dioxide removal (CDR) strategy. Given the large uncertainty in technoeconomic parameters, we perform a Monte Carlo simulation with n=5,000 for each nutrient scenario, assuming uniform distributions of each variable. Technoeconomic variables include (1) farming costs (e.g., capital cost, harvest costs), (2) for carbon sequestration, the fraction of sunk seaweed carbon sequestered for > 100 years in the deep sea, and (3) for GHG emissions mitigation, the net cost and net emissions of seaweed transported and converted into a product (Table 1; see Supplementary Tables 1 and 2 for listings of all variables and relevant sources). Additionally, because seaweed draws carbon from the surface ocean dissolved inorganic carbon pool (which does not maintain instantaneous equilibrium with the atmosphere) and because large-scale seaweed farming can reduce natural carbon uptake by phytoplankton, we include a variable representing the net efficiency of seaweed growth in reducing atmospheric CO_2 ("atmospheric removal fraction"; Supplementary Table 1). Our approach is predicated on large uncertainties associated with most of the variables we analyze, not only in the future but also the present (the relatively few costs reported in the literature are location- and/or species-specific), as well as our primary goal of informing future research by identifying relative differences, sensitivities and trade-offs that are robust across our simulations.

Seaweed production cost

The maps in Figure 1 show the range of modeled seaweed production costs (i.e. $ per ton of harvested dry weight prior to transport) in different regions under the ambient nutrient scenario and assuming the most-productive type of seaweed is grown in each grid cell (Supplementary Fig. 2 shows analogous costs for flux-limited scenario). Minimum modeled costs (Figs. 1a, d) thus reflect high levels of seaweed growth (ambient nutrients) and very low assumed costs of farming in contrast to the maximum costs in Supplementary Fig. 2, which show lower levels of seaweed growth in most areas (flux-limited nutrients) and high-end cost assumptions. Since our ability to accurately assess the role of nutrient constraints as a determinant of yield is a major driver of total uncertainty in cost, our results are thereby likely to encompass a wide range of outlooks, including substantial future reductions in farming costs related to technological breakthroughs, returns to scale, and boosted productivity (e.g., autonomous farms and artificial upwelling).

Although the spread in average cost in the 1% of ocean area where costs are lowest (labels beneath each panel) range from $240-$1,470 per ton of dry weight (tDW) seaweed yield, regional patterns of production costs are relatively consistent across cost simulations (Fig. 1). For example, the equatorial Pacific, Gulf of Alaska, and southeastern edge of South America are consistently among the lowest cost areas to produce seaweed (yellow and green shading in Fig. 1), and there are large swaths of ocean that cannot produce seaweed for <$2,000/tDW in any case (areas shaded blue in Fig. 1). These patterns reflect the combination of seaweed productivity and the associated number of harvests (Supplementary Figs. 3 and 4, respectively). Higher harvest costs can erode the cost advantage of highly productive areas: for example, despite having much lower seaweed yields per unit area, the North Pacific's higher harvest costs lead to production costs that are often similar to those in the Equatorial Pacific (Fig. 1 and Supplementary Fig. S3). Moreover, because transportation of harvested seaweed is not included in the at-farm production costs but rather in the post-cultivation costs (see *Methods*), some areas of open ocean far from ports have low at-farm production costs. On average, the costs of seeded line, total harvest costs, and capital costs dominate total production costs, representing 56(32-92)%, 19(4-38)%, and 17(3-33)% across seaweed types, respectively (Supplementary Fig. 5).

Finally, although global seaweed yield is drastically reduced in simulations that limit nutrient availability to vertical nutrient fluxes, the production costs in the 1% of ocean area with the lowest cost are remarkably similar, ranging from $260-$1,730 per ton of dry weight (tDW). As nutrients would be depleted if seaweed cultivation were to become widespread, this suggests that natural vertical nutrient fluxes might be sufficient to largely sustain productivity in the 1% of ocean areas where seaweed farming is expected to be most feasible.

Net cost of climate benefits

The maps in Figure 2 show net costs of different climate benefits from farmed seaweed. We choose to show the 5th percentile of 5,000 simulations with ambient nutrients to reflect optimistically low cost results that might be achieved with economies of scale (Supplementary Figs. 6 and 7 show results under flux-limited nutrients and for median net costs, respectively). We define the cost to sequester carbon via sinking seaweed as the \$/tCO_2 removed from the atmosphere for at least 100 years, assuming no other economic value. In contrast, costs of emissions avoided by using produced seaweed for food, feed or biofuel are given in units of \$/tCO_2e and in each case reflect seaweed production, transportation and conversion costs, and the product's market value as well as the CO_2-equivalent GHG emissions (CH_4 and N_2O assuming GWP_{100}) displaced by the product net of any emissions related to transportation and processing (see *Methods*).

In the 1% of ocean area where net costs of the relevant climate benefits are lowest, the average cost is much higher per ton of carbon sequestered by sinking seaweed (\$610/tCO_2) than per ton of CO_2-eq emissions avoided—regardless of whether the seaweed is used for food (\$30/tCO_2-eq), animal feed (\$130/tCO_2-eq), or biofuel (\$310/tCO_2-eq). The substantial cost difference between sequestration by sinking and emissions avoided by products is most influenced by the products' market value and the potential to avoid non-CO_2 GHGs, despite the higher cost and emissions required to transport harvested seaweed to port.

In particular, the non-CO_2 GHG emissions that could be avoided by using seaweed for either food consumed by humans or feed consumed by animals effectively multiply the potential climate benefits of a ton of seaweed carbon, whereas the climate benefits of either sinking or converting seaweed to biofuels are constrained by the carbon present in the seaweed itself. Yet carbon sequestration is nonetheless favored in some locations given the high costs of transporting seaweed back to the nearest port (e.g., areas of the equatorial Pacific that are shaded yellow and green in Fig. 2a and blue in Figs. 2c; see also Supplementary Fig. 8).

Key sensitivities

Figure 3 shows the relative importance of all variables in generating spread in our Monte Carlo estimates of production costs and net costs of climate benefits, focusing on the 5% of ocean areas where costs are lowest (Supplementary Fig. 9 shows the same results for flux-limited simulations). These results emphasize which variables are most important to achieving very low costs. Low production costs are most sensitive to the cost of seeded line (secondary line with seaweed seedlings that is wrapped around a structural rope, or nets for some temperate red seaweeds; yellow in Fig. 3a), followed by capital costs (e.g., boats, harvest machines, buoys, anchors and other lines; green in Fig. 3a). Together, seeded line and capital costs account for >90% of the uncertainty in production costs in the places where costs are lowest, and costs are never below \$500/tDW in simulations where seeded line is assumed to cost >\$1 per meter (Figs. 3a and 3d).

Costs of carbon sequestered are quite sensitive to production costs (incl. all parameters shown in Fig. 3a), but the most important single parameter is the fraction of the seaweed carbon that corresponds to equivalent carbon removal from the atmosphere (light green in Fig. 3b). Although this fraction has generally been assumed to be 1, recent studies have shown that air-sea fluxes of CO_2 may not keep pace with carbon uptake by growing seaweed and, among other mechanisms that reduce efficiency, farmed seaweed may diminish natural carbon uptake and export accomplished by phytoplankton[15,19]. The atmospheric removal fraction accounts for >46% of the variation in sequestration costs in the places where costs are lowest, and costs are never below \$500/tCO_2 sequestered unless the removal fraction is assumed to be >0.6 (Figs. 3b and 3e).

Our estimates of cost per GHG emissions avoided are most sensitive to the assumed magnitude of CO_2-equivalent emissions avoided by a seaweed product (light blue in Fig. 3c). The product avoided emissions accounts for >60% of the variation in costs per emissions avoided in the places where costs are lowest, and costs are never more than \$400/tCO_2-eq avoided in simulations where the product avoided emissions are assumed to be >3 tCO_2-eq/tDW seaweed (Figs. 3c and 3f). Yet production costs remain important, and low costs of emissions avoided (<\$200/ tCO_2-eq) can be achieved even when the avoided emissions are <1 tCO_2-eq/tDW if seaweed production costs are very low (Figs. 3c and 3f).

Costs and benefits of large-scale farming seaweed

Figure 4 shows the cumulative potential of GHG emissions avoided or carbon sequestered in the 1% of ocean areas with the lowest costs, shaded with costs per ton based on 5th percentile of 5,000 ambient nutrient simulations (i.e. reflecting optimistically high seaweed yield, low farming costs, and large climate benefits from replacement of agricultural products; Supplementary Figs. 10 and 11 shows results for median costs and flux-limited nutrient scenario). No matter the scenario or percentile, in the 1% of areas with the lowest costs, the costs per ton of CO_2 sequestered are always higher than the costs per ton of CO_2-eq emissions avoided. In the optimistic case depicted in Figure 4, 1 Gt of CO_2-eq might be avoided or 1 Gt of CO_2 sequestered by farming 0.03% and 0.08% of ocean area, respectively, (roughly 100,000 km^2 and 300,000 km^2 or close to the areas of Iceland and Italy, respectively) at an average profit of \$30/tCO_2-eq emissions avoided or at an average cost of \$560/tCO_2 sequestered, respectively. The ocean area required to reach 1 Gt CO_2-eq avoided emissions or 1 Gt CO_2 sequestered annually is very similar between the ambient and flux-limited nutrient simulations, but average costs at the median of Monte Carlo simulations for both nutrient scenarios rise substantially to \$80/tCO_2-eq emissions avoided or \$1,050-\$1,170/tCO_2 sequestered, respectively (Supplementary Figs. 10, 11a, b). These costs increase to \$100-110/tCO_2-eq at 3 Gt CO_2-eq avoided and to \$1,100-1,240/tCO_2 at 3 Gt CO_2 sequestered annually, requiring ocean areas of 0.07-0.10% and 0.16-0.33% for sequestration and avoided emissions, respectively (roughly 250,000-360,000 km^2 and 580,000-1,200,000 km^2, respectively). Moreover, climate benefits increase approximately linearly with area up to 1% of ocean area, reaching totals of >30 Gt CO_2-eq avoided or >15 CO_2 sequestered annually in both the ambient and flux-limited nutrient simulations.

Supplementary Figure 12 shows the locations of the lowest cost areas in Figure 4, which, for sequestration, are concentrated in the equatorial Pacific and Gulf of Alaska, and for avoided emissions products include additional areas offshore of Argentina, the Korean Peninsula, and New Zealand as well as areas of the North and Norwegian Seas. Importantly, we estimate that perhaps 10-15% of lowest cost areas for sequestration and 40-45% of lowest cost areas for avoided emissions are either in highly-trafficked shipping lanes or part of existing marine protected areas (see *Methods*), which could present challenges for seaweed farming in these areas.

Although a small percentage of global ocean area, farming 0.03% of the global ocean area (~100,000 km^2) would represent a forty-fold increase in the area of current seaweed farming (~2,700 km^2; [29,35,36]). Thus, producing seaweed in the lowest cost areas to reach 1 Gt CO_2-eq of emissions avoided or 1 Gt CO_2 sequestered by 2050 would entail the area farmed to increase by roughly 13% or 18% per year, respectively, compared to the 2000-2018 seaweed farming industrial growth rate of 6%[29].Achieving the same level of climate benefits from seaweed by 2030 increases the implied expansion rate of farms to roughly 49% or 69% per year for emissions avoided or carbon sequestered, respectively.

Discussion

Our results suggest that it might be possible to sequester >1 GtCO_2 at costs as low as \$560/tCO_2 if nearly all seaweed carbon corresponds directly to an amount of CO_2 removed from the atmosphere and production costs are reduced to near the lowest published costs (e.g., seeded line and capital costs of <\$0.30/m and \$2,750/ha, respectively[37,38]). Nonetheless, \$560/tCO_2 is comparable to the \$500-600 t/CO_2 costs of direct air capture (DAC) reported by the company Climeworks[39] (but much more than \$94-\$232 DAC costs estimated by Keith et al.[40]). And sequestration costs rise sharply if the assumed atmospheric removal fraction decreases or production costs increase (Supplementary Figs. 7 and 10, Fig. 3e). In comparison, >1 GtCO_2-eq emissions might be avoided at a profit if similarly low production costs are achieved and seaweed products avoid emissions of >2.6 tCO_2-eq/tDW (e.g., by displacing vegetables, legumes, or soy from some regions). Although the cost per emission avoided is typically higher if seaweed is instead used for biofuels (Figure 2; Supplementary Figs. 6, 7), such fuels may command a substantial "green premium" as countries seek to decarbonize aviation and long-distance transportation of freight[4,7,41,42].

Although it is thus conceivable that farmed seaweed could feasibly deliver globally-relevant climate benefits, our modeling and cost estimates are subject to important caveats and limitations. First, modeled economic parameter ranges are broad, spanning a relatively small number of divergent data points. In some cases these ranges were extended downward to reflect future cost reductions. Better constraining these cost ranges for both current and future scenarios would improve the model and reduce uncertainty. Similarly, future work could analyze in greater detail the specific types and scale of agricultural or energy products that might be displaced by seaweed and their GHG emissions. Although the relative benefits of avoiding different GHG emissions versus sequestering carbon for different periods of time are beyond the scope of our analysis, they may be important to investors and decision makers. For example, the fraction of sunk carbon that remains in the deep ocean declines markedly in many places after 100 years[8]; if CDR accounting requires multi-century sequestration, the cost of seaweed-based CDR may become prohibitively high.

There are also large sources of uncertainty that deserve further exploration in the future. For example, we find negligible differences in estimated costs of climate benefits in the lowest cost ocean areas between our two nutrient scenarios (Supplementary Figs. 2, 6, 10-13) using central yield projections from the G-MACMODS model, but estimated costs would change substantially if yields turn out to be systematically higher or lower. The fraction of seaweed carbon that corresponds to equivalent carbon removed from the atmosphere and competition between seaweed and phytoplankton are also critical dynamics that warrant analysis in the context of a fully-coupled earth system model. Moreover, our climate benefit calculations do not include particulate seaweed biomass that may be exported to the deep sea prior to harvest (which may represent ~5% of harvested biomass[21]). Finally, we must continue to evaluate the potential consequences to ocean ecosystems and biogeochemical cycles before seriously considering sinking gigatons of seaweed[19].

Despite these uncertainties and limitations, our analysis supports continued research, development, and demonstration of the potential for seaweed farming to produce meaningful climate benefits. Specifically, our model highlights the most important targets for research and innovation. Biophysical factors such as death and exudation rates are not well-established and may substantially alter projected seaweed yields[33]; regional biogeochemical and Earth system feedbacks could similarly undermine the efficacy of sinking seaweed carbon; and low or narrow demand for seaweed products could limit the potential to offset land-use and fossil GHG emissions. Finally, although some seaweed innovators are focused on farm designs that reduce labor and transportation costs, our results suggest that the keys to low production costs are seeded line and basic farm equipment like boats, buoys, and anchors. But even if seed and capital costs are minimized, seaweed CDR seems likely to be more expensive than alternatives like direct air capture, and it is not clear that there are viable and large markets for seaweed products. These factors, combined with the challenges inherent to verification and monitoring as well as the potential for ecosystem disruption, suggest that expansion of seaweed cultivation should be approached with caution. The outlook for a massive scale-up of seaweed climate benefits is thus decidedly murky, but our findings can help direct research, investments, and decision making to clear the waters.

[*3,242 words*]

Methods

Monte Carlo analysis

Seaweed production costs and net costs of climate benefits were estimated based on outputs of the biophysical and technoeconomic models described below, and associated uncertainties and sensitivities were quantified by repeatedly sampling from uniform distributions of plausible values for each cost and economic parameter (n=5,000 for each nutrient scenario from the biophysical model, for a total of n=10,000 simulations; see Supplementary Figs. 14, 15)[43-48].

Biophysical Model

G-MACMODS is a nutrient-constrained, biophysical macroalgal growth model with inputs of temperature, nitrogen, light, flow, wave conditions, and farming intensity (sub-grid-scale crowding)[30,49], that we use to estimate annual seaweed yield per area (either in tons of carbon or tons of dry weight biomass per km^2 per year)[33]. In the model, seaweed takes up nitrogen from seawater, and that nitrogen is held in a stored pool before being converted to structural biomass via growth[50]. Seaweed biomass is then lost via mortality and exudation, as well as breakage from variable ocean wave intensity. The conversion from stored nitrogen to biomass is based on the minimum internal nitrogen requirements of macroalgae, and the conversion from biomass to units of carbon is based on an average carbon content of macroalgal dry weight (~30%)[51]. The model employs a conditional harvest scheme, where harvest is optimized based on historical growth rate and standing biomass[33].

The G-MACMODS model is parameterized for four types of macroalgae: temperate brown, temperate red, tropical brown, and tropical red. These types employed biophysical parameters from genera that represent over 99.5% of present-day farmed macroalgae (Eucheuma, Gracilaria, Kappahycus,Sargassum, Porphyra, Saccharina, Laminaria, Macrocystis)[36]. Environmental inputs were derived from satellite-based and climatological model output mapped to 1/12-degree global resolution, which resolves continental shelf regions. Nutrient distributions were derived from a 1/10-degree resolution biogeochemical simulation led by the National Center for Atmospheric Research (NCAR) and run in the Community Earth System Model (CESM) framework[34].

Two bounding nutrient scenarios were simulated with G-MACMODS and evaluated using the technoeconomic model analyses described below: the "ambient nutrient" scenario where seaweed growth was computed using surface nutrient concentrations without depletion or competition, and "flux-limited" simulations where seaweed growth was limited by an estimation of the nutrient supply to surface waters (computed as the flux of deep-water nitrate through a 100-m depth horizon). Figures and numbers reported in the main text are based on the ambient nutrient scenario and central estimates of biophysical parameters unless noted otherwise; results based on the flux-limited nutrient scenario are shown in Supplementary Figures.

Technoeconomic model

We estimate the net cost of seaweed-related climate benefits by first estimating all costs and emissions related to seaweed farming, up to and including the point of harvest at the farm location, then estimating costs and emissions related to the transportation and processing of harvested seaweed, and finally estimating the market value of seaweed products and either carbon sequestered or GHG emissions avoided.

Production costs and emissions. Spatially-explicit costs of seaweed production (\$/tDW) and production-related emissions (tCO_2/tDW) are calculated based on ranges of capital costs (\$/km^2), operating costs (incl. labor, \$/km^2), harvest costs (\$/km^2), and transport emissions per distance traveled (tCO_2/km) in the literature (Table 1, Supplementary Tables 1 and 2); annual seaweed biomass (tDW/km^2, for the preferred seaweed type in each grid cell), line spacing, and number of harvests (species-dependent) from the biophysical model; as well as datasets of distances to the nearest port (km), ocean depth (m), and significant wave height (m).

Capital costs are calculated as:

$$c_{cap} = c_{capbase} + \left(c_{capbase} \times (k_d + k_w)\right) + c_{sl} \tag{1}$$

where c_{cap} is the total annualized capital costs per km^2, $c_{capbase}$ is the annualized capital cost per km^2 (e.g., cost of buoys, anchors, boats, structural rope) prior to applying depth and wave impacts, k_d and k_w are the impacts of depth and waviness on capital cost, respectively, each expressed as a multiplier between 0 and 1 modeled using our Monte Carlo method and applied only to grid cells where depth > 500m and/or significant wave height > 3m, respectively, and c_{sl} is the total annual cost of seeded line calculated as:

$$c_{sl} = c_{slbase} \times p_{sline} \tag{2}$$

where c_{slbase} is the cost per meter of seeded line, and p_{sline} is the total length of line per km^2, based on the optimal seaweed type grown in each grid cell.

Operating and maintenance costs are calculated as:

$$c_{op} = c_{ins} + c_{lic} + c_{lab} + c_{opbase} \tag{3}$$

where c_{op} is the total annualized operating and maintenance costs per km^2, c_{ins} is the annual insurance cost per km^2, c_{lic} is the annual cost of a seaweed aquaculture license per km^2, c_{lab} is the annual cost of labor excluding harvest labor, and c_{opbase} is all other operating and maintenance costs.

Harvest costs are calculated as:

$$c_{harv} = c_{harvbase} \times n_{harv} \tag{4}$$

where c_{harv} is the total annual costs associated with harvesting seaweed per km^2, $c_{harvbase}$ is the cost per harvest per km^2 (including harvest labor but excluding harvest transport), and n_{harv} is the total number of harvests per year.

Costs associated with transporting equipment to the farming location are calculated as:

$$c_{eqtrans} = c_{transbase} \times m_{eq} \times d_{port} \tag{5}$$

where $c_{eqtrans}$ is total annualized cost of transporting equipment, $c_{transbase}$ is the cost to transport 1 ton of material 1km on a barge, m_{eq} is the annualized equipment mass in tons, and d_{port} is the ocean distance to the nearest port in km.

The total production cost of growing and harvesting seaweed is therefore calculated as:

$$c_{prod} = \frac{(c_{cap}) + (c_{op}) + (c_{harv}) + (c_{eqtrans})}{s_{dw}} \tag{6}$$

where $\boldsymbol{c_{prod}}$ is total annual cost of seaweed production (growth + harvesting), c_{cap} is as calculated in eq. (1), c_{op} is as calculated in eq. (3), c_{harv} is as calculated in eq. (4), $c_{eqtrans}$ is as calculated in eq. (5), and s_{dw} is the dry weight of seaweed harvested annually per km^2.

Emissions associated with transporting equipment to the farming location are calculated as:

$$e_{eqtrans} = e_{transbase} \times m_{eq} \times d_{port} \tag{7}$$

where $e_{eqtrans}$ is the total annualized CO_2 emissions in tons from transporting equipment, $e_{transbase}$ is the CO_2 emissions from transporting 1 ton of material 1km on a barge, m_{eq} is the annualized equipment mass in tons, and d_{port} is the ocean distance to the nearest port in km.

Emissions from maintenance trips to/from the seaweed farm are calculated as:

$$e_{mnt} = \left(\left(2 \times d_{port}\right) \times e_{mntbase} \times \left(\frac{n_{mnt}}{a_{mnt}}\right) \right) + \left(e_{mntbase} \times d_{mnt}\right) \tag{8}$$

where e_{mnt} is total annual CO_2 emissions from farm maintenance, d_{port} is the ocean distance to the nearest port in km, n_{mnt} is the number of maintenance trips per km^2 per year, a_{mnt} is the area tended to per trip, d_{mnt} is the distance traveled around each km^2 for maintenance, and $e_{mntbase}$ is the CO_2 emissions from traveling 1km on a typical fishing maintenance vessel (e.g. a 14m Marinnor vessel with 2x310hp engines) at an average speed of 9 knots (16.67 km/h), resulting in maintenance vessel fuel consumption of 0.88 l/km [28,52].

Total emissions from growing and harvesting seaweed are therefore calculated as:

$$e_{prod} = \frac{(e_{eqtrans}) + (e_{mnt})}{s_{dw}} \tag{9}$$

where e_{prod} is total annual emissions from seaweed production (growth + harvesting), $e_{eqtrans}$ is as calculated in eq. (7), e_{mnt} is as calculated in eq. (8), and s_{dw} is the dry weight of seaweed harvested annually per km^2.

Market value and climate benefits of seaweed. Further transportation and processing costs, economic value, and net emissions of either sinking seaweed in the deep ocean for carbon sequestration or converting seaweed into usable products are calculated based on ranges of transport costs (\$/tDW/km), transport emissions (tCO_2-eq/t/km), conversion cost (\$/tDW), conversion emissions (tCO_2-eq/tDW), market value of product (\$/tDW), and the emissions avoided by product (tons CO_2e/ton DW) in the literature (Table 1). Market value is globally homogenous and does not vary by region. Emissions avoided by product were determined by comparing estimated emissions related to seaweed products to emissions from non-seaweed products that could potentially be replaced (including non-CO_2 greenhouse gas emissions from land use)[24]. Other parameters used are distance to nearest port (km), water depth (m), spatially-explicit sequestration fraction (%)[53], and distance to optimal sinking location (km; cost-optimized for maximum emissions benefit considering transport emissions combined with spatially-explicit sequestration fraction; see *Distance to sinking point calculation* section below). Each Monte Carlo simulation calculates the cost of both CDR via sinking seaweed and GHG emissions mitigation via seaweed products.

For seaweed CDR, after the seaweed is harvested, it can either be sunk in the same location that it was grown, or be transported to a more economically favorable sinking location where more of the seaweed carbon would remain sequestered for 100 years (see *Distance to optimal sinking point* at the end of *Methods*). Immediately post-harvest, the seaweed still contains a large amount of water, requiring a conversion from dry mass to wet mass for subsequent calculations[33]:

$$s_{ww} = \frac{s_{dw}}{0.1} \tag{10}$$

where s_{ww} is the annual wet weight of seaweed harvested per km^2 and s_{dw} is the annual dry weight of seaweed harvested per km^2.

The cost to transport harvested seaweed to the optimal sinking location is calculated as:

$$c_{swtsink} = c_{transbase} \times d_{sink} \times s_{ww} \tag{11}$$

where $c_{swtsink}$ is the total annual cost to transport harvested seaweed to the optimal sinking location, $c_{transbase}$ is the cost to transport 1 ton of material 1km on a barge, d_{sink} is the distance in km to the economically-optimized sinking location, and s_{ww} is the annually-harvested seaweed wet weight in t/km^2 as in eq. (10).

The cost associated with transporting replacement equipment (e.g., lines, buoys, anchors) to the farming location and hauling back used equipment at the end of its assumed lifetime (1 year for seeded line, 5-20 years for capex by equipment type) in the sinking CDR pathway are calculated as:

$$c_{eqtsink} = \left(c_{transbase} \times (2 \times d_{sink}) \times m_{eq}\right) + \left(c_{transbase} \times d_{port} \times m_{eq}\right) \tag{12}$$

where $c_{eqtsink}$ is the total annualized cost to transport both used and replacement equipment, $c_{transbase}$ is the cost to transport 1 ton of material 1km on a barge, m_{eq} is the annualized equipment mass in tons, d_{sink} is the distance in km to the economically-optimized sinking location, and d_{port} is the ocean distance to the nearest port in km. We assume that the harvesting barge travels from the farming location directly to the optimal sinking location with harvested seaweed and replaced (used) equipment in tow (incl. used seeded line and annualized mass of used capital equipment), sinks the harvested seaweed, returns to the farm location, and then returns to the nearest port (see Supplementary Fig. 16). These calculations assume the shortest sea-route distance (see *Distance to optimal sinking point*).

The total value of seaweed that is sunk for CDR is therefore calculated as:

$$v_{sink} = \frac{\left(v_{cprice} - \left(c_{swtsink} + c_{eqtsink}\right)\right)}{s_{dw}} \tag{13}$$

where $\boldsymbol{v_{sink}}$ is the total value (cost, if negative) of seaweed farmed for CDR in \$/tDW, v_{cprice} is a theoretical carbon price, $c_{swtsink}$ is as calculated in eq. (11), $c_{eqtsink}$ is as calculated in eq. (12), and s_{dw} is annually-harvested seaweed dry weight in t/km^2. We do not assume any carbon price in our Monte Carlo simulations (v_{cprice} is equal to zero), making v_{sink} negative and thus representing a net cost.

To calculate net carbon impacts, our model includes uncertainty in the efficiency of using the growth and subsequent deep-sea deposition of seaweed as a CDR method. The uncertainty is expected to include the effects of reduced phytoplankton growth from nutrient competition, the relationship between air-sea gas exchange and overturning circulation (collectively hereafter referred to as the "atmospheric removal fraction"), and the fraction of deposited seaweed carbon that remains sequestered for at least 100 years. The total amount of atmospheric CO_2 removed by sinking seaweed is calculated as:

$$e_{seqsink} = k_{atm} \times k_{fseq} \times \frac{tC}{tDW} \times \frac{tCO_2}{tC} \tag{14}$$

where $e_{seqsink}$ is net atmospheric CO_2 sequestered annually in tons per km^2, k_{atm} is the atmospheric removal fraction, and k_{fseq} is the spatially-explicit fraction of sunk seaweed carbon that remains sequestered for at least 100 years (see Siegel et al. 2021)[53].

The emissions from transporting harvested seaweed to the optimal sinking location are calculated as:

$$e_{swtsink} = e_{transbase} \times d_{sink} \times s_{ww} \tag{15}$$

where $e_{swtsink}$ is the total annual CO_2 emissions from transporting harvested seaweed to the optimal sinking location in tCO_2/km^2 , $e_{transbase}$ is the CO_2 emissions (tons) from transporting 1 ton of material 1km on a barge (tCO_2/t-km), d_{sink} is the distance in km to the economically-optimized sinking location, and s_{ww} is the annually-harvested seaweed wet weight in t/km^2 as in eq. (10). Since the unit for $e_{transbase}$ is tCO_2/t-km, the emissions from transporting seaweed to the optimal sinking location are equal to $e_{transbase} \times d_{sink} \times s_{ww}$, and the emissions from transporting seaweed from the optimal sinking location back to the farm are equal to 0 (since the seaweed has been deposited already, so seaweed mass to transport is now 0). Note that this does not yet include transport emissions from transport of equipment post-seaweed-deposition (see eq. 16 below and Supplementary Fig. 16).

The emissions associated with transporting replacement equipment (e.g., lines, buoys, anchors) to the farming location and hauling back used equipment at the end of its assumed lifetime (1 year for seeded line, 5-20 years for capex by equipment type)[28,38] in the sinking CDR pathway are calculated as:

$$e_{eqtsink} = \left(e_{transbase} \times (2 \times d_{sink}) \times m_{eq}\right) + \left(e_{transbase} \times d_{port} \times m_{eq}\right) \tag{16}$$

where $e_{eqtsink}$ is the total annualized CO_2 emissions in tons from transporting both used and replacement equipment, $e_{transbase}$ is the CO_2 emissions from transporting 1 ton of material 1km on a barge, m_{eq} is the annualized equipment mass in tons, d_{sink} is the distance in km to the economically-optimized sinking location, and d_{port} is the ocean distance to the nearest port in km. We assume that the harvesting barge travels from the farming location directly to the optimal sinking location with harvested seaweed and replaced (used) equipment in tow (incl. used seeded line and annualized mass of used capital equipment), sinks the harvested seaweed, returns to the farm location, and then returns to the nearest port. These calculations assume the shortest sea-route distance (see *Distance to optimal sinking point*).

Net CO_2 emissions removed from the atmosphere by sinking seaweed are thus calculated as:

$$e_{remsink} = \frac{\left(e_{seqsink} - \left(e_{swtsink} + e_{eqtsink}\right)\right)}{s_{dw}} \tag{17}$$

where $\boldsymbol{e_{remsink}}$ is the net atmospheric CO_2 removed per ton of dry weight seaweed, $e_{seqsink}$ is as calculated in eq. (14), $e_{swtsink}$ is as calculated in eq. (15), $e_{eqtsink}$ is as calculated in eq. (16), and s_{dw} is annually-harvested seaweed dry weight in t/km^2.

Net cost of climate benefits.

Sinking. To calculate the total net cost and emissions from the production, harvesting, and transport of seaweed for CDR, we combine the cost and emissions from the sinking-pathway cost and value modules. The total net cost of seaweed CDR per dry weight ton of seaweed is calculated as:

$$c_{sinknet} = c_{prod} - v_{sink} \tag{18}$$

where $c_{sinknet}$ is the total net cost of seaweed for CDR per dry weight ton harvested, c_{prod} is the net production cost per ton DW as calculated in eq. (6), and v_{sink} is the net value (or cost, if negative) per ton seaweed DW as calculated in eq. (13).

The total net CO_2 emissions removed per dry weight ton of seaweed is calculated as:

$$e_{sinknet} = e_{remsink} - e_{prod} \tag{19}$$

where $e_{sinknet}$ is the total net atmospheric CO_2 removed per dry weight ton of seaweed harvested annually (tCO_2/tDW/year), $e_{remsink}$ is the net atmospheric CO_2 removed via seaweed sinking annually as calculated in eq. (17), and e_{prod} is the net CO_2 emitted from production and harvesting of seaweed annually as calculated in eq. (9). For each Monte Carlo simulation, locations where $e_{sinknet}$ is negative (i.e., net emissions rather than net removal) are not included in subsequent calculations since they would not be contributing to CDR in that scenario.

Total net cost is then divided by total net emissions to get a final value for cost per ton of atmospheric CO_2 removed:

$$c_{pertonsink} = \frac{c_{sinknet}}{e_{sinknet}} \tag{20}$$

where $c_{pertonsink}$ is the total net cost per ton of atmospheric CO_2 removed via seaweed sinking ($/t$CO_2$ removed), $c_{sinknet}$ is total net cost per ton seaweed DW harvested as calculated in eq. (18) ($/tDW), and $e_{sinknet}$ is total net atmospheric CO_2 removed per ton seaweed DW harvested as calculated in eq. (19) (tCO_2/tDW).

GHG emissions mitigation. Instead of sinking seaweed for CDR, seaweed can be used to make products (incl. but not limited to food, animal feed, and biofuels). Replacing convention products with seaweed-based products can result in "avoided emissions" if the emissions from growing, harvesting, transporting, and converting seaweed into products is less than the total greenhouse gas emissions (incl. non-CO_2 GHGs) embodied in conventional products that seaweed-based products replace.

When seaweed is used to make products, we assume it is transported back to the nearest port immediately after being harvested. The annualized cost to transport the harvested seaweed and replacement equipment (e.g., lines, buoys, anchors) is calculated as:

$$c_{transprod} = \frac{\left(c_{transbase} \times d_{port} \times \left(s_{ww} + m_{eq}\right)\right)}{s_{dw}} \tag{21}$$

where $c_{transprod}$ is the annualized cost per ton DW seaweed to transport seaweed and equipment back to port from the farm location, $c_{transbase}$ is the cost to transport 1 ton of material 1 km on a barge, m_{eq} is the annualized equipment mass in tons, d_{port} is the ocean distance to the nearest port in km, s_{ww} is the annual wet weight of seaweed harvested per km^2 as calculated in eq. (10), and s_{dw} is the annual dry weight of seaweed harvested per km^2.

The total value of seaweed that is used for seaweed-based products is calculated as:

$$v_{product} = v_{mkt} - \left(c_{transprod} + c_{conv}\right) \tag{22}$$

where $v_{product}$ is the total value (cost, if negative) of seaweed used for products ($/tDW), v_{mkt} is how much each ton of seaweed would sell for given the current market price of conventional products that seaweed-based products replace ($/tDW), $c_{transprod}$ is as calculated in eq. (21), and c_{conv} is the cost to convert teach ton of seaweed to a usable product ($/tDW).

The annualized CO_2 emissions from transporting harvested seaweed and equipment back to port are calculated as:

$$e_{transprod} = \frac{\left(e_{transbase} \times d_{port} \times \left(s_{ww} + m_{eq}\right)\right)}{s_{dw}} \tag{23}$$

where $e_{transprod}$ is the annualized CO_2 emissions per ton DW seaweed to transport seaweed and equipment back to port from the farm location, $e_{transbase}$ is the CO_2 emissions from transporting 1 ton of material 1km on a barge, m_{eq} is the annualized equipment mass in tons, d_{port} is the ocean distance to the nearest port in km, s_{ww} is the annual wet weight of seaweed harvested per km^2 as calculated in eq. (10), and s_{dw} is the annual dry weight of seaweed harvested per km^2.

Total emissions avoided by each ton of harvested seaweed DW are calculated as:

$$e_{avprod} = e_{subprod} - \left(e_{transprod} + e_{conv}\right) \tag{24}$$

where e_{avprod} is total CO_2-eq emissions avoided per ton of seaweed DW per year (incl. non-CO_2 GHGs using a Global Warming Potential (GWP) time period of 100 years), $e_{subprod}$ is the annual CO_2-eq emissions avoided per ton seaweed DW by replacing a conventional product with a seaweed-based product, $e_{transprod}$ is as calculated in eq. (23), and e_{conv} is the annual CO_2 emissions per ton seaweed DW from converting seaweed into usable products. $e_{subprod}$ was calculated by converting seaweed DW to caloric content[54] for food/feed and comparing emissions intensity per kcal to agricultural products[24], or by converting seaweed DW into equivalent biofuel content with a yield of 0.25 tons biofuel per ton DW[55] and dividing the CO_2 emissions per ton fossil fuel by the seaweed biofuel yield.

To calculate the total net cost and emissions from the production, harvesting, transport, and conversion of seaweed for products, we combine the cost and emissions from the product-pathway cost and value modules. The total net cost of seaweed for products per dry weight ton is calculated as:

$$c_{prodnet} = c_{prod} - v_{product} \tag{25}$$

where $c_{prodnet}$ is the total net cost per dry weight ton of seaweed harvested for use in products, c_{prod} is the net production cost per ton DW as calculated in eq. (6), and $v_{product}$ is the net value (or cost, if negative) per ton DW as calculated in eq. (22).

The total net CO_2-eq emissions avoided per dry weight ton of seaweed used in products is calculated as:

$$e_{prodnet} = e_{avprod} - e_{prod} \tag{26}$$

where $e_{prodnet}$ is the total net CO_2-eq avoided per dry weight ton of seaweed harvested annually (tCO_2/tDW/year), e_{avprod} is the net CO_2-eq emissions avoided by seaweed products annually as calculated in eq. (24), and e_{prod} is the net CO_2 emitted from production and harvesting of seaweed annually as calculated in eq. (9). For each Monte Carlo simulation, locations where $e_{prodnet}$ is negative (i.e., net emissions rather than net emissions avoided) are not included in subsequent calculations since they would not be avoiding any emissions in that scenario.

Total net cost is then divided by total net emissions avoided to get a final value for cost per ton of CO_2-eq emissions avoided:

$$c_{pertonprod} = \frac{c_{prodnet}}{e_{prodnet}} \tag{27}$$

where $c_{pertonprod}$ is the total net cost per ton of CO_2-eq emissions avoided by seaweed products (\$/tCO_2-eq avoided), $c_{prodnet}$ is total net cost per ton seaweed DW harvested for products as calculated in eq. (25) (\$/tDW), and $e_{prodnet}$ is total net CO_2-eq emissions avoided per ton seaweed DW harvested for products as calculated in eq. (26) (tCO_2/tDW).

Parameter ranges for Monte Carlo simulations

For technoeconomic parameters with two or more literature values (see Supplementary Table 1), we assumed that the maximum literature value reflected the 95th percentile and the minimum literature value represented the 5th percentile of potential costs or emissions. For parameters with only one literature value, we added +- 50% to the literature value to represent greater uncertainty within the modeled parameter range. Values at each end of parameter ranges were then rounded prior to Monte Carlo simulations as follows: capital costs, operating costs, and harvest costs to the nearest \$10,000/km^2, labor costs and insurance costs to the nearest \$1,000/km^2, line costs to the nearest \$0.05/m, transport costs to the nearest \$0.05/t/km, transport emissions to the nearest 0.000005 tCO_2/t/km, maintenance transport emissions to the nearest 0.0005 tCO_2/km, product avoided emissions to the nearest 0.1 tCO_2-eq/tDW, conversion cost down to the nearest \$10/tDW on the low end of the range and up to the nearest \$10/tDW on the high end of the range, and conversion emissions to the nearest 0.01 tCO_2/tDW.

We extended the minimum range values of capital costs to \$10,000/km^2 and transport emissions to 0 to reflect potential future innovations, such as autonomous floating farm setups that would lower capital costs and net-zero emissions boats that would result in 0 transport emissions. To calculate the minimum value of \$10,000/km^2 for a potential autonomous floating farm, we assumed that the bulk of capital costs for such a system would be from structural lines and floatation devices, and we therefore used the annualized structural line (system rope) and buoy costs from Camus et al. (2019)[38] rounded down to the nearest \$5,000/km^2. The full ranges used for our Monte Carlo simulations and associated literature values are shown in Supplementary Table 1.

Distance to optimal sinking point

Distance to the optimal sinking point was calculated using a weighted distance transform (path-finding algorithm, modified from code by Omar Richardson (2020)[56]) that finds the shortest ocean distance from each seaweed growth pixel to the location at which the net CO_2 removed is maximized (incl. impacts of both increased sequestration fraction and transport emissions for different potential sinking locations) and the net cost is minimized. This is not necessarily the location in which the seaweed was grown, since the fraction of sunk carbon that remains sequestered for 100 years is spatially heterogeneous (see Siegel et al., 2021)[53]. For each ocean grid cell, we determined the cost-optimal sinking point by iteratively calculating equations 11-20 and assigning d_{sink} the distance calculated by weighted distance transform to each potential sequestration fraction 0.01-1.00 in increments of 0.01. With the exception of transport emissions, the economic parameter values used for these calculations were the averages of unrounded literature value ranges - we assumed that the maximum literature value reflected the 95th percentile and the minimum literature value represented the 5th percentile of potential costs or emissions, or for parameters with only one literature value, we added +- 50% to the literature value to represent greater uncertainty within the modeled parameter range. For transport and maintenance transport emissions, we extended the minimum values of the literature ranges to zero to reflect potential net-zero emissions transport options and used the mean values of the resulting ranges. The d_{sink} that resulted in minimum net cost per ton CO_2 for each ocean grid cell was saved as the final d_{sink} map, and the associated sequestration fraction value that the seaweed is transported to via d_{sink} was assigned to the original cell where the seaweed was farmed and harvested (Supplementary Fig. 19). If the cost-optimal location to sink using this method was the same cell where the seaweed was harvested, then d_{sink} was 0km and the sequestration fraction was not modified from its original value (Supplementary Fig. 18).

Comparison of seaweed production costs

Although there are not many estimates of seaweed production costs in the scientific literature, our estimates for the lowest-cost 1% area of the ocean (\$240-\$1,470/tDW) are broadly consistent with previously published results: seaweed production costs reported in the literature range from \$120-\$1,710/tDW[37,38,57,58], but are highly dependent on assumed seaweed yields. For example, Camus et al. (2019)[38] calculate a cost of \$870/tDW assuming minimum yield of 12.4 kgDW/m of cultivation line (equivalent to 8.3 kgDW/m^2 using 1.5m spacing between lines). This is roughly equal to the highest-yield grid cell our the ambient nutrient scenario results (8.4 kgDW/m^2; Supplementary Fig. 3). Using the economic values from Camus et al. (2014) but with our estimates of average yield for the lowest 1% cost areas (4.7 kgDW/m^2) gives a much higher average cost of \$2,300/tDW. Contrarily, van den Burg et al. (2016)[37] calculate a cost of \$1,710/tDW using a yield of 20 tDW/hectare (i.e. 2 kg/m^2). Instead assuming our average yields from lowest-cost areas (i.e. 4.7 kgDW/m^2 or 47 tDW/hectare) would decrease the cost estimated by Van den Burg et al. (2016) to \$730/tDW. Most recently, Capron et al. (2020)[58] calculate an optimistic scenario cost of \$120/tDW based on an estimated yield of 120 tDW/hectare (12 kg/m^2; 2.5 times higher than the average in our lowest-cost areas). Again, instead assuming the average yield in our lowest-cost areas would raise Capron et al.'s to \$310/tDW—somewhat higher than our lowest cost simulation in the cheapest 1% ocean areas (\$240/tDW).

Data Sources

Seaweed biomass harvested. We use spatially-explicit data for seaweed harvested globally under both ambient and flux-limited nutrient scenarios from the G-MACMODS seaweed growth model, presented in Arzeno-Soltero et al. (2022)

Fraction of deposited carbon sequestered for 100 years. We use data from Siegel et al. (2021) interpolated to our 1/12-degree grid resolution.

Distance to nearest port. We use the Distance from Port V1 dataset from Global Fishing Watch (https://globalfishingwatch.org/data-download/datasets/public-distance-from-port-v1) interpolated to our 1/12-degree grid resolution.

Significant wave height. We use data for annually-averaged significant wave height from the European Center for Medium-range Weather Forecasts (ECMWF) interpolated to our 1/12-degree grid resolution.

Ocean depth. We use data from the General Bathymetric Chart of the Oceans (GEBCO).

Shipping lanes. We use data of Automatic Identification System (AIS) signal count per ocean grid cell, interpolated to our 1/12-degree grid resolution. We define a major shipping lane grid cell as any cell with $>2.25 \times 10^8$ AIS signals, a threshold that encompasses most major trans-Pacific and trans-Atlantic shipping lanes as well as major shipping lanes in the Indian Ocean, North Sea, and coastal routes worldwide.

Marine Protected Areas (MPAs). We use data from the World Database on Protected Areas (WDPA) and define a MPA as any ocean WDPA >20 km^2.

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Author contributions

S.J.D., K.A.D. and B.T.S. conceived the initial study. S.J.D., K.A.D., B.T.S., I.A-S., M.L., C.F. and J.D. developed the research and methodology, with inputs and insights from J.H. J.D. conducted the analyses. All authors interpreted the results and implications. J.D. and S.J.D. produced the figures. J.D. drafted the manuscript with significant input and revisions from all authors.

Competing interests

The authors declare no competing interests.

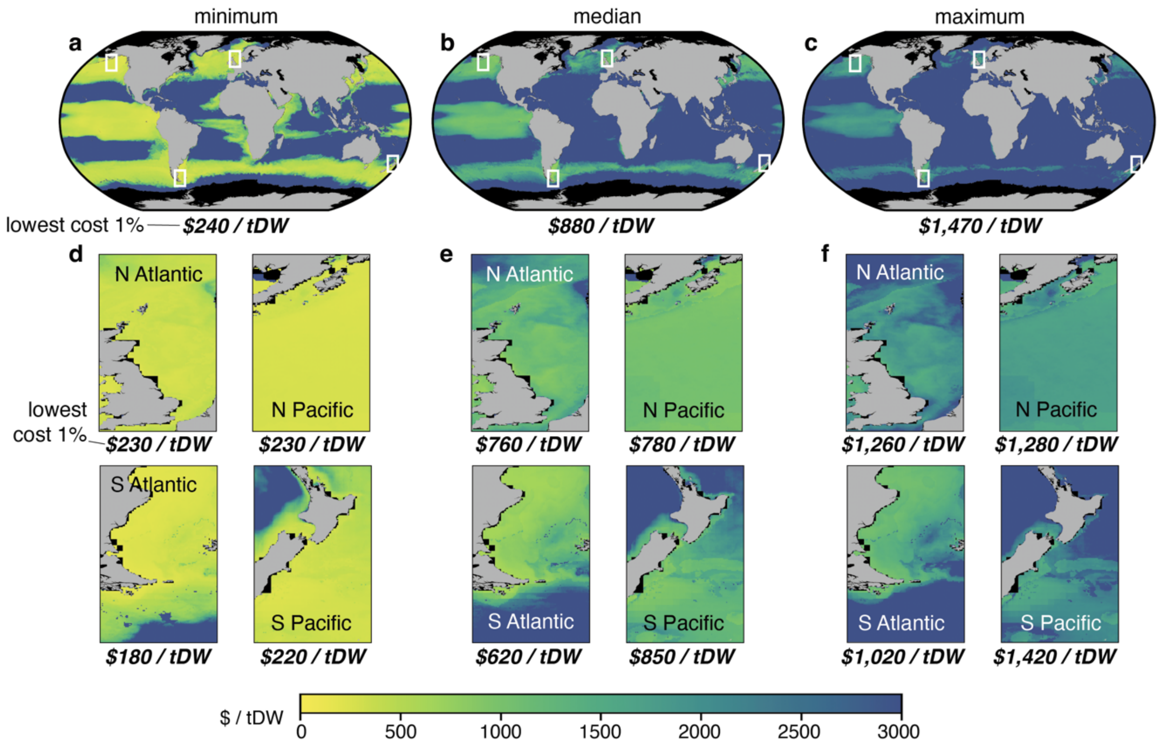

Figure 1 | Seaweed production costs. Estimated seaweed production costs vary considerably depending on assumed costs of farming capital, seeded lines, labor, and harvest (transport of harvested seaweed is not included). Across ambient nutrient simulations, average cost in the 1% of global ocean areas with lowest cost ranges from $240/tDW (**a**) to $1,470/tDW (**c**), with a median of $880/tDW (**b**). Regional insets (**d-f**) reveal small-scale features in particularly low-cost areas. Supplementary Fig. 2 shows maps for flux-limited simulations.

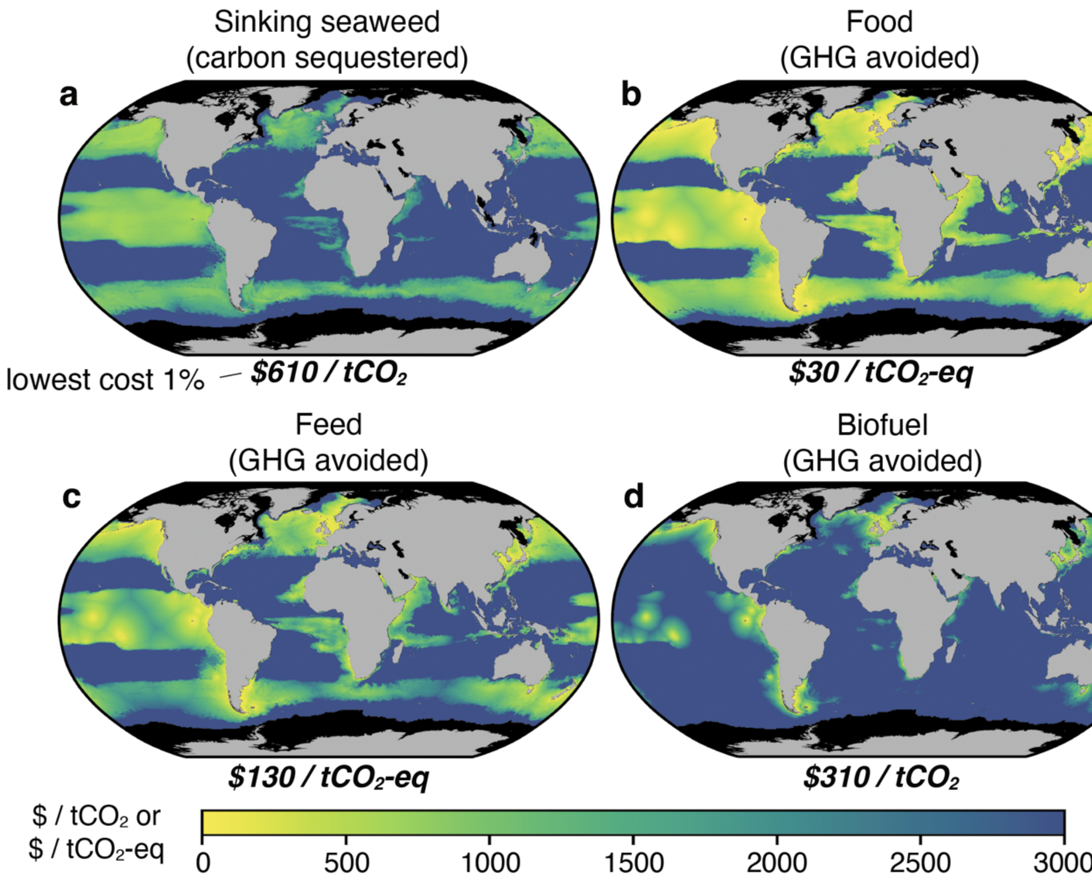

Figure 2 | Net cost of potential seaweed climate benefits. Costs of using farmed seaweed to sequester carbon or avoid GHG emissions vary in space according to estimated production costs as well as spatially-explicit differences in the costs and net emissions of transportation, sinking or conversion, and replacement of conventional market alternatives with seaweed products. Differentiation between seaweed product groups is based on emissions avoided by seaweed products and market value for each product type. Maps show optimistically low net costs (5th percentile) from ambient nutrient simulations. Average cost in the 1% of global ocean areas with lowest cost ranges from \$30/tCO_2-eq avoided when seaweed is used for food (**b**) to \$610/tCO_2 sequestered by sinking seaweed (**a**). Supplementary Figs. 6 and 7 show maps for flux-limited simulations and median costs, respectively.

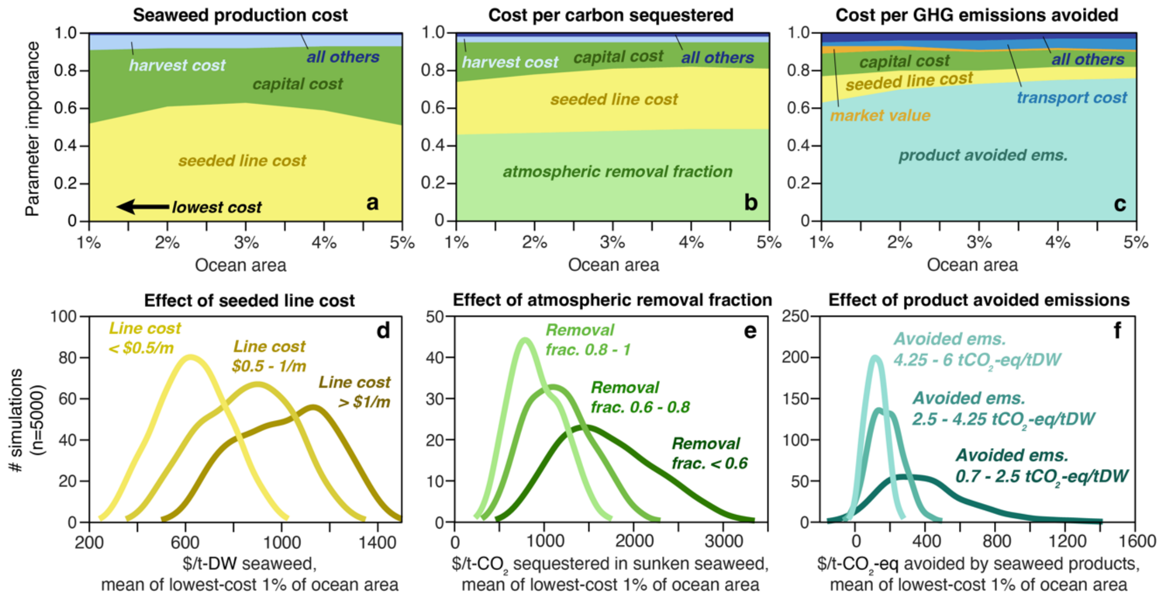

Figure 3 | Key cost sensitivities of seaweed production and climate benefits. Across Monte Carlo simulations in the 5% of ocean area where costs are lowest, estimated seaweed production cost is especially sensitive to the cost of seeded line and capital costs (**a**), whereas costs of carbon sequestration (**b**) and GHG emissions avoided (**c**) are strongly influenced by the fraction of seaweed carbon that corresponds to an equivalent amount removed from the atmosphere and the assumed emissions avoided by seaweed products, respectively. Binning simulations by ranges in the most important parameters shows that the lowest production and climate benefit costs depend upon seeded line costs <\$0.50/m (**d**), an assumed atmospheric removal fraction of >0.8 (**d**)**,** and avoided emissions >2.5 tCO_2-eq/tDW (**f**). Supplementary Fig. 9 shows cost sensitivities in flux-limited simulations.

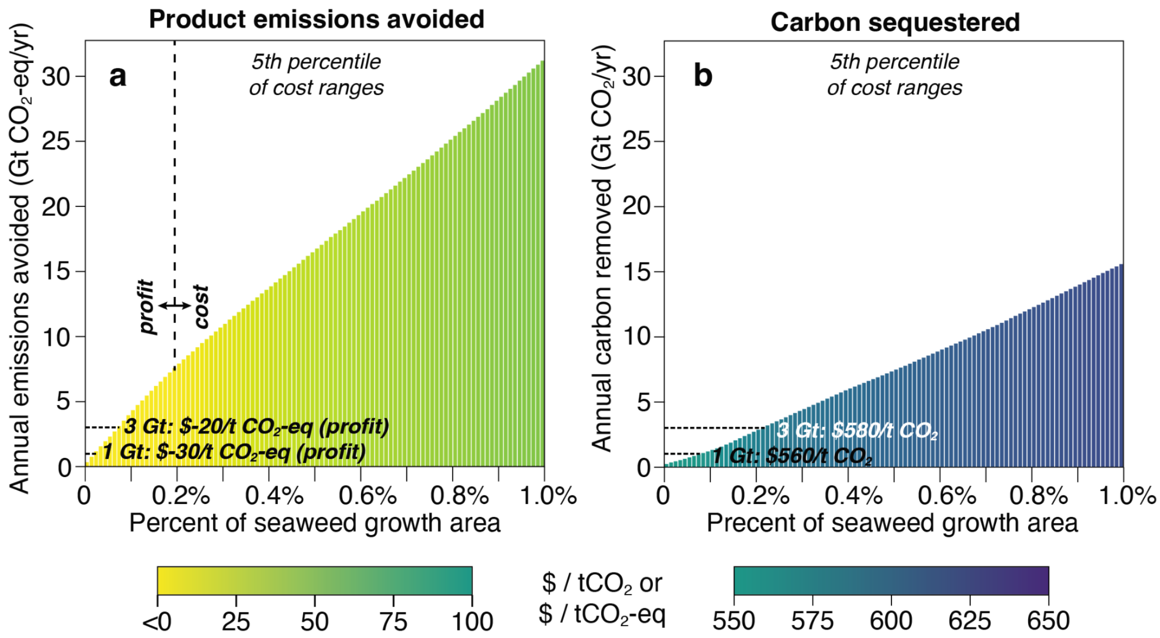

Figure 4 | Cumulative potential climate benefits of large-scale seaweed farming. Total GHG emissions avoided (**a**) or carbon sequestered (**b**) each year could reach gigaton-scales if seaweed were farmed over large areas of the ocean. Bars show the potential climate benefits as a function of the lowest-cost ocean area (0.1% of ocean area is roughly 360,000 km^2, nearly the area of Germany and 130 times the total area of current seaweed farms), and colors indicate the average cost (or profit) per tCO_2-eq or tCO_2 sequestered of optimistically low net costs (5th percentile) from ambient nutrient simulations. Supplementary Figs. 10 and 11 show cumulative potential and costs at the median and in flux-limited simulations.

Table 1 | Ranges of selected variables used in our technoeconomic analysis.

Variable	Unit	Model Range	Values reported in literature
Capital costs	\$/km^2/year	10,000 – 1,000,000	929,676 [37] 550,000 – 950,000 [58] 375,910 [57] 210,580 [38]
Seeded line cost	\$/m	0.05 – 1.45	1.38 [37] 0.13 [38]
Harvest costs	\$/harvest	120,000 – 400,000	381,265 [38] 138,000 [37]
Transport cost per ton of material	\$/t/km	0.1 – 0.35	0.225 [37]
Transport emissions per ton of material	tCO_2/t/km	0 – 0.000045	0.00003 [28]
Maintenance boat emissions	tCO_2/km	0 – 0.0035	0.0023653 (calculated using methods from [28,52])
Atmospheric removal fraction	fraction (unitless)	0.4 – 1	0.5 (global average, from preliminary experiment by authors using [34] informed by [15])
Seaweed market value for product end-use	\$/tDW	400 – 800	Food: 500-800 (dried seaweed wholesale price from [59]) Feed: 400-500 (values per ton dry animal feed and soybean meal from [37,60], assuming a direct replacement with dry seaweed) Fuel: 415 (dried seaweed price for bioethanol production, calculated based on bioethanol yield per ton seaweed and maximum of historical E85 fuel prices from [61], modeled range 400-500)
GHG emissions avoided by replacement with seaweed product	tCO_2e/tDW	0.7 – 6.0	Food: 1-6 (considering global average emissions from GHGs per kcal for pulses, vegetables, fruits, oil crops, and cereals, from [24]) Feed: 2-3 (considering global average emissions from GHGs per kcal for oil crops and cereals, +- 50% uncertainty, from [24]) Fuel: 0.7-1 (assuming 3.2-3.5 tCO_2/t fossil fuel by fuel type from [62] and 0.25 t bioethanol/tDW yield from [55], and energy density equivalence conversions by fuel type)

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Supplementary Information

Economic and biophysical limits to seaweed-based climate solutions

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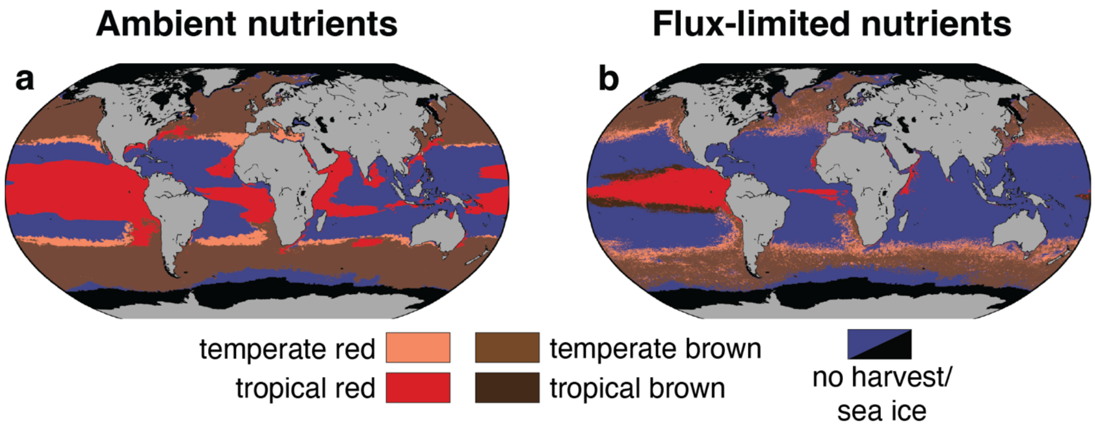
Supplementary Table 1 | Technoeconomic model variables. Note: references for literature values are listed at the end of the Supplementary Information.

Variable	Unit	Model Range	Values reported in literature
Capital costs	$\$/km^2/year$	10,000 – 1,000,000	929,676 [1] 550,000 – 950,000 [2] 375,910 [3] 210,580 [4]
Operating and maintenance costs	$\$/km^2/year$	60,000 – 70,000	69,000 [1] 63,320 [4]
Seeded line cost	$/m	0.05 – 1.45	1.38 [1] 0.13 [4]
Labor costs (excl. harvest labor)	$\$/km^2/year$	38,000 – 120,000	115,485 [4] 41,800 [1]
Harvest costs (incl. harvest labor, excl. harvest transport)	$/harvest	120,000 – 400,000	381,265 [4] 138,000 [1]
Transport cost per ton of material	$/t/km	0.1 – 0.35	0.225 [1]
Transport emissions per ton of material	$tCO_2/t/km$	0 – 0.000045	0.00003 [5]
Maintenance boat emissions	tCO_2/km	0 – 0.0035	0.0023653 (calculated using methods from [5,6])
Insurance costs	$\$/km^2/year$	35,000 – 105,000	70,000 [1]
Aquaculture license costs	$\$/km^2/year$	1,000 – 2,000	1,420 [4]
Atmospheric removal fraction	fraction (unitless)	0.4 – 1	0.5 (global average, from preliminary experiment by authors using [7] informed by [8])
Seaweed market value for product end-use	$/tDW	400 – 800	Food: 500-800 (dried seaweed wholesale price from [9]) Feed: 400-500 (values per ton dry animal feed and soybean meal from [1,10], assuming a direct replacement with dry seaweed) Fuel: 415 (dried seaweed price for bioethanol production, calculated based on bioethanol yield per ton seaweed and maximum of historical E85 fuel prices from [11], modeled range 400-500)
Conversion cost	$/tDW	20 – 80	48 (calculated with data from [12] assuming plant meets full feedstock capacity)

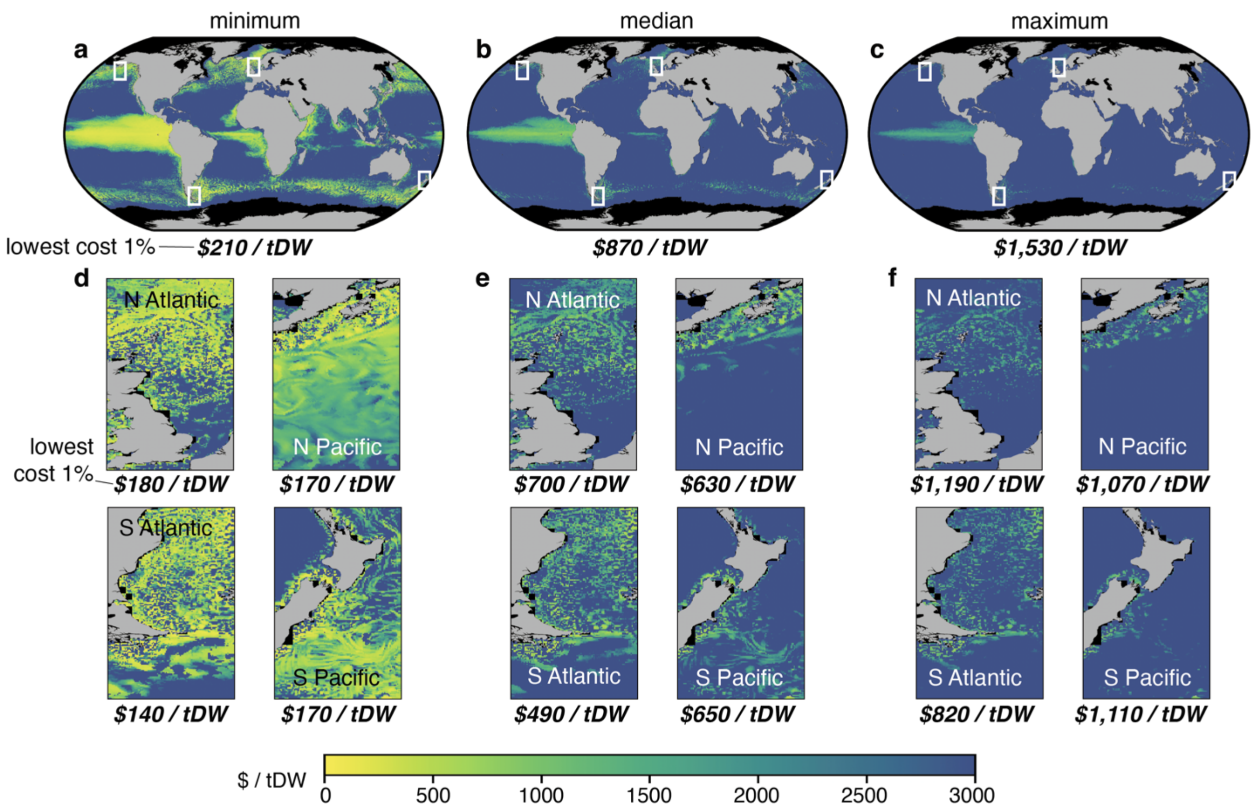
Conversion emissions	tCO_2/tDW	0 – 0.01	0.0057 (calculated using data and methods from [12])
Depth impact on capex	multiplier (unitless)	0 – 1	1 (estimation used in [1] that offshore depth can double capex)
Significant wave height impact on capex	multiplier (unitless)	0 – 1	No literature value; author assumption that waviness impacts capital lifetime similarly to depth impact
GHG emissions avoided by replacement with seaweed product	tCO_2e/tDW	0.7 – 6.0	Food: 1-6 (considering global average emissions from GHGs per kcal for pulses, vegetables, fruits, oil crops, and cereals, from [13]) Feed: 2-3 (considering global average emissions from GHGs per kcal for oil crops and cereals, +- 50% uncertainty, from [13]) Fuel: 0.7-1 (assuming 3.2-3.5 tCO_2/t fossil fuel by fuel type from [14], 0.25t bioethanol/tDW from [12], and energy density equivalence conversions by fuel type)

Supplementary Table 2 | Constants in model.

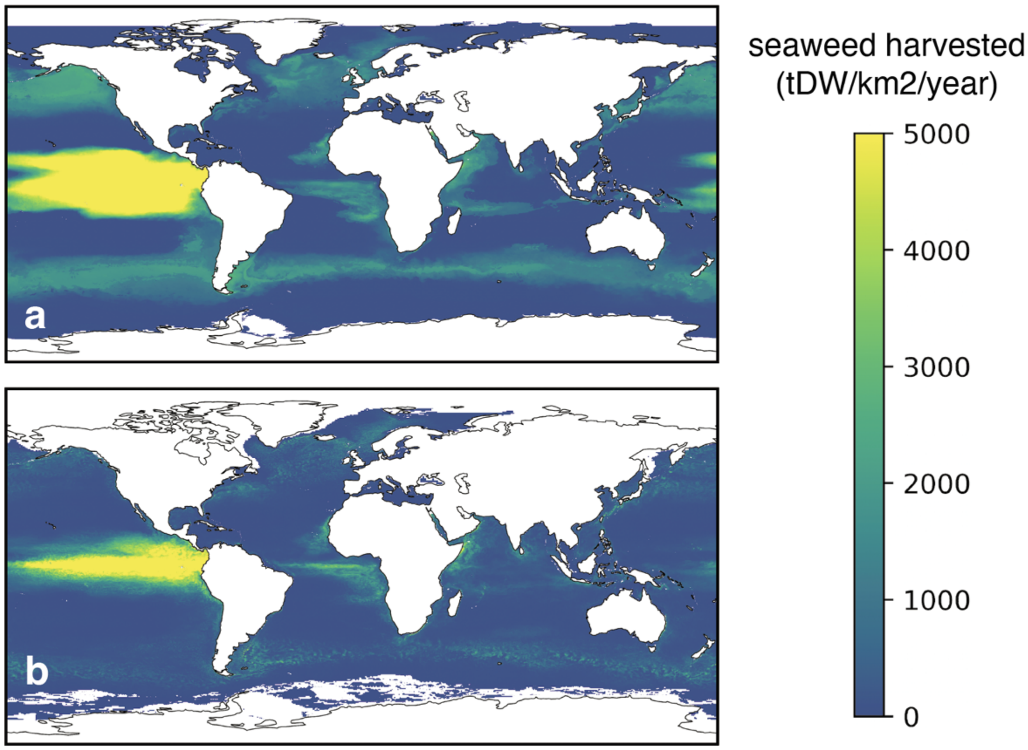
Parameter	Unit	Model Range	Source
Total length of cultivation line per unit area	m/km^2	Tropical red: 5,000,000 Temperate red: 20,000,000 Tropical brown: 751,880 Temperate brown: 666,667	Calculated using species-specific line spacing from [15]
Capital and other annualized equipment mass	t/km^2/year	Tropical red: 1,231.87 Temperate red: 4,927.50 Tropical brown: 185.24 Temperate brown: 164.25	Calculated using line spacing (above) and methods from extended methods in [5]
Number of maintenance trips	trips/km^2/year	6	5
Fraction of sunk carbon sequestered for 100 years	fraction (unitless)	0 – 1	16
Depth beyond which capex increases via depth_mult	m	500	17
Significant wave height beyond which capex increases via wave_mult	m	3	18
Seaweed carbon fraction	tC/tDW	0.3	15,19
Seaweed caloric content	Kcal/tDW	2,980,000	20
Bioethanol yield from seaweed	t/tDW	0.25	12



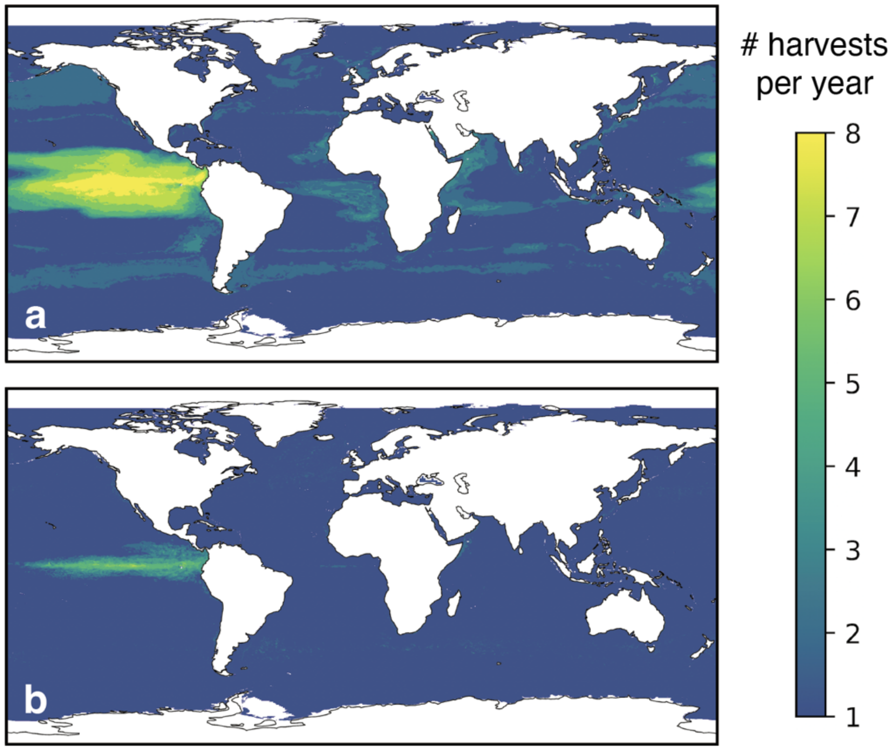
Supplementary Figure 1 | Seaweed preferred species. The species that results in the most harvested biomass is shown for each ocean grid cell for the G-MACMODS ambient nutrient scenario (**a**) and flux-limited nutrient scenario (**b**). Modified from [15].



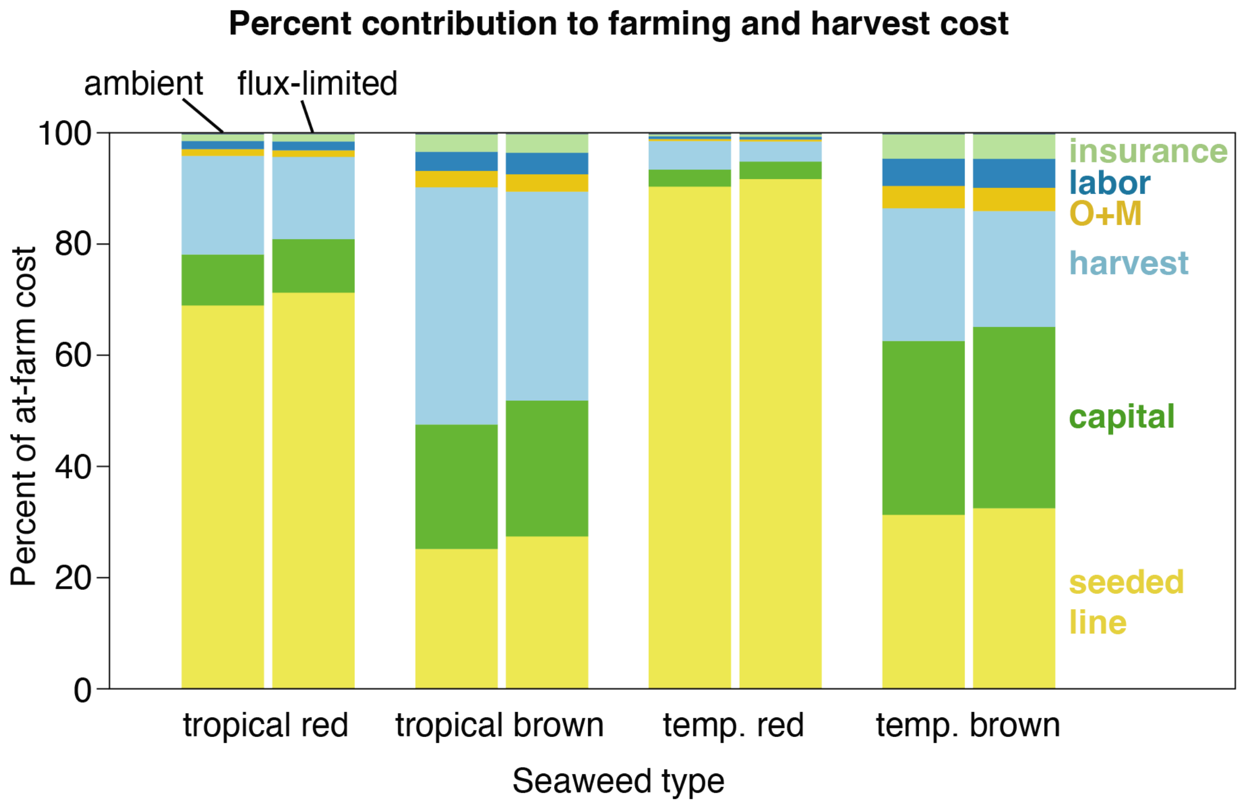
Supplementary Figure 2 | Seaweed production and harvest cost using flux-limited nutrient scenario. Estimated seaweed production costs vary considerably depending on assumed costs of farming capital, seeded lines, labor, and harvest (transport of harvested seaweed is not included). Across flux-limited nutrient simulations, average cost in the 1% of global ocean areas with lowest cost ranges from $210/tDW (**a**) to \$1,530/tDW (**c**), with a median of \$870/tDW (**b**). Regional insets (**d-f**) reveal small-scale features in particularly low-cost areas.



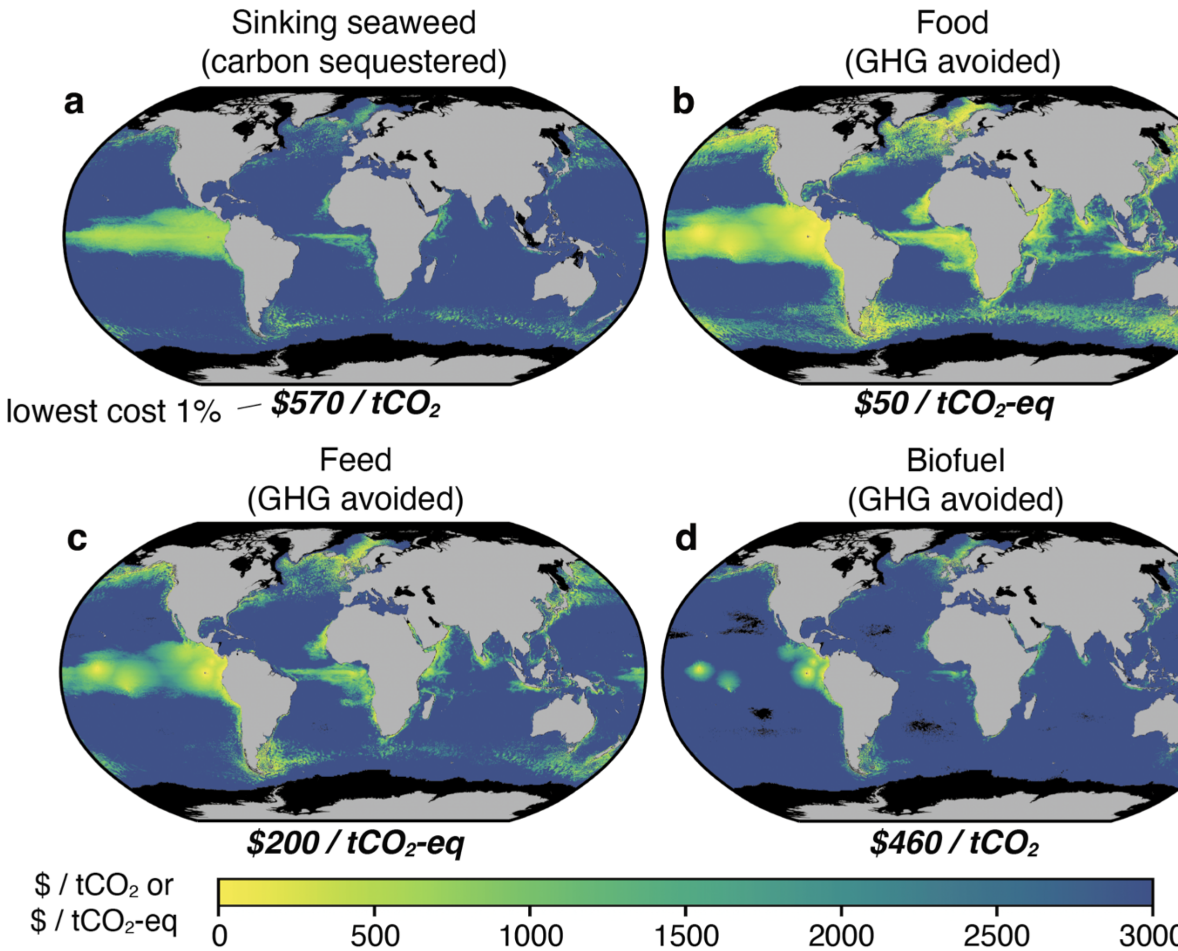
Supplementary Figure 3 | Annual seaweed biomass harvested. Maps show amount of seaweed harvested annually (tDW/km^2/year) using ambient (**a**) and flux-limited (**b**) nutrients in G-MACMODS [15]



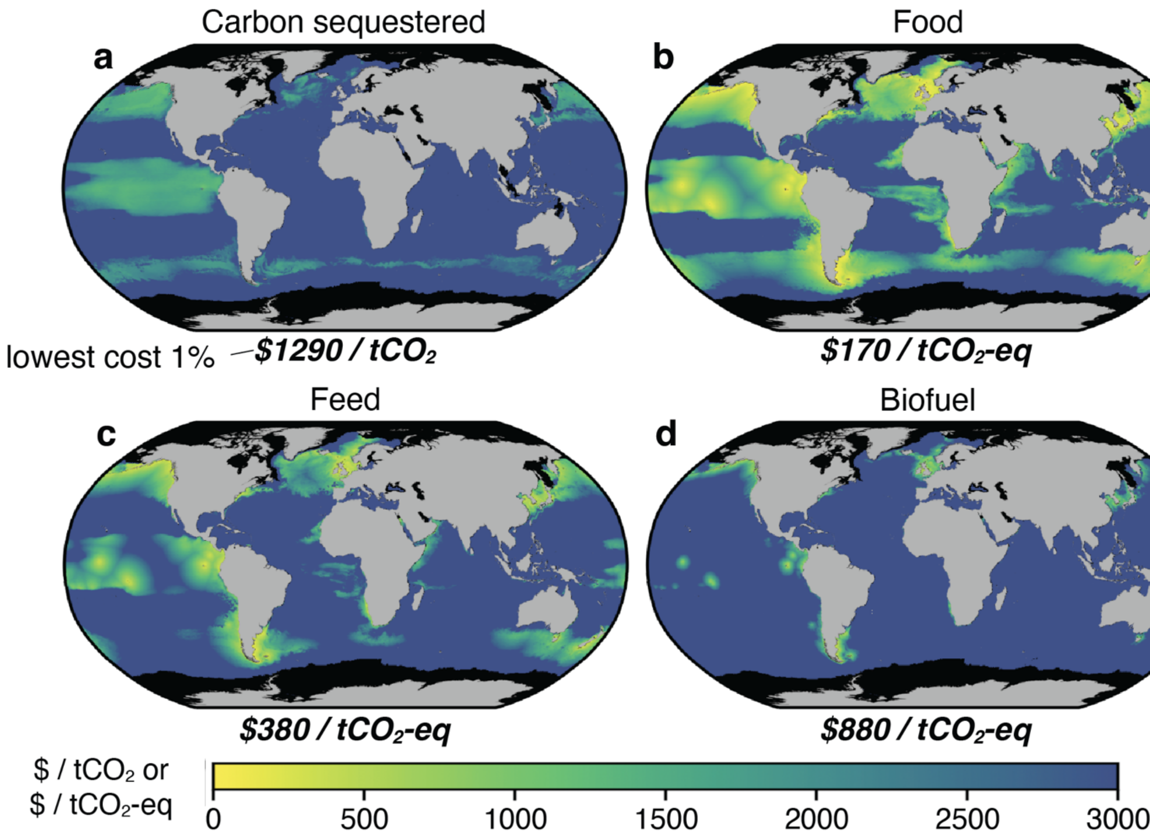
Supplementary Figure 4 | Number of harvests required to reach maximum annual yield. Maps show number of harvests per year using ambient (**a**) and flux-limited (**b**) nutrients in G-MACMODS [15].



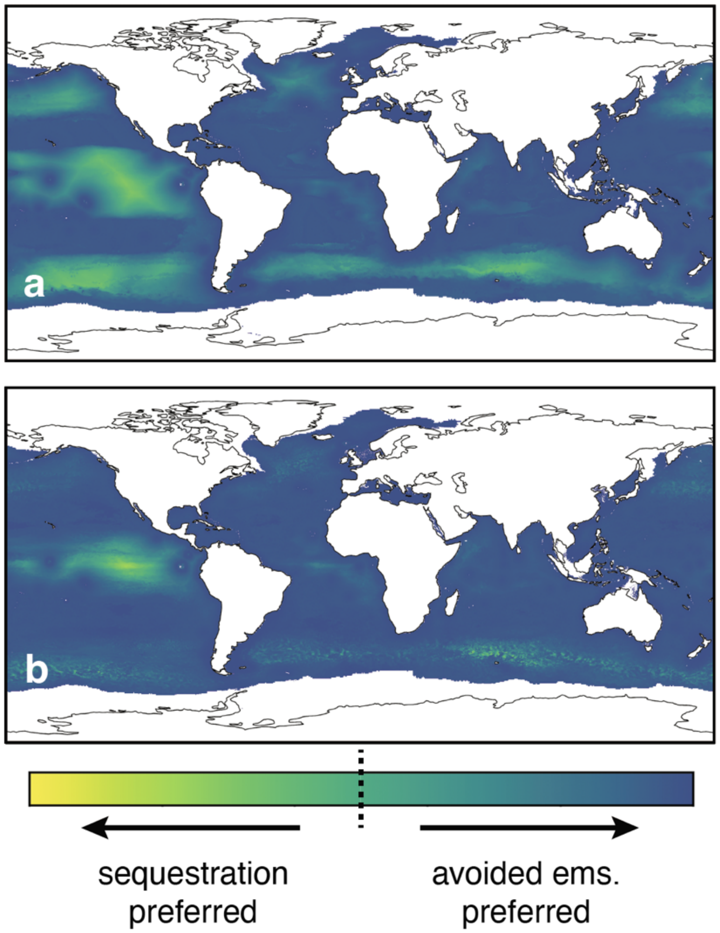
Supplementary Figure 5 | Summary of total farming cost breakdown per km^2. Percent of total \$/km^2 seaweed farming cost for four seaweed types in ambient (left bar for each type) and flux-limited (right bar for each type) simulations. Note: does not include transportation costs.



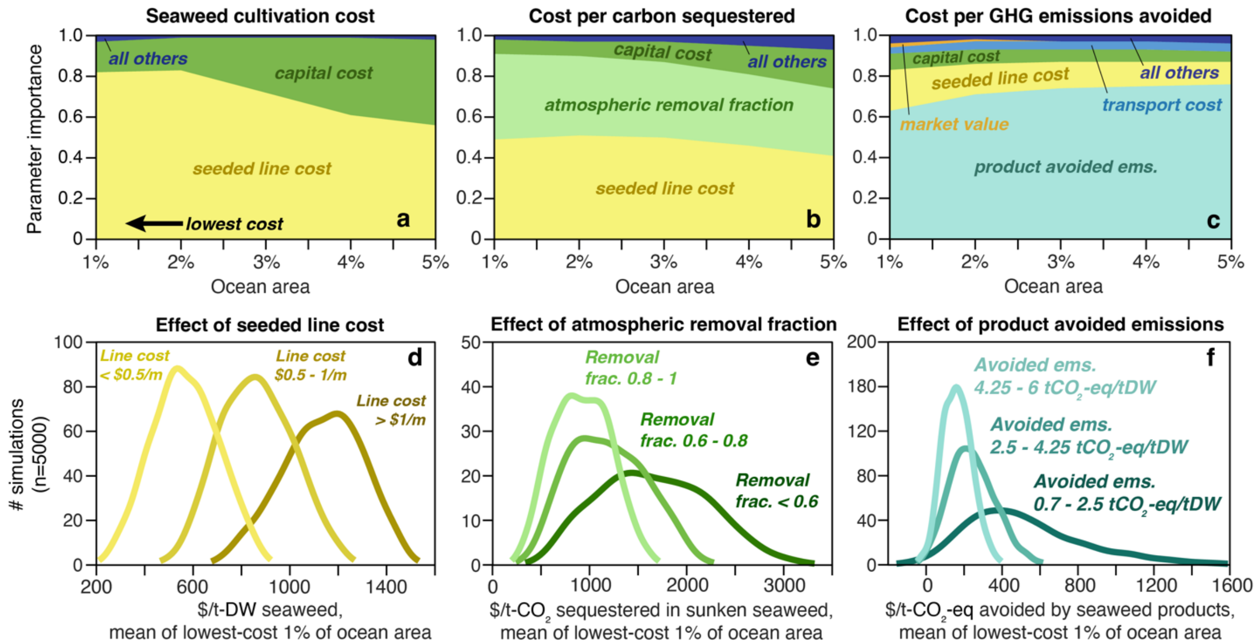
Supplementary Figure 6 | Net cost of potential seaweed climate benefits for flux-limited nutrient simulations. Costs of using farmed seaweed to sequester carbon or avoid GHG emissions vary in space according to estimated production costs as well as spatially-explicit differences in the costs and net emissions of transportation, sinking or conversion, and replacement of conventional market alternatives with seaweed products. Differentiation between seaweed product groups is based on emissions avoided by seaweed products and market value for each product type. Maps show optimistically low net costs (5th percentile) from flux-limited nutrient simulations. Average cost in the 1% of global ocean areas with lowest cost ranges from \$50/tCO_2-eq avoided when seaweed is used for food (**b**) to \$570/tCO_2 sequestered by sinking seaweed (**a**).



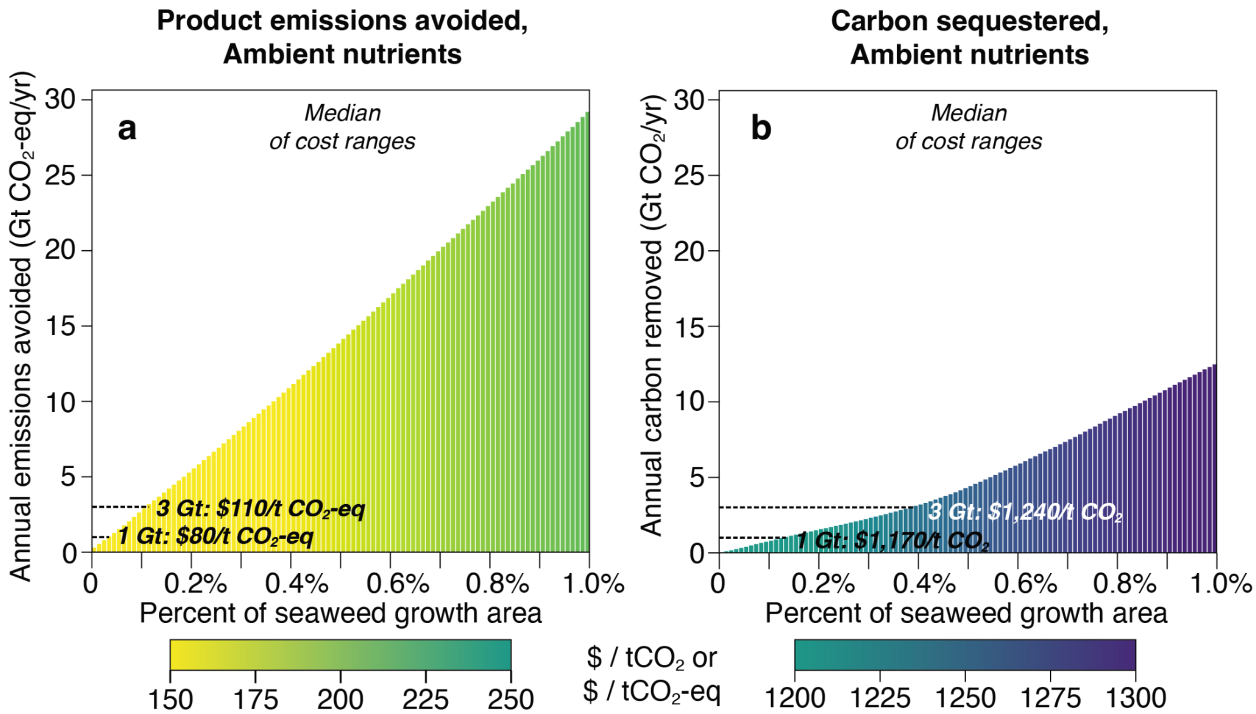
Supplementary Figure 7 | Median net cost of potential seaweed climate benefits. Costs of using farmed seaweed to sequester carbon or avoid GHG emissions vary in space according to estimated production costs as well as spatially-explicit differences in the costs and net emissions of transportation, sinking or conversion, and replacement of conventional market alternatives with seaweed products. Differentiation between seaweed product groups is based on emissions avoided by seaweed products and market value for each product type. Maps show median costs from ambient nutrient simulations. Average cost in the 1% of global ocean areas with lowest cost ranges from \$30/tCO_2-eq avoided when seaweed is used for food (**b**) to \$610/tCO_2 sequestered by sinking seaweed (**a**).



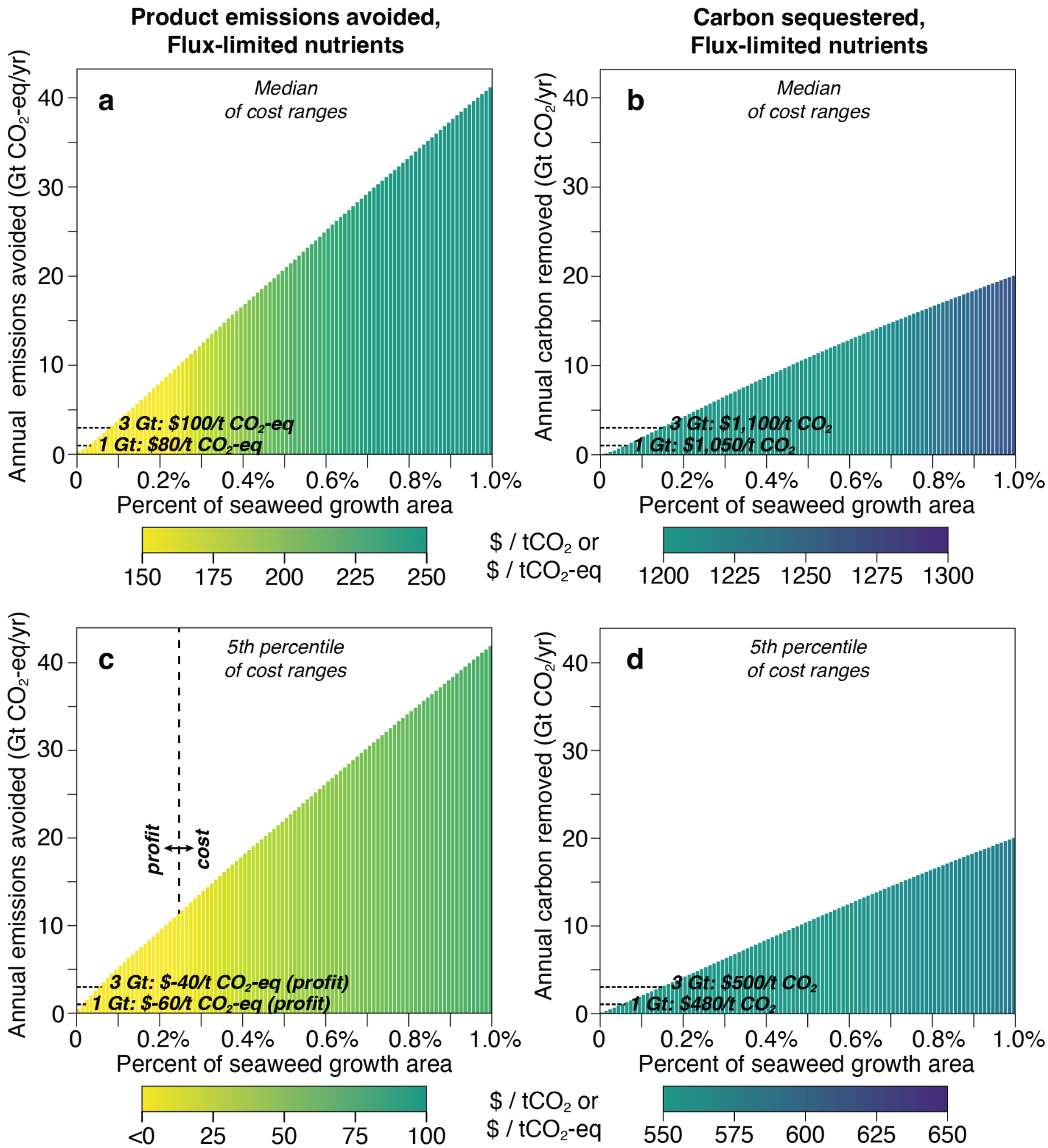
Supplementary Figure 8 | Economic preference for sinking or products by location. Maps show the average across all ambient (**a**) and flux-limited (**b**) simulations of whether carbon sequestration via sinking (yellow-green shades) or GHG emissions mitigation via products (green-blue shades) is cheaper. Sequestration via sinking is generally only preferred in locations farthest from port.



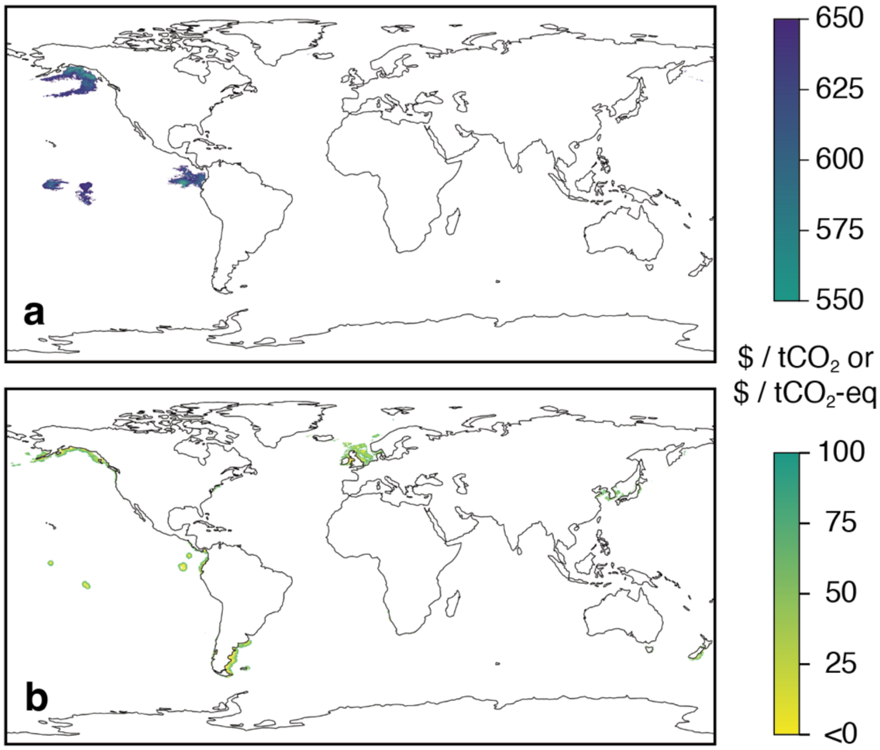
Supplementary Figure 9 | Key cost sensitivities of seaweed production and climate benefits for flux-limited nutrient simulations. Across our Monte Carlo simulations in the 5% of ocean area where costs are lowest, estimated seaweed production cost is especially sensitive to the cost of seeded line and capital costs (**a**), whereas costs of carbon sequestration (**b**) and GHG emissions avoided (**c**) are strongly influenced by the fraction of seaweed carbon that corresponds to an equivalent amount removed from the atmosphere and the assumed emissions avoided by seaweed products, respectively. Binning simulations by ranges in the most important parameters shows that the lowest production and climate benefit costs depend upon seeded line costs <$0.50/m (**d**), an assumed atmospheric removal fraction of >0.8 (**d**), and avoided emissions >2.5 tCO_2-eq/tDW (**f**).



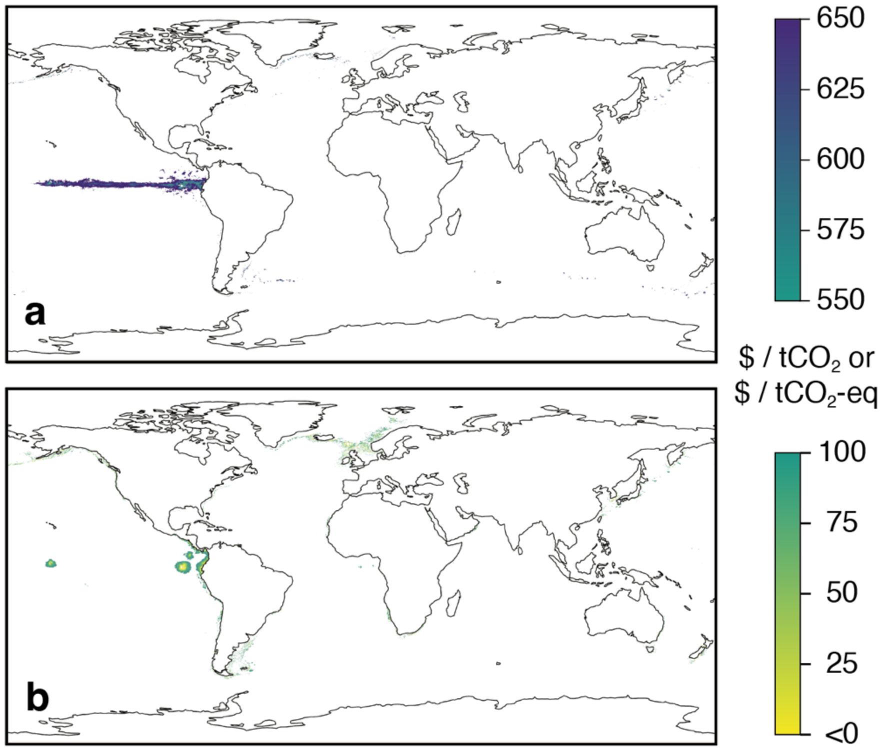
Supplementary Figure 10 | Cumulative potential climate benefits of large-scale seaweed farming using median of cost simulations. Total GHG emissions avoided (**a**) or carbon sequestered (**b**) each year could reach gigaton-scales if seaweed were farmed over large areas of the ocean. Bars show the potential climate benefits as a function of the lowest-cost ocean area (0.1% of ocean area is roughly 360,000 km^2, nearly the area of Germany and 130 times the total area of current seaweed farms), and colors indicate the average cost (or profit) per tCO_2-eq or tCO_2 sequestered of median net costs from ambient nutrient simulations.



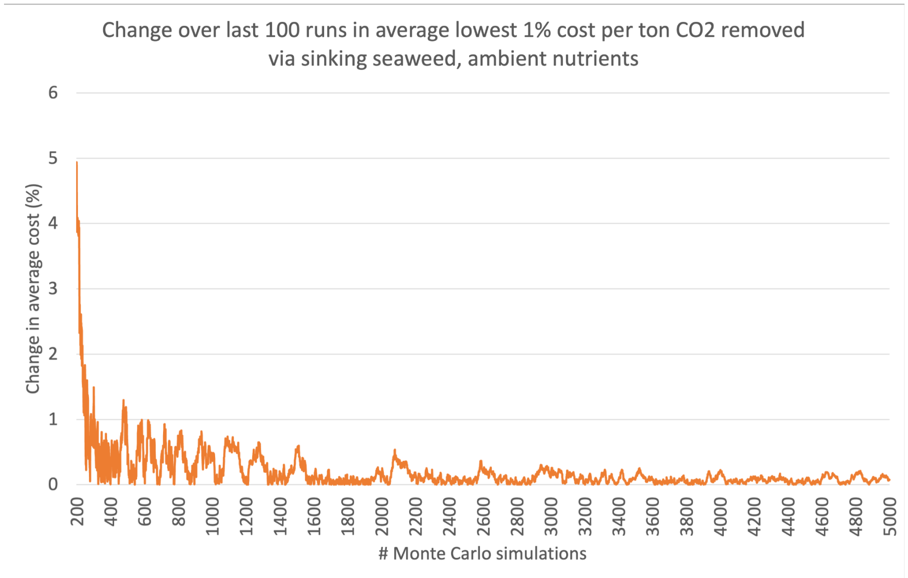
Supplementary Figure 11 | Cumulative potential climate benefits of large-scale seaweed farming using flux-limited nutrient simulations. Total GHG emissions avoided (**a**) or carbon sequestered (**b**) each year could reach gigaton-scales if seaweed were farmed over large areas of the ocean. Bars show the potential climate benefits as a function of the lowest-cost ocean area (0.1% of ocean area is roughly 360,000 km^2, nearly the area of Germany and 130 times the total area of current seaweed farms), and colors indicate the average cost (or profit) per tCO_2-eq or tCO_2 sequestered of median (**a, b**) and optimistically low (5th percentile; **c, d**) net costs from flux-limited nutrient simulations.

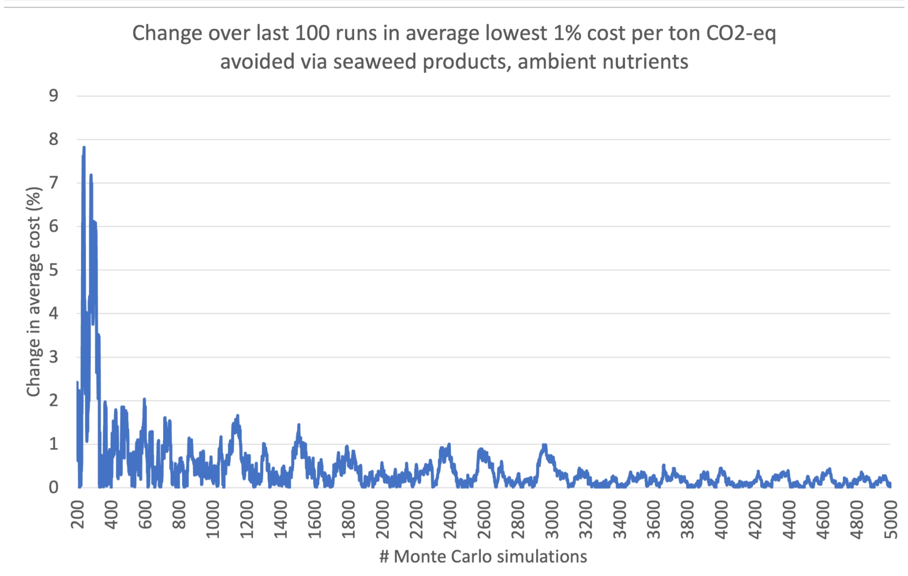


Supplementary Figure 12 | Maps of lowest cost areas in Fig. 4. Maps show lowest-cost areas in the cheapest 1% of seaweed growth area for carbon sequestration (**a**) and GHG emissions avoided (**b**) in the 5th percentile of ambient nutrient simulations, with the color of shaded areas representing the net cost per ton of CO_2 or CO_2-eq.

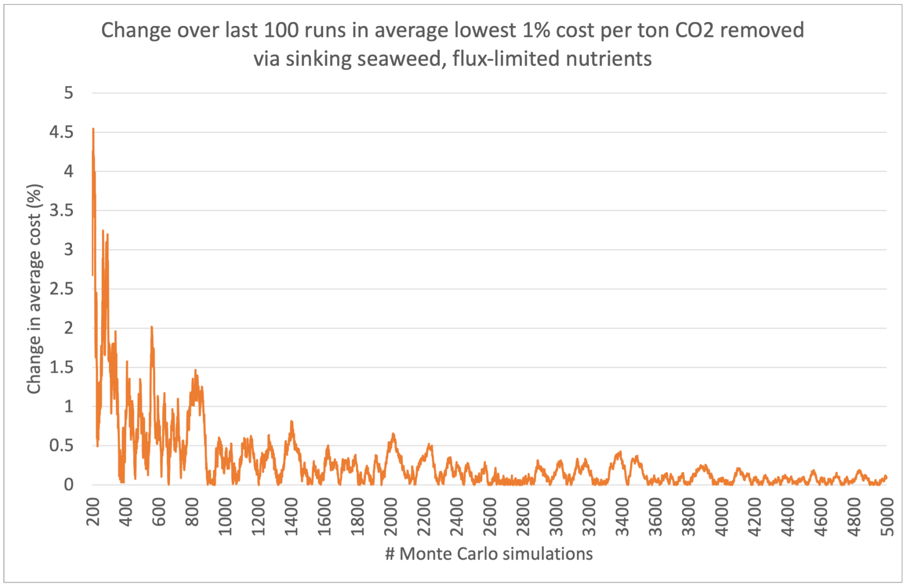


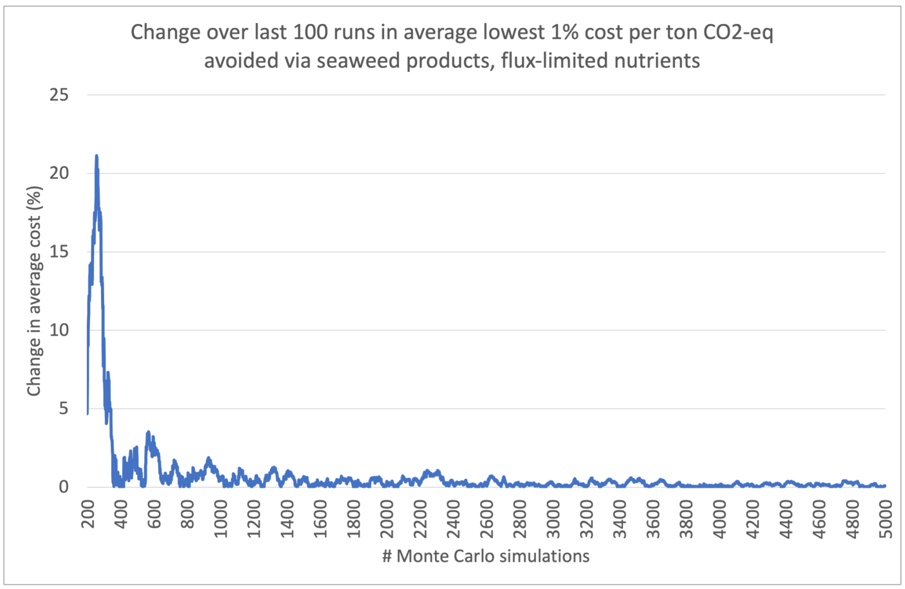
Supplementary Figure 13 | Maps of lowest cost areas in Supplementary Fig. 9 Maps show lowest-cost areas in the cheapest 1% of seaweed growth area for carbon sequestration (**a**) and GHG emissions avoided (**b**) in the 5th percentile of flux-limited nutrient simulations, with the color of shaded areas representing the net cost per ton of CO_2 or CO_2-eq.



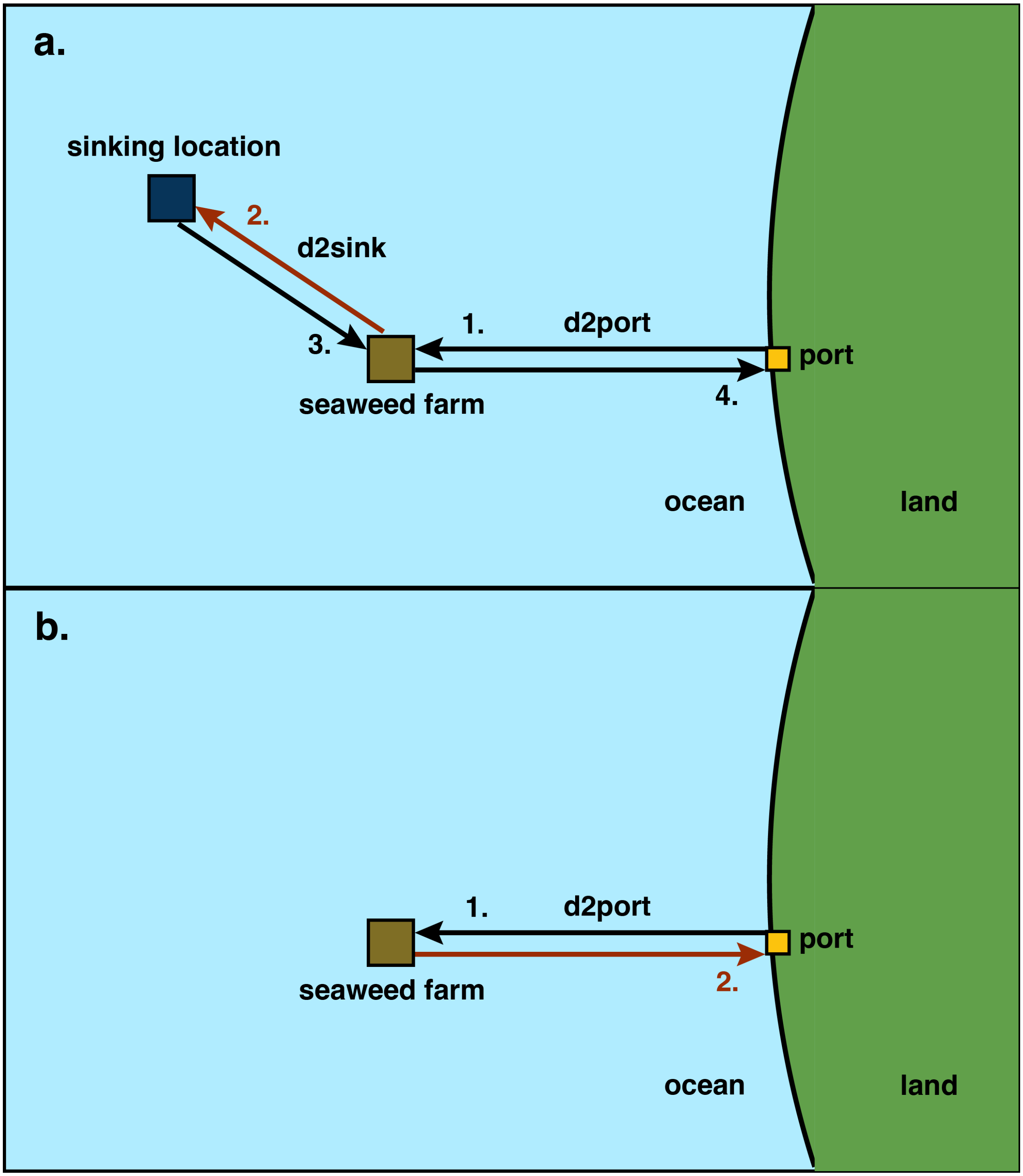


Supplementary Figure 14 | Change in ambient nutrient scenario average costs of CDR (top) and avoided emissions (bottom) with successive Monte Carlo simulations. Monte Carlo simulation number (n) is shown on the x-axis, and the % change in the cheapest 1% area average cost over the previous 100 runs is shown on the y-axis.

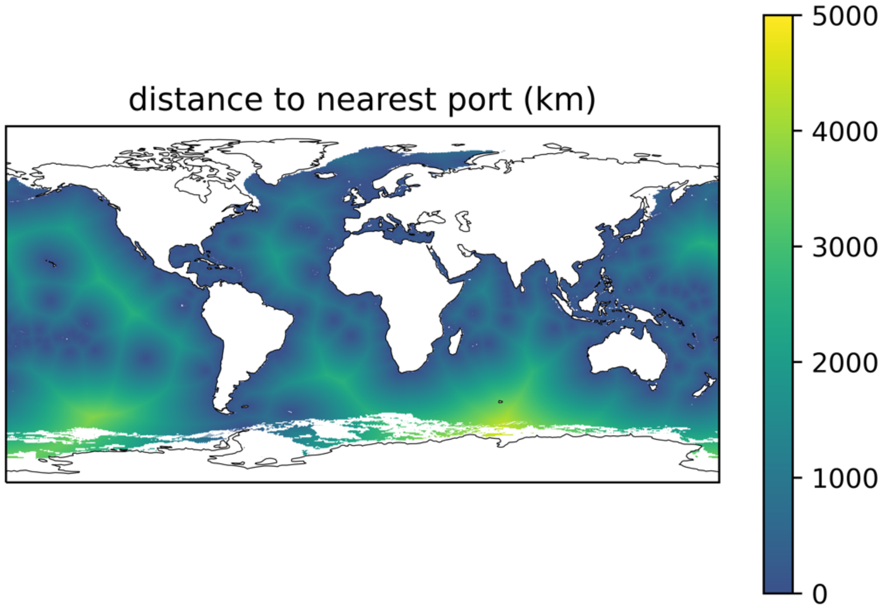




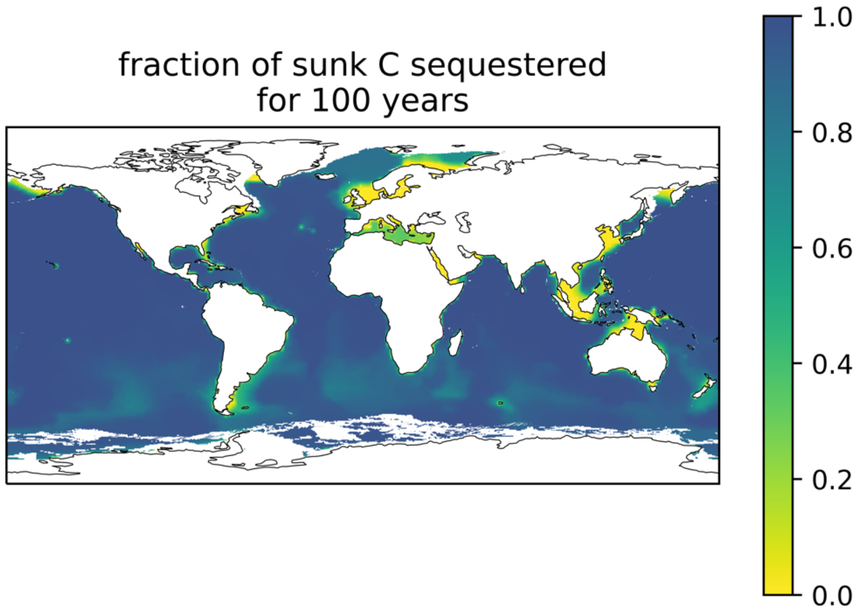
Supplementary Figure 15 | Change in flux-limited nutrient scenario average costs of CDR (top) and avoided emissions (bottom) with successive Monte Carlo simulations. Monte Carlo simulation number (n) is shown on the x-axis, and the % change in the cheapest 1% area average cost over the previous 100 runs is shown on the y-axis.



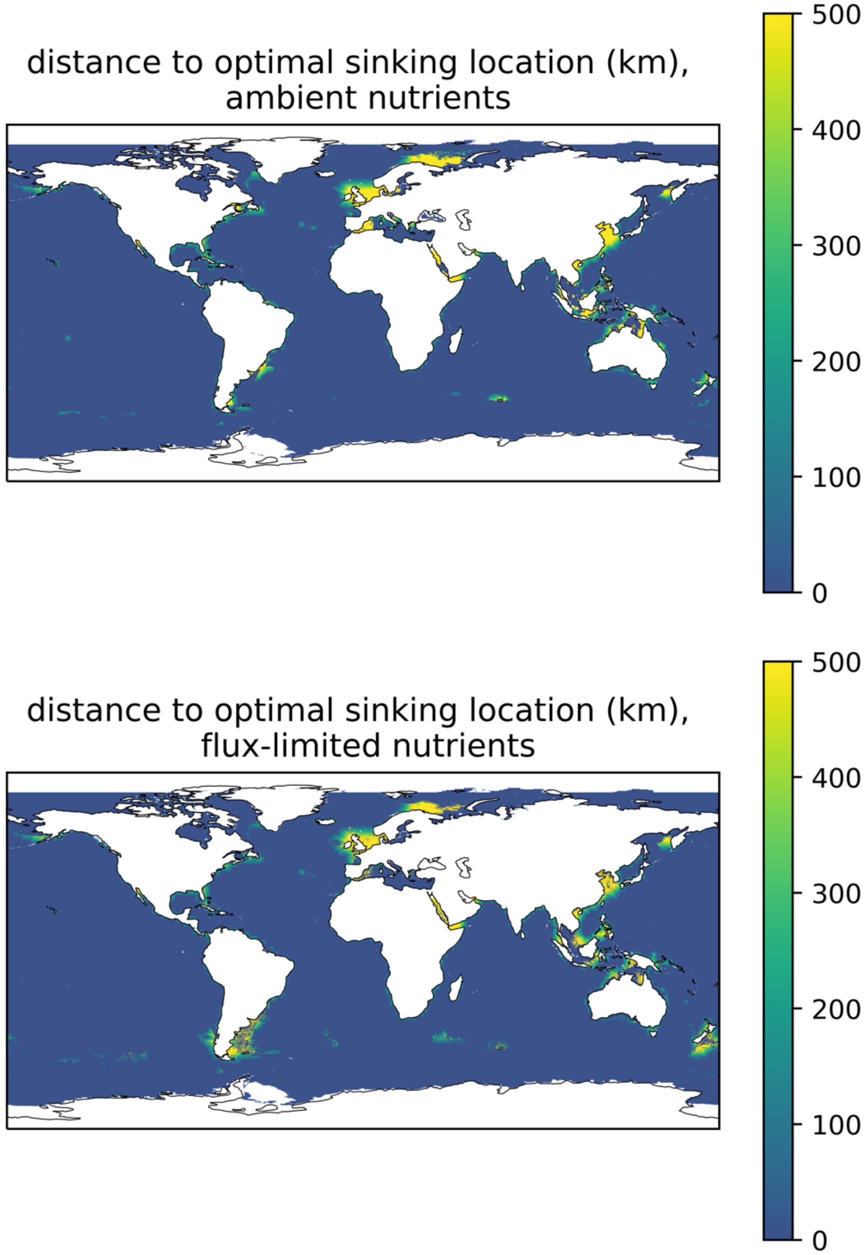
Supplementary Figure 16 | Schematic of model transport framework for carbon sequestration via sinking (a) and avoided GHG emissions via products (b). Arrows indicate direction of transport, numbers next to arrows indicate order of transport steps, and red arrows indicate that harvested seaweed is being transported during that step.



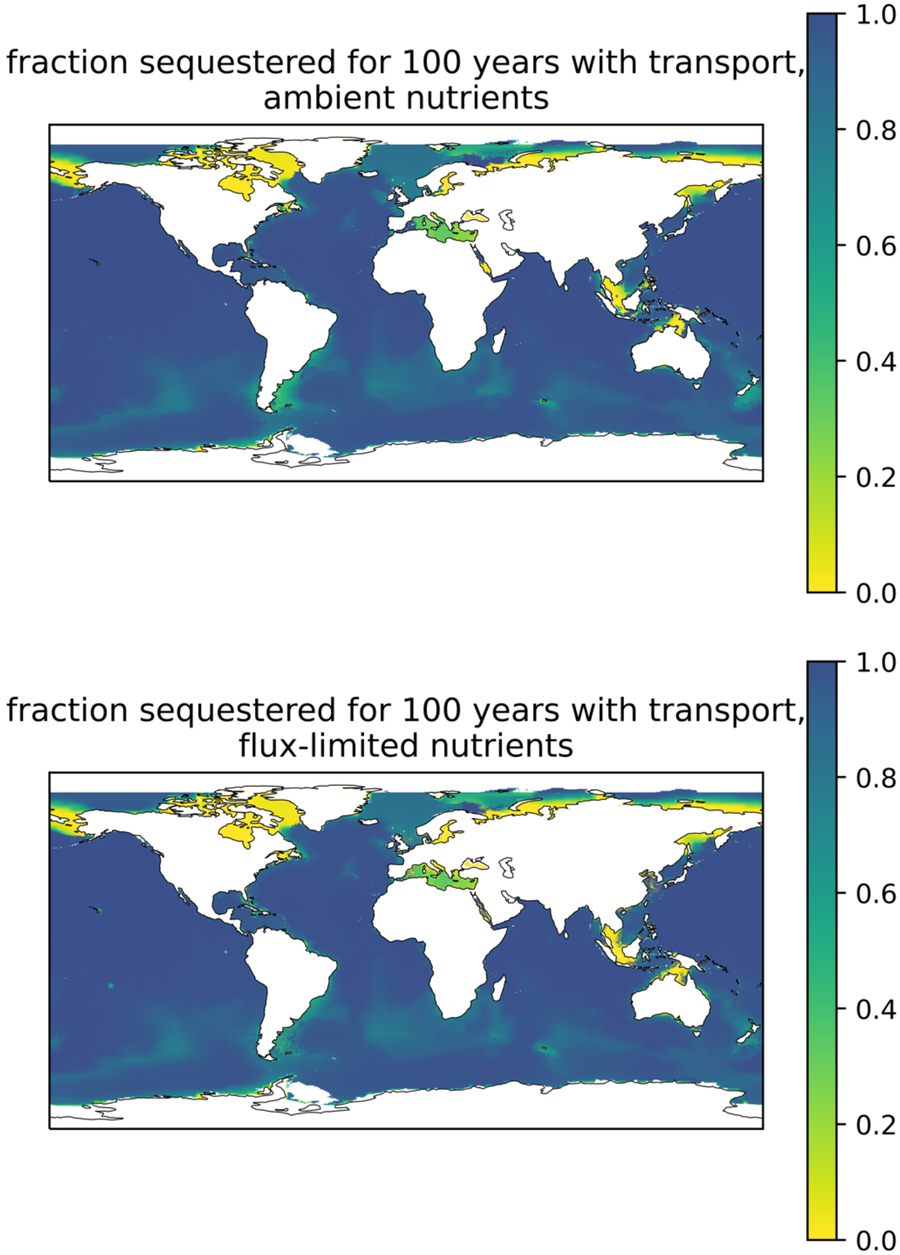
Supplementary Figure 17 | Distance to port. Map shows the distance to the nearest port (km) from every ocean grid cell, interpolated from the Global Fishing Watch Distance from Port V1 dataset.



Supplementary Figure 18 | Fraction of deposited carbon sequestered for 100 years. Data from Siegel et al. (2021)[16] was interpolated to 1/12-degree grid resolution.



Supplementary Figure 19 | Distance to economically-optimized sinking location. Maps show the shortest ocean distance from each seaweed growth pixel to the location at which the net CO_2 removed is maximized (incl. impacts of both increased sequestration fraction and transport emissions for different potential sinking locations) and the net cost is minimized for ambient (top) and flux-limited (bottom) scenarios. See *Methods* for detailed discussion of calculations.



Supplementary Figure 20 | Fraction of deposited carbon sequestered for 100 years with transport to optimal sinking location. After being transported to the optimal sinking location, the fraction sequestered for that location is applied to the grid cell where the seaweed was grown. The resulting adjusted fraction sequestered maps used in our economic calculations are shown for ambient (top) and flux-limited (bottom) nutrient scenarios.

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