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YSSP Report

Young Scientist Summer Program

The Global Benefits of Large-Scale Seaweed Farming

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This report represents the work completed by the author during the IIASA Young Scientists Summer Program (YSSP) with approval from the YSSP supervisor.

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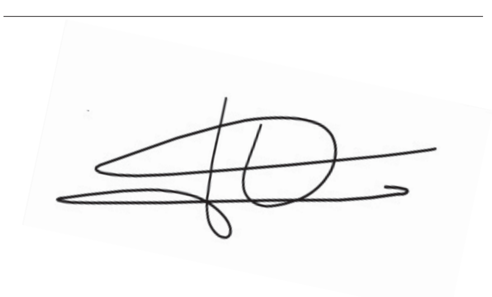

ABSTRACT

Agricultural expansion to meet humanity's growing needs for food and materials is a leading driver of land-use change and threatens to exacerbate ongoing crises of climate change and biodiversity loss. Seaweed biomass, farmed in the ocean as one facet of the rapidly growing 'Blue Economy', could help to mitigate these problems by providing a suitable, even advantageous, substitute for food, animal feed, and biofuels altogether, which could significantly displace demand for terrestrially-produced crops. In addition, recent research has demonstrated that the production of ruminant livestock can be drastically improved by supplementing their feed with the red seaweed *Asparagopsis spp*. Here we develop a range of scenarios to explore how increasing seaweed utilization may affect land-use change and carbon emissions, and estimate where corresponding sea-use change would occur. For each scenario, we i) use IIASA's GLOBIOM (Global Biosphere Management Model) to provide a detailed estimation of the terrestrial benefits, and ii) map the geographic potential of 35 commercially important seaweed species and use a spatial optimization algorithm to identify where and how much each could be grown to meet the scenario. Our results show that ca. 349 million hectares of global ocean could support seaweed farms and that cultivating *Asparagopsis spp* for ruminant feed could mitigate up to 2 Gt CO_2e and provides the highest marginal gains for land use. We also find that substituting human diets at a rate of 10% globally would spare up to 100 Mha of natural lands. These findings suggest that several global challenges could be simultaneously addressed by expanding the production of seaweed, however further work is needed to ensure that these farms will be environmentally, technically, and economically viable.

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1 Introduction

Demand for agricultural products is set to increase rapidly in the coming decades due to population growth and growing per capita consumption [1]. Agricultural production is already a leading driver of land-use change [2], and meeting this additional demand will require both an intensification and extensification of agricultural lands [3], which will have profound consequences for biodiversity loss [4, 5] and climate change [6]. These effects will likely degrade numerous social and environmental assets and threaten to upset progress towards many global initiatives, such as the global biodiversity agreements, Paris climate targets of 1.5° C and several of the United Nation's Sustainable Development Goals.

Given that almost three quarters of the Earth's surface is covered by ocean, many have argued that an expansion of the ocean-based economy, or the Blue Economy as it has come to be known, could provide a way to meet this rising demand, without causing further land-use change [7, 8]. In addition to easing land-use issues, producing certain goods at sea as part of the Blue Economy could actually prove advantageous over conventional terrestrial production. For example, marine foods are increasingly seen as being key to diversifying food systems, promoting small-scale producers, and combatting malnutrition worldwide [9] and offshore wind deployment enjoys numerous benefits over its terrestrial counterpart [10, 11].

Ocean-based seaweed farming, in particular, presents several unique opportunities and advantages over terrestrial agriculture. Similar to terrestrial crops like soy and maize, seaweed biomass is highly versatile and can be used as an input in numerous traditional and novel industries, including human food systems, livestock feeds, and biofuel production [12, 13, 14]. However, unlike terrestrial products like soy and maize which are used broadly in these same industries, seaweeds can be grown in the ocean without the need for intensive use of pesticides, fertilizers and irrigation. Seaweed farms also have the potential to provide a range of ecosystem services such as bioremediation in nutrient-laden coastal waters, habitat creation for marine flora and fauna, and sequestration of atmospheric carbon [15, 16, 17, 14, 18, 19]. This array of possible seaweed farming benefits has prompted several researchers to envision a world where large areas of the ocean are converted to seaweed production and to estimate the potential benefits that may accrue from such a strategy (Table 1). However, like many terrestrial ecosystems, marine ecosystems are also under threat from overexploitation, climate change, and habitat loss [20]. And while seaweed farming can provide local socio-ecological benefits in some contexts, in others, negative consequences and trade-offs may occur [21].

Whilst estimates of the global potential for seaweed farming are promising in terms of the sheer magnitude, a more integrated systems perspective is needed to assess the desirability and viability of attempting to farm seaweeds on such large scales and to get a sense of both the benefits and costs that may accrue. Here we approach these questions using a combination of species distribution modelling, scenario analysis, spatial prioritization and partial equilibrium modelling to i) estimate the probably biophysical extent of 35 commercially viable seaweed species, ii) define feasible seaweed substitution pathways for food, feed, and biofuel by 2050, iii) use the Global Biomass Optimization Model (GLOBIOM) [22], to provide an integrated assessment for each pathway of the impacts large-scale seaweed farming could have on a range of important land-use indicators, and iv) spatially prioritize where seaweed farming is most likely to develop on a regional scale for each of these pathways.

Table 1: Possible Benefits of Large-Scale Seaweed Farming

Ocean Area (million km^2)	Ocean Area (%)	Projected Benefit	Reference
0.216	0.06	2.2 Gt wet weight of human food	[14]
32.5	9	12 billion tons of biomethane p.a.	[23]
32.5	9	53 billion tons of CO_2 removal p.a.	[23]
1.0	0.3	10 billion tons biomass for various uses p.a.	[24]
7.3	3	5.1 billion tons of CO_2eq offsetting p.a.	[25]
0.5	0.03	50 million tons of protein p.a.	[26]
0.5	0.03	15 million tons algae oil p.a.	[26]
0.5	0.03	10 million tons nitrogen removal p.a.	[26]
0.5	0.03	1 million tons phosphorous removal p.a.	[26]
0.5	0.03	135 million tons carbon assimilation p.a.	[26]
0.5	0.03	1,250 million MWh bioenergy potential p.a.	[26]
0.5	0.03	1 million km^2 land sparing	[26]
0.5	0.03	500 km^3 freshwater sparing	[26]

2 Methods

We employ several numerical methods to achieve our objectives of assessing the potential environmental impacts of large-scale seaweed farming (Figure 1).

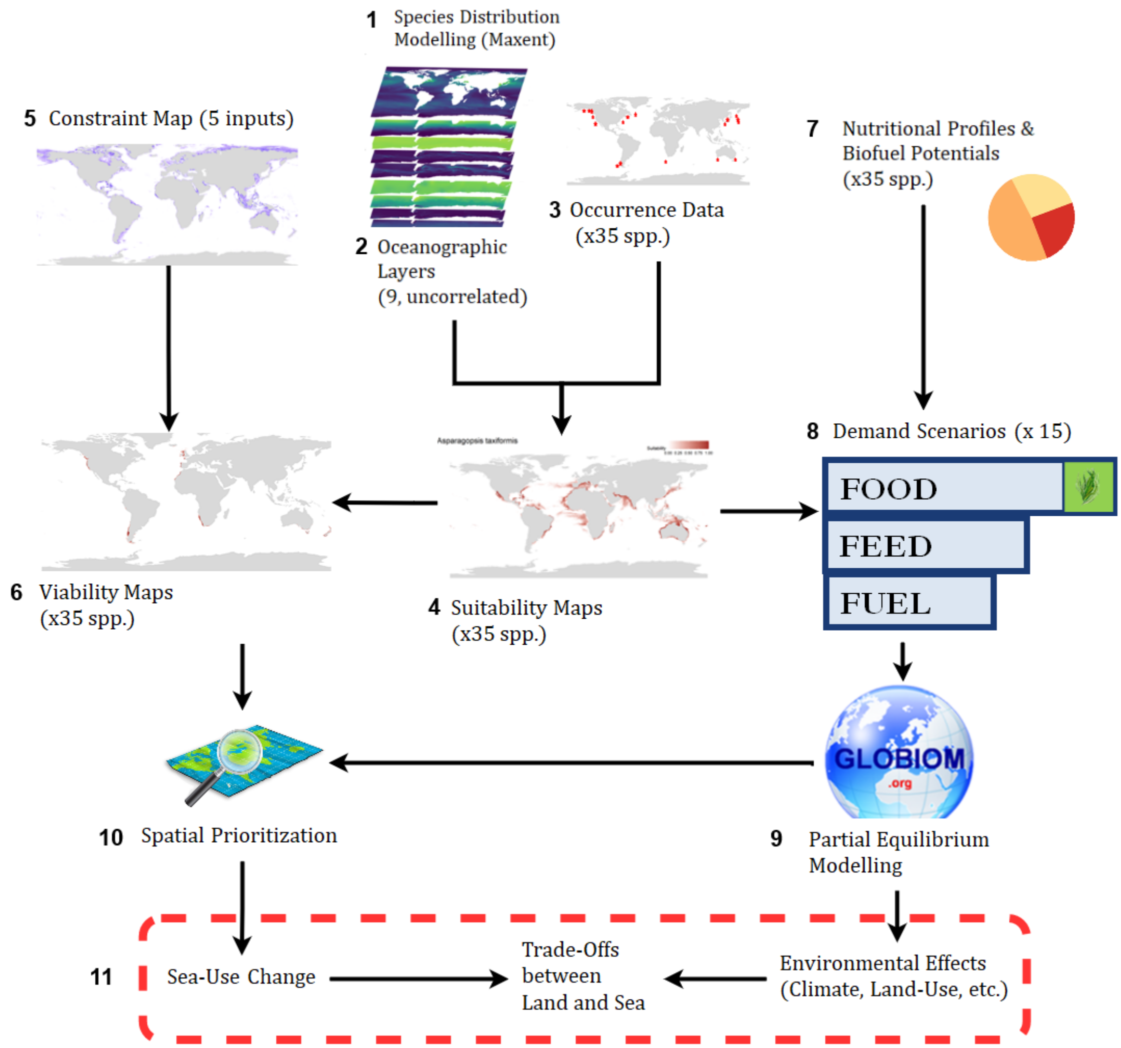

Figure 1: 1 Species distribution modelling using *R* package *maxnet*; **2** Nine spatial data layers of oceanographic variables (temperature, light, etc.) at 9km resolution from Bio-Oracle v. 2.0 [27] ; **3** Geo-referenced occurrence data from online collections (see text); **4** 35 Suitability maps showing where each seaweed species of interest could be cultivated; **5** Constraint map generated from the product of 5 layers of socio-economic constraints (e.g. depth, distance from port, shipping traffic, etc.); **6** 35 Viability maps generated from the product of each suitability map and the constraint map; **7** Data on nutritional profiles (protein, lipid, energy), bio-fuel conversion efficiencies, and production potential for each species of interest; **8** Demand scenarios were developed based on likely substitution proportions and the global suitability of seaweed species; **9** Each scenario was compared to a baseline scenario in GLOBIOM [22] to estimate the impact on land-use, emissions, water, and fertilizer use in 2050; **10** An iterative algorithm was used to quantify the extent of areas likely to be developed, and to assess each region's ability to meet the demand projected by GLOBIOM under each scenario; **11** The environmental benefits projected by GLOBIOM were divided by the predicted sea-use change to obtain an estimate of the relative trade-off of developing a given amount of area for seaweed farming.

2.1 The Potential Supply and Distribution of Seaweed Aquaculture

2.1.1 Species Distribution Modelling

For each of the 35 species of interest, we constructed Maxent species distribution models based on presence-only occurrence data, a suite of spatially-explicit oceanographic data layers, and the R package *maxnet.* Maxent was chosen because of its track record for outperforming other species distribution models [28, 29, 30]. It has also been used to model the potential distribution of agricultural crops [31, 32, 33], the presence of seaweeds in both both wild [34] and cultivated contexts [35]. We used spatial oceanographic data with a resolution of roughly 9km from Bio-Oracle v. 2.0 [27], using the *sdmpredictors* package. Following previous studies, we use a variety of oceanographic variables (sea-surface temperature, light availability, water quality, and water movement) to predict suitable areas where seaweed can be grown [35, 34]. Similar to Wiltshire and Tanner [35], we identify those layers which are highly correlated (> 0.7) and only use one from each set of correlate variables. This resulted in nine variables being included in the analysis (mean nitrate, maximum PAR, mean sea surface temperature, temperature range, pH, diffuse attenuation mean, current velocity mean, current velocity max, and mean salinity). We imported occurrence data for all seaweed species in the phyla Chlorophyta, Rhodophyta, and Ochrophyta from the following databases, Macroalgae Herbarium [36], Ocean Biodiversity Information System [37], Global Biodiversity Information Facility [38, 39, 40],and Atlas of Living Australia [41, 42, 43] We removed observations that were flagged as having 'rounded coordinates' or incorrectly recorded coordinates, and observations for which coordinates were not available. We kept any observations that were flagged as being a human observation, a machine observation, a material sample, a living specimen, or a preserved specimen. To avoid observations that could be denoting samples held in a collection, we removed any observations whose coordinates did not intersect a shape file of exclusive economic zones. Finally, we changed the names of several records for which taxonomic changes have occurred in recent years (*Neopyropia tenera, Neopyropia yezoensis, Saccharina japonica, Saccharina latissima*). After duplicates were removed we had a database of 116,341 records comprising 151 unique species.

During the first round of modelling, it was found that roughly 30% of the occurrence data was not overlapping with the oceanographic layers. Given that the occurrence dataset had already been scrubbed of occurrence data points on land, we assume that this mismatch is due to the resolution of the raster layers not covering data points that are located very close to complex coastlines. To better capture these datapoints, we interpolated the cells in boundary of the raster layers to have the mean values of all non-NA cells in a 3x3 cell moving window using the 'focal' function from the package *terra.* After performing this operation, the model fitting reported $< 5\%$ mismatches for each species.

The outputs of the *maxnet* are spatial raster maps where each cell value represents 'raw' output, which ranges from 0 to 1. We chose this output type because, unlike logistic or cumulative outputs from Maxent, raw-type output does not requirement additional post-processing assumptions [44]. Because we constructed these models using presence only data, we define the threshold above which presence is likely by identifying the point at which the sum of the sensitivity and specificity is maximized [45].

After identifying threshold values and removing those cells that fell below the threshold for each species, we convert the remaining cells to 1 to create 35 masks where each species could be farmed. To estimate the overall extent of possible seaweed farming, we overlayed these masks to create an overall Unconstrained layer that shows everywhere at least one species could be cultivated.

2.1.2 Constraint Layers

Beyond the environmental suitability that we defined in the species distribution modelling above, we identified six additional socio-economic and environmental factors that are likely to limit the suitability of sites in the ocean for large-scale seaweed aquaculture development (Depth, Distance to the Nearest Port, Shipping, Wave Energy, MPAs, Native Seaweed Distribution). For each of these constraints, we obtained spatially explicit data layers, which we resampled to match the resolution of the oceanographic data layers. Each one was processed according to Table 2 and then normalized to create layers with cell values from 0 - 1 where 0 represents the most constrained and 1 represents the least constrained. These layers were then multiplied together to create an overall global map of constraints (Figure S8). For the purposes of spatial prioritization, we masked this overall constraint map by each of the 35 species-specific suitability maps to create 35 viability maps, where for each 9 km^2 cell, each of the 35 species has a viability index from 0 to 1. We also iteratively masked the overall Unconstrained layer by each constraint layer to estimate the impact that each constraint may have on the overall potential distribution of seaweed farms.

2.1.3 Nutrition and Biofuel Potential of Seaweeds

We performed a literature search to collate information on the productivity, water content, nutritional composition, energy content, and fuel conversion efficiency of various seaweed species. We collected data for taxa with greater than 10 occurrences in our occurrence database and were able to find information on either food, feed, or fuel utility for 35 seaweed species.

Table 2: Constraint Layers and Assumptions

Constraint	Description	Assumptions/Processing	Source
Depth	Measured in meters,	Normalize layer such that depths greater than 200m are non-viable (0), and depths from 0-200 decrease linearly to 200.	[27]
Distance to Port	Measured in km according to list of ports catalogued by Global Fishing Watch	Normalize layer such that smallest distance is 1 and largest distance is 0.	[49]
Shipping	Derived from AIS data	Linearized via double logarithm of difference between cell value and moving window average around each cell; a threshhold of 2.89 was chosen after visual inspection to remove the heaviest trafficked areas	[50]
Wave Energy	Combined mean wind and wave energy.	Normalize layer such that least energy is 1 and most energy is 0.	[51]
Marine Protected Areas	Presence of MPAs	Areas with IUCN designations of a V or VI are assumed to be non-viable	[52]
No Non-Natives	Remove non-native potential	Cells were removed if a species is predicted in a region but there is no recorded occurrence	See Section 2.1.1
50% Coverage	Scalar multiplier	Assume seaweed farms will only take up 50% of viable space	See Figure S1

We assume that each of these species may not be useful for all uses under consideration. Therefore, we use the following criteria to categorize each species into one or several 'uses'. For the human food scenarios, we only consider those taxa that are designated as 'food' by White and Wilson [46]. For animal feed scenarios, we assume that any species can be utilised, however we limit our analyses to those species for which peer-reviewed data on their nutritional profiles exists. We calculate the total energy density per kg of dry matter according to the equation $Energy(kcal) = 4(g_{protein} + g_{carbohydrates}) + 9(g_{fat})$ [47], and assume that of this, 80% is metabolizable energy [48] (See Table 3 for the full dataset of nutritional profiles used in this analysis). Because the factors controlling the productivity of seaweed farms are not well understood, productivity can vary considerably between and within species, and productivity is likely to increase as the technology improves, we assume a constant amount of production per unit area of 20 tonnes of dry weight per year.

To ensure that seaweeds could feasibly be substituted for the full range of terrestrial commodities, we performed a k-means cluster analysis based on the expected energy, protein, and lipid density, by dry weight, of seaweeds and terrestrial crops (Figure 2). The level at which seaweeds could feasibly substitute in livestock diets will be likely be different for each species of livestock and seaweed. For example, Costa et al. [53] report on a range of livestock

Table 3: Nutritional Profiles of Commercially Viable Seaweed Species.

Taxa	Protein min (%)	Protein max (%)	Carb. min (%)	Carb. max (%)	Lipid min (%)	Lipid max (%)	Energy min (kcal/kg)	Energy max (kcal/kg)	Source
Alaria esculenta	9	20	46	51	1	2	2290	3020	[13, 48, 55, 56, 57, 58]
Ascophyllum nodosum	3	15	59.1	59.1	3.5	8.6	2794.5	3738	[48, 13, 59]
Asparagopsis armata	21.5	27.7	37.9	44.1	1.3	4.7	2493	3295	[60]
Asparagopsis taxiformis	17.4	17.7	39.1	41.9	6.1	7.2	2808	3027.6	[61, 62]
Caulerpa lentillifera	10	13	38	59	0.9	1.1	1997.4	2979.9	[56, 58]
Caulerpa racemosa	17.8	18.4	33	41	9.8	9.8	2914	3258	[56, 58]
Chondracanthus chamissoi	10.6	17.8	39.3	76.9	0.4	2.4	2032	4004	[60]
Chondrus crispus	6.6	21	55	68	1	3	2555.6	3830	[48, 56, 61, 58]
Codium fragile	8	11	39	67.2	0.5	1.5	1925	3263	[56, 60, 58]
Costaria costata	17.3	19.1	5.7	5.7	2.2	2.2	1118	1190	[60]
Durvillaea antarctica	7	12.5	47.2	72.6	0.7	4.9	2231	3845	[63, 60]
Eisenia arborea	7.4	11.4	50.8	58.4	0.5	0.7	2373	2855	[60]
Eucheuma denticulatum	4.6	5.2	27.3	28.7	2	2.4	1456	1572	[62]
Fucus vesiculosus	3	17	46.8	46.8	1.9	4	2163	2907.5	[48, 13, 56, 58]
Gelidium amansii	18.5	18.5	75.2	75.2	0.6	0.6	3802	3802	[64]
Gracilaria chilensis	13.5	21.2	50.8	67.3	1.3	2.8	2689	3792	[60, 58]
Gracilaria verrucosa	9.5	27	63	76	0.8	2.5	2975.6	4345	[65, 66]
Kappaphycus alvarezii	4.6	5.2	27.3	28.7	2	2.4	1456	1572	*Inferred from E. denticulatum
Laminaria digitata	5.8	15	48	48	1	1	2242	2610	[56, 13, 57, 58]
Laminaria hyperborea	4.7	8.1	52	61	0.9	1.7	2347.2	2915.2	[57, 67]
Macrocystis pyrifera	8	15.7	15.8	75.5	0.3	0.8	979	3720	[60, 13]
Neopyropia yezoensis	31	44	44.4	44.4	2.1	2.1	3205	3725	[56, 58]
Palmaria palmata	8	35	46	56	0.7	3	2223	3910	[13, 48, 56]
Porphyra umbilicalis	29	39	43	43	0.3	0.3	2907	3307	[56]
Saccharina japonica	7	8	51.9	51.9	1	1.9	2446	2567	[56, 58]
Saccharina latissima	5	26	52	61	0.5	1.1	2325	3579	[48, 55, 56, 57, 13, 58]
Ulva lactuca	7.1	28.3	36	65.5	0.3	3.7	1752.2	4085	[56, 59, 61, 60, 13, 58]
Ulva pertusa	20	26	47	47	0.9	2	2761	3100	[56, 58]
Ulva reticulata	17	20	50	58	1.7	2.3	2833	3327	[56]
Undaria pinnatifida	12	23	45	52.8	1	3.4	2374.5	3338	[56, 60, 58]

types and find that for pigs and ruminants inclusion rates of less than 10% can be achieved without adverse penalties on livestock growth or feed conversion parameters; for poultry, penalty-free inclusion rates can be even higher (< 20%). Nevertheless, while these limits will likely impede uptake beyond a certain level of feeding livestock whole seaweeds, the substitution potential for livestock feed could be well above these figures if key compounds and amino acids are extracted from seaweeds and used in livestock feed formulas [54]. Similarly, for fuel scenarios, we limit our species' suitability to those for which peer-reviewed data on fuel conversion pathways and conversion efficiencies for fuels of interest exists in the peer-reviewed literature (Table S4). The possible uses for each seaweed species are summarised in Table S1.

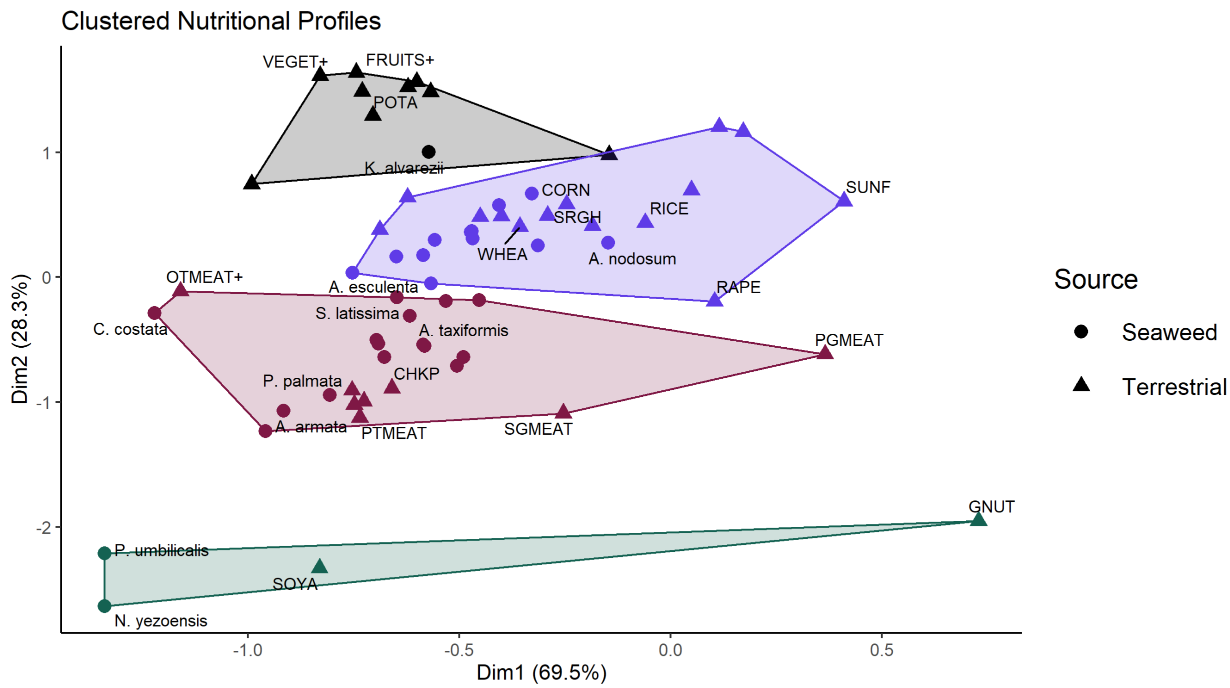

Figure 2: A principle components analysis was used to cluster terrestrial commodities and seaweed species by energy (kcal/kg), protein (g/kg) and lipid density (g/kg). The diversity of seaweeds means that they are well distributed amongst the major terrestrial commodities and could therefore substitute for these terrestrial products on a nutritional basis. For terrestrial product definitions see Table S5

2.2 Future Demand

2.2.1 The Substitution Potential of Seaweeds

To gain a sense of the magnitude of potential substitution of seaweeds for food, feed, and fuel products, we searched the peer reviewed literature for studies that explored the current and potential rates of seaweed consumption. As food, seaweeds are generally found to have nutritional profiles and assemblages of bioactive compounds that make seaweeds a desirable component in human diets [68, 69, 58, 70, 71]. However, up to now, seaweed consumption as food has been generally limited to East Asia, with Korea, China, and Japan having the highest consumption rates in the world [72]. For example, today it is estimated that seaweeds make up roughly 2% of the diets of Korean men [73]. Whilst consumption has been constrained historically, the numerous benefits associated with seaweed has led to suggestions that in the future it would not be unreasonable to expect that seaweeds could constitute up to 5% of our diets globally [14]. Whilst consumption of unprocessed seaweeds may be limited to a certain extent by high iodine content and the propensity to accumulate heavy metals [74, 75, 76], novel techniques associated with producing plant-based and cell-based meats may allow the incorporation of much higher proportions of seaweed-derived calories [77].

Reviews examining the prospect of incorporating seaweeds into the diets of livestock reflect similar findings. Across many common livestock species and at low substitution rates, seaweeds have been shown to be a favourable source of metabolizable energy and protein [13, 53]. As with human food, due to high mineral content, and for some seaweed species, low protein content, there may be limits to inclusion in the diets of commercially produced livestock, with some negative effects on growth being reported at high substitution rates [54, 78]. Although studies on high substitution rates are scarce, there is evidence of a population of sheep living on the Orkney islands that derive almost all of their nutrition from seaweeds [79], which suggests that high substitution rates may be possible without adverse consequences.

In addition to being a promising source of energy and protein, the bioactive compounds contained in some seaweeds may prove beneficial. Of particular interest that we will explore here, is the recent discovery that seaweeds in the genus *Asparagopsis*, when included as a supplement ($< 1\%$) in ruminant feeds can cause staggering reductions in the methane production [80, 81, 82]. At the same time, this supplementation also appears to increase the feed conversion efficiency of livestock by a substantial amount, such that improvements of at least 14% are possible. To date comparable effects have been demonstrated in beef cattle [83], dairy cows [84], and sheep [81], and is expected to exist for all ruminants [82].

The potential to turn seaweed biomass into fuel products has also been extensively researched and reviewed [85, 86, 87]. Similar to terrestrial crops, seaweeds can be used as feedstocks for several production pathways, including in the production of bio-ethanol, bio-diesel, and bio-gas, with each species and processing technique leading to a different overall conversion efficiency [85]. Whilst numerous fuel types are possible, the production of transport fuels from algae has been identified as an important opportunity due to the rapidly rising demand for these fuels and the severe limitations of meeting this demand using first- and second-generation biofuel feedstocks [88].

2.2.2 Demand Scenarios

Using this information, we developed a range of scenarios whereby seaweed biomass substitutes for human diets, livestock diets, and/or 1^{st} generation biofuel feedstocks. These scenarios account for substitution pathways extending from 2020 to 2050 and assume that any increase in seaweed production for the purpose of one product (e.g. food) perfectly displaces the production of an equivalent amount, quantified by embodied energy density (kcal or MJ) of terrestrial production. We do not specify which terrestrial crops would be displaced, instead assuming that the diversity of seaweed biomass (as shown in Figure 2) allows for it to substitute for any crop. We chose 2050 as our end date because it is sufficiently distant that we would expect the large-scale development of seaweed farms to be feasible, and because it is sufficiently near-term that the environmental impacts of our scenarios would be meaningful given the urgency of climate change and land-use change. We initially estimated global supply by overlaying our 35 suitability maps and assuming that seaweed can be produced at a rate of 20 tonnes of dry matter per hectare per year. We chose to use the maximum biophysical potential to obtain this estimate because it relies on fewer assumptions of constraints and provides a better sense of the upper limit of potential. This yielded a rough estimate that unconstrained global seaweed production potential is on the order of 46 billion tonnes per year, which is well in excess of any feasible substitution scenarios.

For each scenario we set a target proportion of substitution (e.g. 10%) and assume that adoption takes place steadily from 2020 until 2050 4. For each of these three seaweed uses, we explore two target levels, large and small, to get a sense of how the magnitude of substitution may affect the system. Because of the uncertainty about the effect on high substitution rates on the feed conversion efficiency of livestock, we tested two additional Feed-10 scenarios where we apply a feed conversion penalty of 1% and 5%. In addition, we also developed scenarios to explore how introduction of the anti-methanogenic red seaweed, *Asparagopsis*, into ruminant diets would compare to these other scenarios. We use the findings from Roque et al. [83] to assume a supplementation rate of 0.05% for only ruminants (0.5R), a feed conversion benefit of 14% (FCE), and a methane reduction effect of 68% (CH4). For the purpose of these analyses, we model the two main benefits of *Asparagopsis* supplementation both separately (Aspa-0.5R-FCE; Aspa-0.5R-CH4) and together (Aspa-0.5R). Finally, we also explore how different combinations of these basic scenarios perform (designated as 'All') to get a sense of the extreme potential of seaweed substitution.

Table 4: Demand Scenarios

Scenario Type	Scenario Name	By 2050, seaweed replaces:	Other Effects
Food	Food-01	1% of global diets	none
	Food-10	10% of global diets	none
Feed	Feed-01	1% of All Livestock Diets	none
	Feed-10	10% of All Livestock Diets	none
	Feed-10-01	10% of All Livestock Diets	FCE penalty: 0.01
	Feed-10-05	10% of All Livestock Diets	FCE penalty: 0.05
Feed - *Asparagopsis*	Aspa-0.5R-CH4	0.5% of Ruminant diets	Methane reduction: 0.68
	Aspa-0.5R-FCE	0.5% of Ruminant diets	FCE increase: 0.14
	Aspa-0.5R	0.5% of Ruminant diets	Methane reduction: 0.68 FCE increase: 0.14
Fuel	Fuel-10	10% of transport fuels	none
	Fuel-50	50% of transport fuels	none
All	All-Low	Food-01 + Feed-01 + Fuel-10	none
	All-High	Food-10 + Feed-10 + Fuel-50	none
All - *Asparagopsis*	All-Low-Aspa	Food-01 + Feed-01 + Fuel-10	Methane reduction: 0.68 FCE increase: 0.14
	All-High-Aspa	Food-10 + Feed-10 + Fuel-50	Methane reduction: 0.68 FCE increase: 0.14

2.2.3 Partial Equilibrium Modelling in GLOBIOM

We use the Global Biomass Optimization Model (GLOBIOM) [22] to investigate the extent to which a global increase in seaweed consumption within each sector might impact land-use change and carbon emissions. At its core, GLOBIOM takes demand data, based on projections of population growth and consumption, and uses land and commodity data to predict the optimal distribution of agricultural production based on maximizing economic surplus (for more detail see www.globiom.org). It can then predict a range of environmental and socio-economic indicators based on this production, including land-use change, greenhouse gas emissions, water-use and fertilizer use. It also accounts for trade across 37 aggregated economic regions by tracking the regional production costs for goods and assuming that trade will take place between regions where cost-imbalances occur. Because the practice of seaweed farming is still in its infancy everywhere except for a handful of countries, data on price and production potential was deemed not reliable enough to build seaweed species directly into GLOBIOM's algorithm. Instead, for each scenario, seaweed production was simulated by subtracting a fixed amount of demand for each commodity. Because seaweeds are highly variable in their nutritional profiles and energy content, we assume that for each scenario, an increase in seaweed consumption will decrease demand uniformly for all terrestrial commodities.

This is implemented slightly differently for each class of scenarios, due to variation in the mechanics of how demand is formulated within GLOBIOM. For Food scenarios, we reduce the global demand for caloric energy, for Feed scenarios we decrease the per unit input of feed crops for livestock, and for Fuel scenarios we decrease the total demand for first-generation biofuels. We simulate three decadal time-steps, from 2020 to 2050, and treat 2050 as the target year whereby the scenario target will have been achieved. For example, under the Feed-01 scenario, there is 0 demand reduction in 2020, 1% demand reduction in 2050, and a linear slope in demand reduction between these two endpoints. For the Feed/Aspa scenarios, we assume a linear increase in coverage from 0% in 2020, to 100% in 2050, with the proportion of animals receiving supplementation seeing a decrease in enteric fermentation emissions and increase in feed conversion efficiency according to the scenario parameters described in Table 4. We quantify the global benefits of seaweed farming on land-use change, carbon emissions, agricultural water use and fertilizer use by comparing the outputs of each scenario against a baseline scenario in which no seaweed is substituted in any sector. For the purposes of this analysis, the baseline scenario assumes the same GDP and population growth as the "Middle of the Road" Shared Socio-economic Pathway (SSP2) [89, 90]. For the Food and Fuel scenarios, we implicitly assume that the price of seaweed biomass is equal to the biomass being displaced, for the Feed scenarios, this assumption is explicitly incorporated into GLOBIOM's calculations.

2.2.4 Spatial Prioritization

We implemented a spatial prioritization algorithm to identify the possible extent and distribution of seaweed cultivation for each region, and to assess how likely it would be for each region to produce enough seaweed to meet the substitution assumptions in each demand scenario. This prioritization rests upon the assumption that seaweed farming will be most likely to develop in areas where at least one species has a high viability index and a high production potential. Because the outputs of our species distribution models are difficult to compare across species [91], we refrain from assuming that our viability index is relevant for calculating production potential. Instead, we assume that production potential, P, for a given 9 km^2 cell can be expressed as $P = A_c * p_c * W_d * k_d(s)$, where A_c is the area of the cell in hectares, p_c is the proportion of that cell used for seaweed farming, W_d is the dry weight production per year per hectare of seaweed biomass in kilograms, and $k_d(S)$ is the energy density (depending on the scenario, either metabolizable or fuel conversion potential) of a kilogram of biomass of the seaweed species, S (For specific values of $k_d(S)$ see Tables 3 and S4. For the purpose of this analysis, we conservatively estimate p_c to be 0.5, although in reality current large-scale farms in Korea and China likely exceed this figure (See Figure S1.

For each scenario, substitution demand was calculated by recording the amount of reduction in demand for all relevant crop types in GLOBIOM for 2050 due to the substitution scenario. This quantity was converted to gross energy content based on the specific energy content of each crop type and aggregated to obtain an overall substitution demand. The algorithm then attempts to match this demand by iteratively selecting cells from the highest viability index to the lowest, in step sizes of 0.01. If a cell contains two species with an equivalent viability index, the species with the highest production potential is chosen. After each iteration, the total production generated by all of the selected cells is calculated and compared to the demand. If supply does not exceed demand after the 50^{th} iteration (viability index of 0.5), the algorithm ends and demand is not met. This assumes that seaweed farms will not be developed in places where, on average, constraints are higher than other locations. We further limit the types of species that can be selected by the algorithm by removing seaweeds that were not categorised as being a potential feedstock for each scenario (e.g. Food, Feed, Fuel). And, because the outputs of the species distribution models extend beyond the likely native ranges of a given species, we remove species if there are no documented occurrences of that species within the region.

This prioritization was run globally and for each of the 37 GLOBIOM regions (See Table S6) to identify where seaweed farming is likely to occur and the amount of ocean area required to meet the substitution requirements for each scenario. The relative global benefit of each scenario was calculated by dividing the overall benefits by the amount of ocean area that would be required to produce seaweed to meet the substitution requirements of that scenario.

3 Results

3.1 Cultivation Potential

We estimate that globally seaweed farms have the potential to extend over 349 Mha of the world's oceans, which represents just under 1% of the world's oceans. 3 (See Supplementary Material for suitability maps for each species). As can be seen in Figure 3, whilst the biophysical potential for cultivating seaweeds is considerably larger, the extent of viable space is highly limited by the additional constraints that we have included in our analysis. Nevertheless, if we assume an average level of production of 20 tonnes of dry matter per hectare, this amount of space could produce roughly 7 billion tonnes of biomass for food, feed, and/or fuel. Unsurprisingly, most of this potential is found close along the coasts where depths are low, ports are nearby, and wave energy is likely to be less. However, there are regions where seaweed farming potential is quite large even away from coastlines. For example, in Indonesia, where seaweed farming is already practiced on a large-scale in shallow, coastal areas, there is considerable potential between the major islands (Figure 3). Other regions with a large amount of potential include current major producers like Korea and China, and regions with very little current seaweed farming like Australia, Western/Northern Europe and the USA.

The results of our spatial prioritization reveal that, globally, the substitution demand from all of our basic scenarios could be easily met by this level of potential. However, some regions will not be able to be self-sufficient and would have to rely on a certain amount of international trade (Figure 4B). In some cases this is simply due to a lack of marine space (e.g. Congo, Ukraine), in some it is due to high amounts of future demand (e.g. India, China), and in others the assemblage of present seaweed species is not rich enough (e.g. many of the regions under the Aspa scenario).

3.2 Global Benefits of Large-Scale Seaweed Production

3.2.1 Land, Water, and Fertilizer Savings

All of the basic scenarios lead to reductions in global cropland compared to the baseline, although the magnitude of this effect differs considerably between scenario types and intensity. For example, replacing 10% of human food with seaweed or seaweed-derived products (Food-10) could spare more than 99 million hectares of natural land and forest (Figure 5A). Interestingly, this is more than ten times the benefit of the ca. 9 million hectares seen in the more conservative 1% scenario. The next best performing scenario is Aspa-0.5R, which

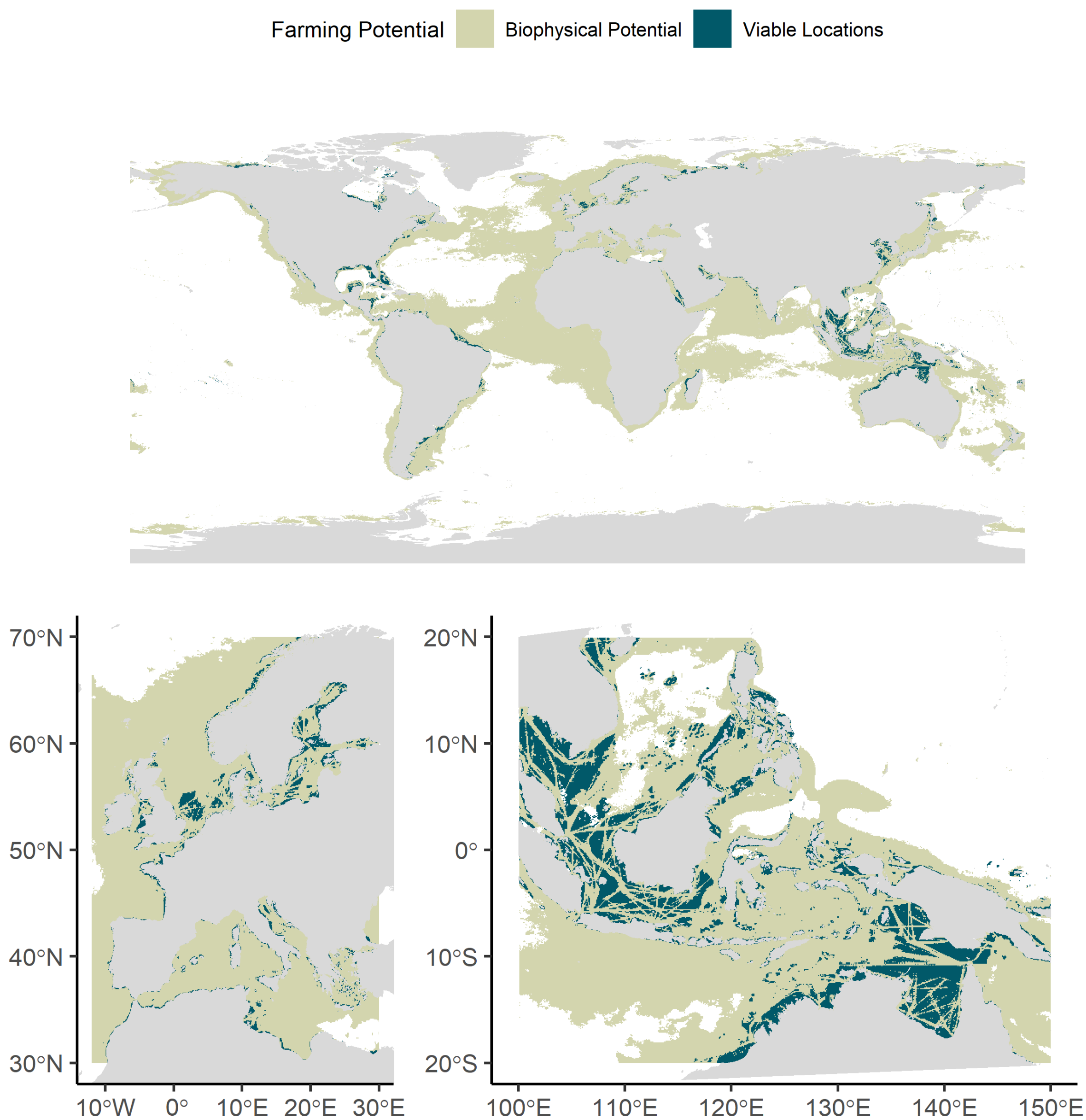

Figure 3: The global potential for seaweed farming, shown here in yellow, represents an overlay of all suitable cells for seaweed farming, based on species distribution models from 35 commercially important species and constrained by depth, distance to the nearest port, shipping traffic, mean wave energy, the presence of marine protected areas, and limiting potential to areas where each species is likely to natively occur. The overall biophysical potential (in green), shows the broad extent of areas where seaweed farming is biophysically possible.

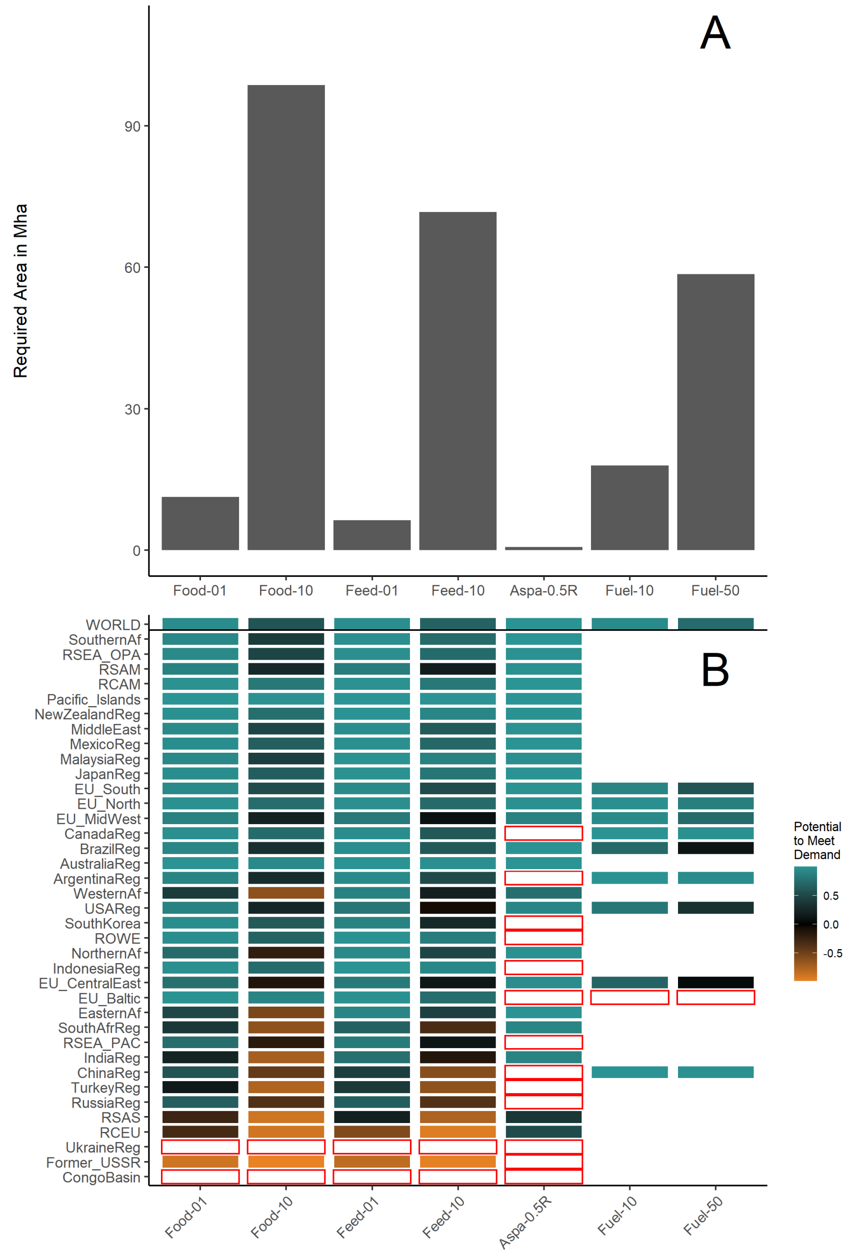

Figure 4: A. The global amount of ocean area required to meet each scenario. B. The potential for the world and each GLOBIOM region (See Table S6 for definitions) to meet the substitution demand of each scenario. Potential is calculated according to the expression $\frac{S_{R,max} - D_{R,S}}{S_{R,max} + D_{R,S}}$, where $S_{R,max}$ is the maximum potential supply for the region, R, and $D_{R,S}$ is the local demand in that region for the scenario, S. Positive values indicate that demand can be met for that scenario, with higher magnitudes indicating ample supply left over. Negative values indicate that demand cannot be met, with higher magnitudes indicating the size of the deficit. Missing tiles with a black border indicate that no supply was possible due to the absence of suitable seaweed species, while missing tiles with no border indicate that there is no demand in that region for biofuels.

Table 5: The possible savings from producing seaweed at a large-scale to global emissions, fertilizer use, land sparing, and agricultural water use. The left section shows the total benefits from each scenario, the middle columns shows the amount of global ocean that would be required to meet the substitution demand from each scenario, and the right section shows the benefits relative to the amount of sea-use change required in Mha.

Scenario	**Natural Lands**	**Annual Emissions**	**Water**	**Fertilizer - N**	**Fertilizer - P**	**Ocean Area Required**	**Natural Lands**	**Emissions**	**Water**	**Fertilizer - N**	**Fertilizer - P**
	(Mha)	($MtCO_2e$)	(km^3)	(1000t)	(1000t)	(Mha)	(Mha/ Mha)	($MtCO_2e$/ Mha)	(km^3/ Mha)	(1000t / Mha)	(1000t / Mha)
Food-01	9.0695	69.6	4.2	1931	192.1	11.33	0.80	6.14	0.37	170.40	16.95
Food-10	99.5252	635.4	59.5	19952.9	3097.8	98.63	1.01	6.44	0.60	202.30	31.41
Aspa-0.5R-CH4	0.1438	2121.9	0.2	114.9	9.9	0.70	0.21	3031.13	0.29	164.13	14.14
Aspa-0.5R-FCE	41.7996	327.9	2.9	1349.8	237.4	0.70	59.71	468.40	4.14	1928.18	339.12
Aspa-0.5R	41.7998	2356.1	2.9	1349.8	237.4	0.70	59.71	3365.68	4.14	1928.18	339.12
Feed-01	1.5416	2.6	1.8	1061.3	97.9	6.36	0.24	0.41	0.28	166.98	15.40
Feed-10	18.6352	77.8	10.3	9603.8	1454.4	71.73	0.26	1.08	0.14	133.90	20.28
Feed-10-01	13.8391	44.5	9.3	8804.4	1334	71.73	0.19	0.62	0.13	122.75	18.60
Feed-10-05	-3.5895	-115.5	7.6	6046.2	897.4	71.73	-0.05	-1.61	0.11	84.30	12.51
Fuel-10	1.1404	7.2	1.1	921.1	80	17.97	0.06	0.40	0.06	51.26	4.45
Fuel-50	5.269	20.2	8.1	4133.7	603.1	58.54	0.09	0.35	0.14	70.62	10.30
All-Low	11.5222	74.4	6	3465.7	378.3	35.66	0.32	2.09	0.17	97.20	10.61
All-High	137.7971	709.1	75.1	34237.8	5208.1	228.89	0.60	3.10	0.33	149.58	22.75
All-Low-AspaR	54.657	2409.5	7.7	4626.4	649.9	35.66	1.53	67.58	0.22	129.75	18.23
All-High-AspaR	196.4579	3051.1	77.2	35977.4	5446.3	228.89	0.86	13.33	0.34	157.18	23.79

* Note: Aspa-0.5R-CH4 and Aspa-0.5R-FCE explore the disaggregated effects of *Asparagopsis* supplementation and do not reflect real-world scenarios.

would spare an estimated 42 million hectares. Substituting 10% of livestock feed would also a have considerable land savings of 18 million hectares, and substituting 50% of first generation biofuel stocks would spare 5 million hectares. Whilst most scenarios yield reductions in both grassland and cropland, the high feed- and high fuel-use scenarios both see increases in grassland of 8 million and 1.5 million hectares, respectively, compared to the baseline. If we assume that feed substitutions of up to 10% have feed conversion penalties, we see the benefits of seaweed substitution diminish and eventually give way to costs for forests and natural lands if there is a 5% feed conversion penalty (Table 5). Interestingly, the marginal benefits of substitution appear to increase as the scale of substitution increases, with the larger scenarios in each category yielding a better ratio of benefit to sea use.

When combined scenarios are also considered, even larger land savings are possible, with the most ambitious scenario, All-High-Aspa, saving almost 200 million hectares (Table 5). It is important to note that for most of these scenarios, the majority of savings are in non-forested natural lands, with forests making up less than a quarter of total land savings.

Whilst this land sparing is not uniformally distributed, there is a consistent pattern of effects, with most savings occurring in China, Brazil and Western Africa under Food-10 (See for example Figure 6A,B). To meet this demand, the spatial prioritization reveals that the optimal distribution of farming effort would involve a large amount of production in Indonesia, Northern Europe, the USA, and the Saudi Arabian peninsula (Figure 6C). In terms of production, much of Africa and South America is left out of this scenario.

When water and fertiliser use are considered, the Food-10 scenario again outperforms the others, with annual water savings of almost 60 km^3 (Figure 5C), and nitrogen savings of 20 million tonnes (Figure 5D). While the pattern of nitrogen use closely follows the reductions in cropland, the effect on water use of displacing feed and fuel is more complex. Feed-10 and Fuel-50 yield similar water savings of 10.3 and 8.1 km^3, respectively. Some of the savings in water for these categories are actually offset by an increase in usage from some crop types, possibly due to the lost residual meal from biofuel production that would have been used as animal feed.

3.2.2 Emissions

Increasing seaweed utilization in almost all scenarios leads to a decrease in emissions, and as with the impacts on land-use change, these are highly variable across substitution scenarios (Figure 5B). The scenario with the greatest potential to reduce emissions is Aspa-0.5R, with the potential to mitigate 2.1 Gt of CO_2e per year by 2050. This is an almost four times greater potential than the next best scenario, Food-10. Of the remaining basic scenarios,

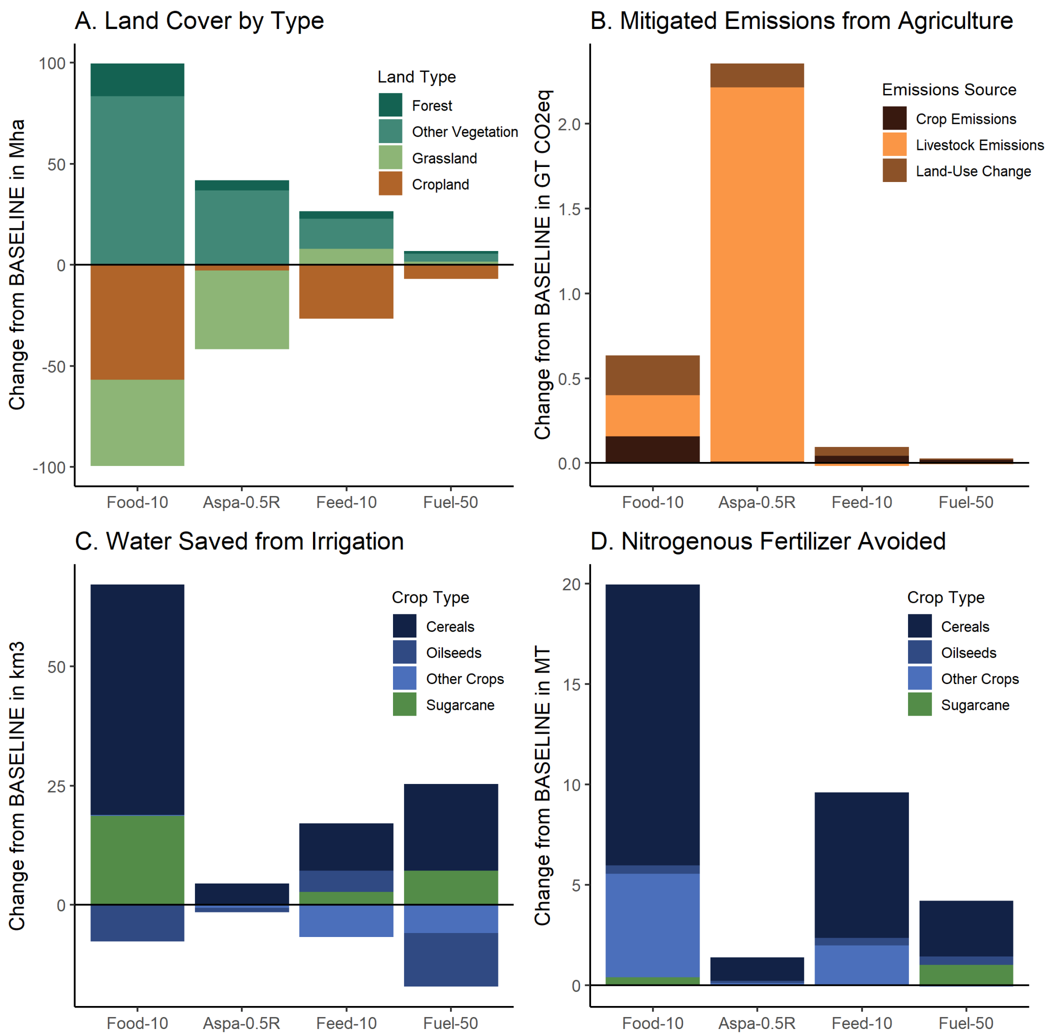

Figure 5: The effects of seaweed substitution were calculated using GLOBIOM to predict the level of each indicator in 2050 for each scenario and comparing those levels against the baseline GLOBIOM scenario.

Feed-10 mitigates 77 megatonnes CO_2e per year and Fuel-50 only 20 megatonnes CO_2e per year.

In the case of Aspa-0.5R, 94% of mitigation comes from the reduction of enteric methane, and almost all of the remaining 6% comes from a reduction in land-use change due to the improved feed conversion efficiency of ruminant livestock. In the Food-10 scenario, these mitigation effects are spread out more evenly between land-use change, livestock emissions, and emissions from crops. Interestingly, the Feed-10 scenario leads to a small increase in emissions from livestock, however this is the response of cheaper feed in response to the substitution (oversupply for crops) which triggers lower animal product prices, and a rebound

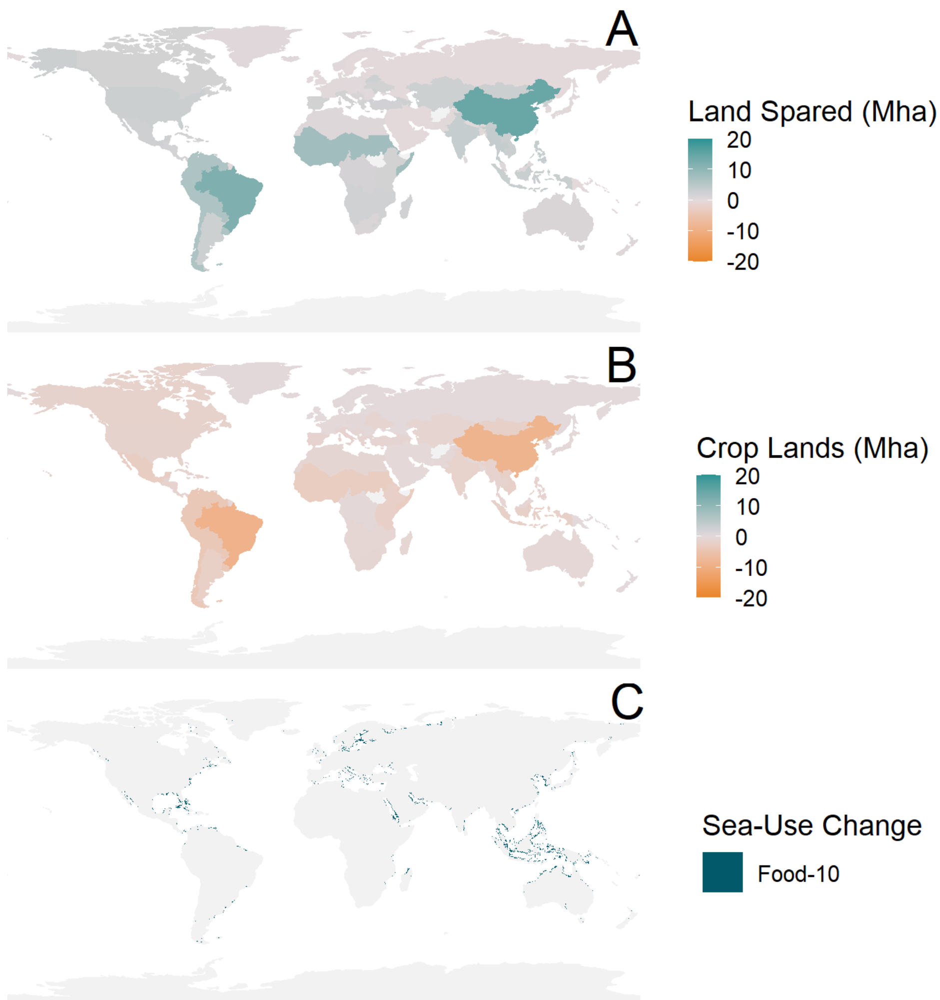

Figure 6: The land- and sea-use trade-offs associated with the Food-10 scenario in 2050, which assumes seaweeds are incorporated into human diets at a rate of 10% by 2050. A shows the regional savings in terms of natural lands. B shows the reduction in crop land, and C. shows the optimal distribution of seaweed farming to achieved the substitution demand of Food-10.

effect of the consumption.

The combined scenarios show the importance of *Asparagopsis* as a tool to mitigate carbon emissions from agriculture, with Aspa-0.5R outperforming All-High by a considerable margin, and accounting for 77% of the total emissions reductions of All-High-Aspa, the most extreme scenario (Table 5).

4 Discussion

4.1 Global and Regional Supply Potential

Our estimate of the global viable space for seaweed farming, ca. 349 Mha, sits near the lower end of previous estimates. These range from 50 Mha [26], to 4,800 Mha [25] to 10,000 Mha [92]. As Figure 3 shows, there is a large difference between the amount of area that could physically be farmed and the amount of area that could realistically be farmed, which is the likely source for this wide range of estimates.

There are some sources of possible error in our analysis which could cause global potential to be less or greater than our estimate. For example, the distribution of occurrence data could be subject to sampling bias [93], which could cause the Maxent model to underrepresent areas where seaweeds naturally occur or affect our Native-Only constraint layer.

The fact that we only modelled 35 commercially viable species of seaweed due to data constraints could also be a source of undercounting potential. All of the seaweeds we include here are either presently farmed or collected from the wild and thus a market exists for their biomass. This makes their use and the expansion of their production much more likely than other less-utilized species. Nevertheless, there are at least 291 species of seaweed with a recorded history of use worldwide, many of which may be just as useful as food, feed, or fuel feedstock as those we have chosen for our analysis [46], and thus the map of suitable areas for seaweed farming is likely even more filled in than what we have presented in Figure 3. There is also a very limited understanding of the variety of uses each of these lesser-known species might have. A case in point is the only recent discovery of the utility of *Asparagopsis* in ruminant feed, and the surge of commercial ventures that have rushed in to capitalize on this discovery [94, 95]. It is highly likely that there are many other discoveries waiting to be made which could cause new species with novel biophysical envelopes to enlarge the distribution of viable space for seaweed farms. Technological advances such as the refinement of cultivation techniques, selective breeding to maximize yield, or genetic engineering could all lead to an intensification of production and therefore increase the global supply potential.

As discussed, seaweed farming could potentially be a potent tool for combatting climate change, however at the same time it is also vulnerable to climate change impacts via rising ocean temperatures and changing carbon concentrations [96]. These effects could cause declines in productivity on a local scale or lead to large-scale range shifts that make the farming of preferred or traditional species impossible. This is already being seen in both cultivated seaweeds [97] and wild populations [98]. These patterns make it likely that the parameters upon which we based our estimates of seaweed production potential, are likely to shift over the next several decades to 2050. Future work will attempt to incorporate this future uncertainty into account when assessing and predicting the future distribution and production of seaweed farms.

We have demonstrated that the global potential for seaweed production is considerable, however numerous technical, logistical, economic, and environmental barriers to achieving this scale of production remain [99]. Much of the growth in the industry in recent years has been fueled by off-the-bottom farming in places like Indonesia and the Philippines, however this kind of cultivation can only be done in very shallow, protected coastal areas [8] and may be less productive than floating cultivations due to a higher vulnerability to temperature mediated disease [100]. But floating farms, especially those built for long-term large-scale production, will be resource-intensive and in some contexts this may presently undermine both the profitability and environmental rationale for pursuing seaweed cultivation [101, 102], especially when compared to off-the-bottom farming [103]. The competition for space in the marine environment will also pose a significant challenge to scaling seaweed production as the various sectors of the Blue Economy ramp up growth [104]. Our estimate of global potential assumes that seaweed farming would cover at most 50% of suitable areas, which would allow for other sea-uses in and amongst farms, which could be further enabled by a strong marine spatial planning framework. Indeed, an emerging strategy for improving the viability of offshore seaweed farms is to integrate farming with other sectors of the blue economy. For example, seaweed could be cultivated alongside other organisms in an integrated multi-trophic aquaculture (IMTA) system [105] which has the added benefit of closing-the-loop on nutrient cycling and can increase the productivity of both seaweed and non-seaweed cultivars while also reducing the environmental footprint of both [106, 107]. Similar to the integration of wind energy and agriculture on land, offshore wind farms may also prove to be an advantageous place to farm seaweed as both enterprises can benefit from shared capital costs and can occupy the same space with minimal conflict [108, 109], which maybe prove to be especially relevant considering the scale of planned offshore wind energy in some places [110, 111].

4.2 Seaweed Adoption

For each of the scenarios that we have considered here, the factors governing adoption dynamics and substitution will likely vary considerably. For example, in human diets these will likely be contingent upon palatability, consumer preference, and the success of understanding and marketing the unique health benefits of seaweed consumption [112]. Given that the highest global consumers of seaweed in East Asia likely consume seaweed as 2% of their diets [73] and in places seaweed is becoming a popular ingredient [113], it is not difficult to imagine the Food-01 scenario coming to pass. However, the high mineral content and strong flavours of seaweeds [114] could pose significant barriers to consumption at higher proportions unless progress is made into incorporating seaweed biomass into novel foods, like plant-based meats.

For feed, adoption will depend more on the demand for specific macronutrient profiles and the cost at which seaweed-derived products can be produced relative to terrestrial alternatives. Unless the seaweed farming industry can reliably produce a high-quality product at a competitive price then adoption scenarios like Feed-10 are unlikely to be realized. But as the *Asparagopsis* effect demonstrates, emerging research into the health, meat quality, and efficiency benefits that can be gained from incorporating seaweed into livestock diets could also serve to increase adoption. For example, the feed conversion efficiency benefits that come along with the anti-methanogenic effect of *Asparagopsis* supplementation could allow for substantial cost savings for farmers and thus increase their willingness to pay for seaweed products. However, this may only serve to increase the breadth of adoption to a certain point and may not lead to substantial seaweed substitution in feed.

Seaweed demand may also be stimulated by government policies that create programs based on payments for ecosystem services or a carbon price. While there remains some uncertainty as to the magnitude of carbon sequestration that can be gained from operating a seaweed farm [115], there is likely some amount of benefit [116, 117], the monetization of which could allow for seaweed farms to become more competitive with terrestrial production. Additionally, the science behind the bioremediation potential of seaweed farms is starting to show that substantial amounts of nitrogen and phosphorous could be absorbed and monetized [118].

Whilst we have assumed in this analysis that increasing seaweed supply will serve to decrease demand for terrestrial products, this direct relationship may not hold in practice. In the worse-case scenario, an increase in seaweed supply could, instead of displacing demand, display a rebound effect [119], whereby an increase in supply leads to a drop in prices and a resulting increase in demand. Future research should focus on building seaweed cost data and production potential into partial equilibrium models like GLOBIOM to further explore this potential. Additionally, many of the benefits we have described here implicitly assume a range of assumptions pertaining to future land-use and consumption which have the potential to diverge considerably from our current expectation [120].

4.3 Balancing Costs and Benefits of Large-Scale Seaweed Production

Previous work has found that shifting diets away from terrestrial livestock and towards cultured marine animals (without considering seaweeds) could spare 90 million hectares of land [121], which is comparable to the 100 million ha found in our Food-10 scenario. In terms of carbon benefits from upscaling seaweed production, previous work has suggested that 0.05–0.29 Gt CO_2e could be sequestered per year in 2050 [122]. These estimates are only slightly lower than our All-Low and All-High scenarios, 0.07 Gt CO_2e, and 0.71 Gt CO_2e, respectively. However, if we consider the possible benefits of the *Asparagopsis* effect, the carbon savings could potentially be tripled. Note however that while we have assumed that all ruminant livestock will respond uniformly to supplementation, both in terms of methane reduction and feed conversion benefit, in reality it is unlikely that this will be the case. Response variation due to livestock type, seaweed quality, and diet are all likely. While this could mean that lower carbon benefits are realized, but on the other hand, we have assumed a 68% reduction in methane emissions given a supplementation rate of 0.5%, and already much higher reductions have already been demonstrated [83], and the efficacy of these supplements will likely only increase as the technology is refined.

The finding that the Food- scenarios performed generally better than the Feed- scenarios is likely due to the inherent energy and material losses that are associated with feeding plants to animals for food, rather than simply eating the plants themselves. This is consistent with findings that plant-based diets are generally more sustainable than meat-based diets [123, 124].

An important limitation of this study is the absence of data on the carbon costs of farming seaweed. As has been demonstrated in various life-cycle analyses, the carbon cost of growing seaweed in the marine environment can be significant [101, 102]. On the other hand, during the growth phase of a seaweed farm, a large proportion of primary productivity is exported from the farm, some of which is presumed to end-up sequestered in the benthos or in the deep sea [116, 117]. Incorporating a rigorous accounting of these costs and benefits is an important next step in this research. However, given the staggering potential of *Asparagopsis* to reduce emissions, and the very limited amount of biomass needed to achieve this effect, it is clear that from an emissions perspective the best seaweed strategy for mitigating the impact of the agricultural sector on carbon emissions is to grow *Asparagopsis* to supplement ruminant feed. Another important strategy which we have not considered in our analysis is disposing all or most of the harvested biomass of a seaweed farm in the deep sea as a form of sequestration [17, 23, 25]. If we consider our upper limit global estimate of 7 billion tonnes of dry matter per year, and, assuming an average of 25% carbon content [125] and a ratio of CO_2:C of 3.66, we could sequester more than 6 Gt per year in this manner. However, the carbon costs of production at such a scale are still unknown. And, in addition to being economically infeasible in the absence of a high price on carbon, such a strategy lacks any of the land-use, water, or fertilizer benefits that consuming this biomass would provide.

Future work should focus on closely examining whether there are indeed any downsides to implementing large-scale *Asparagopsis* cultivation and feed supplementation. As our species distribution modelling has shown S2, members of *Asparagopsis* have the potential to spread across a wide range, which could prove challenging from a bio-security perspective. Already in the Mediterranean, *Asparagopsis taxiformis* is highly invasive and is associated with poorer faunal assemblages than other native seaweeds [126, 127]. Were it to be farmed at a large-scale in places where it is not native, the potential for escape and ecological degradation is likely, even in places that might be at the edge of its range [128]. If widely adopted, the feed conversion efficiency benefits of *Asparagopsis* supplementation will likely lead to a increase in ruminant product consumption, which could have other local environmental consequences [129, 130], as well as consequences for human health [131].

Beyond the large-scale benefits that we have explored here, practicing seaweed farming on a large-scale will generate numerous other local and regional impacts [15]. For example, we have not considered the habitat value that might be generated from extensive stands of seaweed farms [18]. In the case of large seaweeds like kelps, it is possible that large farms may reflect native seaweed forests in some ways, whereas for smaller seaweeds habitat provisioning benefits may be more modest. The bioremediation of eutrophic coastal ecosystems is also an oft-cited ecological benefit of seaweed farming [132, 133, 134] which could also be enormously important in some local contexts, however the extent to which this benefit will be sustained as seaweed farming scales up and moves further offshore needs further study.

5 Conclusion

The potential to effect positive impacts on land-use and carbon emissions via expanding offshore seaweed farming is substantial. We find that globally there is at least 349 million hectares of suitable ocean area in which 35 functionally diverse seaweeds species could be grown. This potential is not uniformly distributed over the globe however, with some regions and nations possessing a greater share of diversity of those seaweeds we considered, and a larger area of suitable space in which to develop seaweed farms. The possible global benefit of this potential will be dependent on what these farms grow, and what that produce is used for. Our analysis suggests when considering the marginal benefit of developing a given area of ocean, growing *Asparagopsis* for ruminant feed will deliver the largest magnitude of benefits to land-use, emissions reduction, water and fertilizer use. In terms of gross potential, if the diets of all ruminants were supplemented in this way by 2050, it would lead to a mitigation potential of greater than 2 Gt per year. However, due to the relatively small amount of per animal supplement needed ($< 1\%$), this strategy has a smaller overall potential to deliver benefits to land-use, water, and fertilizer use. Instead, using seaweed as human food has the greatest potential to lead to benefits for these indicators. For example, substituting 10% of human diets with seaweed, or seaweed-derived food products, would spare almost 100 Mha of natural lands. Whilst using seaweeds as biofuels and as livestock feed, can also deliver benefits, these uses would be considerably less effective.

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6 Supplementary Information

Table S1: Assumed Uses for Commercially Viable Seaweed Species

Taxa	FOOD	FEED	FUEL
Alaria esculenta	+	+	+
Ascophyllum nodosum		+	+
Asparagopsis armata		+	
Asparagopsis taxiformis	+	+	
Caulerpa lentillifera	+	+	
Caulerpa racemosa	+	+	
Chondracanthus chamissoi	+	+	
Chondrus crispus	+	+	
Codium fragile	+	+	
Costaria costata	+	+	
Durvillaea antarctica	+	+	
Eisenia arborea		+	
Enteromorpha clathrata	+		+
Enteromorpha prolifera	+		+
Eucheuma denticulatum		+	
Fucus serratus			+
Fucus vesiculosus	+	+	+
Gelidium amansii	+	+	+
Gracilaria chilensis		+	+
Gracilaria gracilis			+
Gracilaria verrucosa	+	+	+
Kappaphycus alvarezii	+	+	+
Laminaria digitata		+	+
Laminaria hyperborea	+	+	+
Macrocystis pyrifera	+	+	+
Neopyropia yezoensis	+	+	+
Palmaria palmata	+	+	+
Porphyra umbilicalis	+	+	
Saccharina japonica	+	+	+
Saccharina latissima	+	+	+
Ulva lactuca	+	+	+
Ulva pertusa	+	+	+
Ulva reticulata	+	+	
Undaria pinnatifida	+	+	+

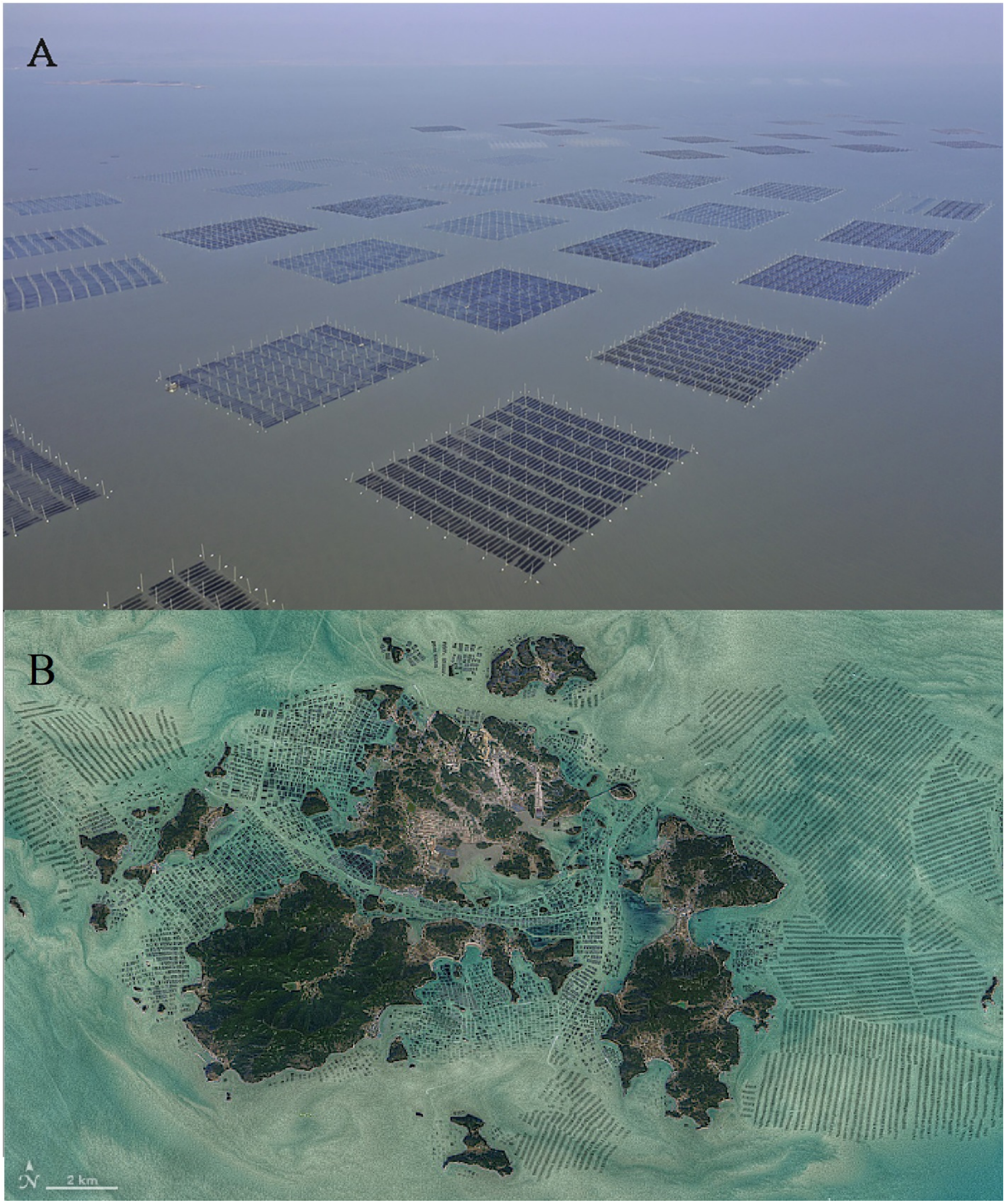

Figure S1: A. Aerial photograph of a *Neopyropia yezoensis* farm near Qingdao, Shandong Province. Each square is 2.2 ha. Taken from [135]; B. Seaweed farming around Nohwa island in South Korea. NASA image by Norman Kuring/NASA's Ocean Color Web, using Landsat data from the U.S. Geological Survey. Accessed September 14, 2021.

Table S2: The area in Mha of global potential for seaweed farming after each constraint layer is applied.

Added Constraint	**Area (Mha)**
Unconstrainted	9365
Depth	2397
Port Distance	2397
Shipping	2397
Wave Energy	2234
MPAs	2162
Native Only	1750
Low Viability	699
50% Coverage	349

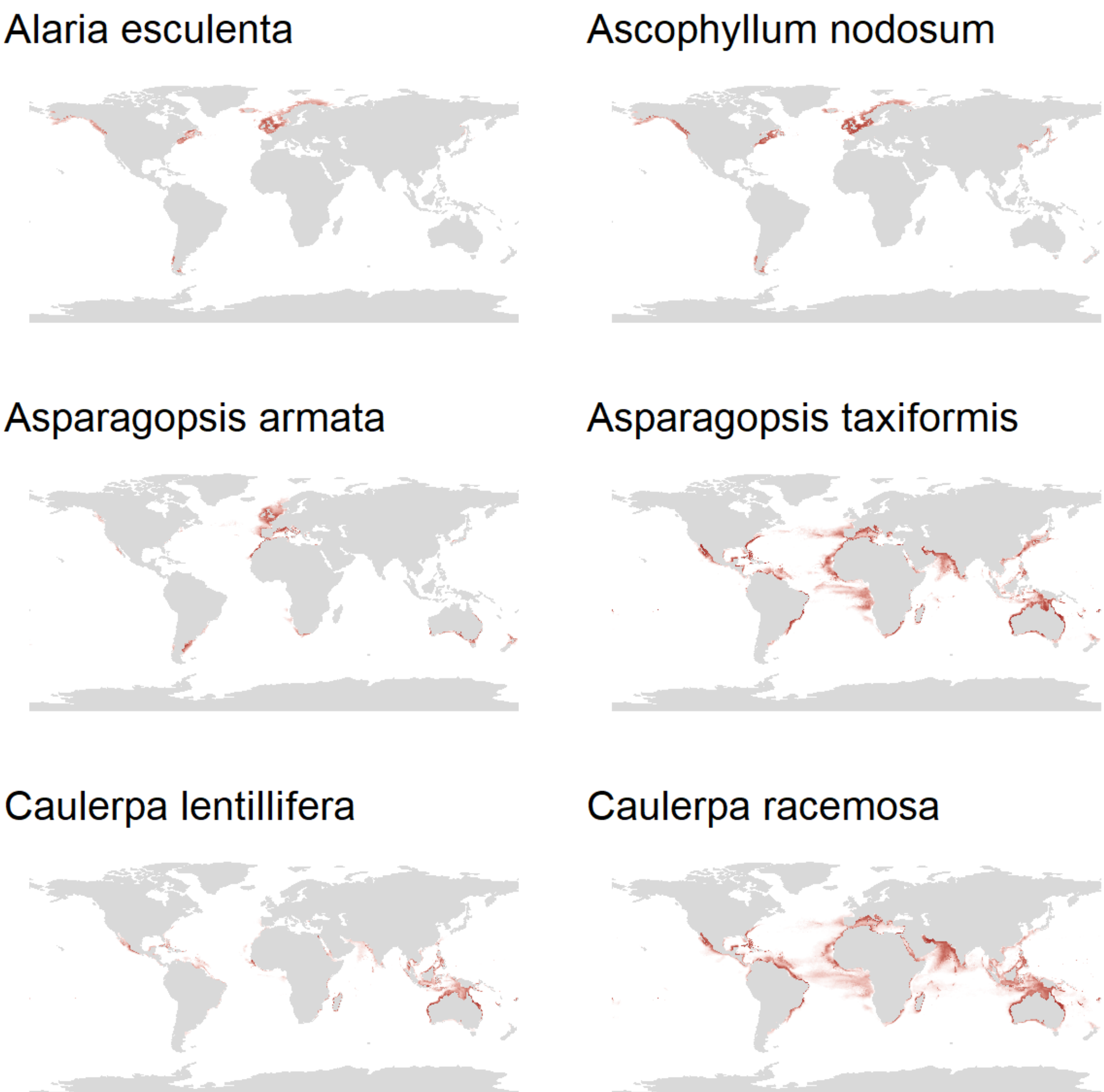

Figure S2: Global Potential for A.esculenta, A.nodosum, A.armata, A.taxiformis, C.lentillifera, C.racemosa.

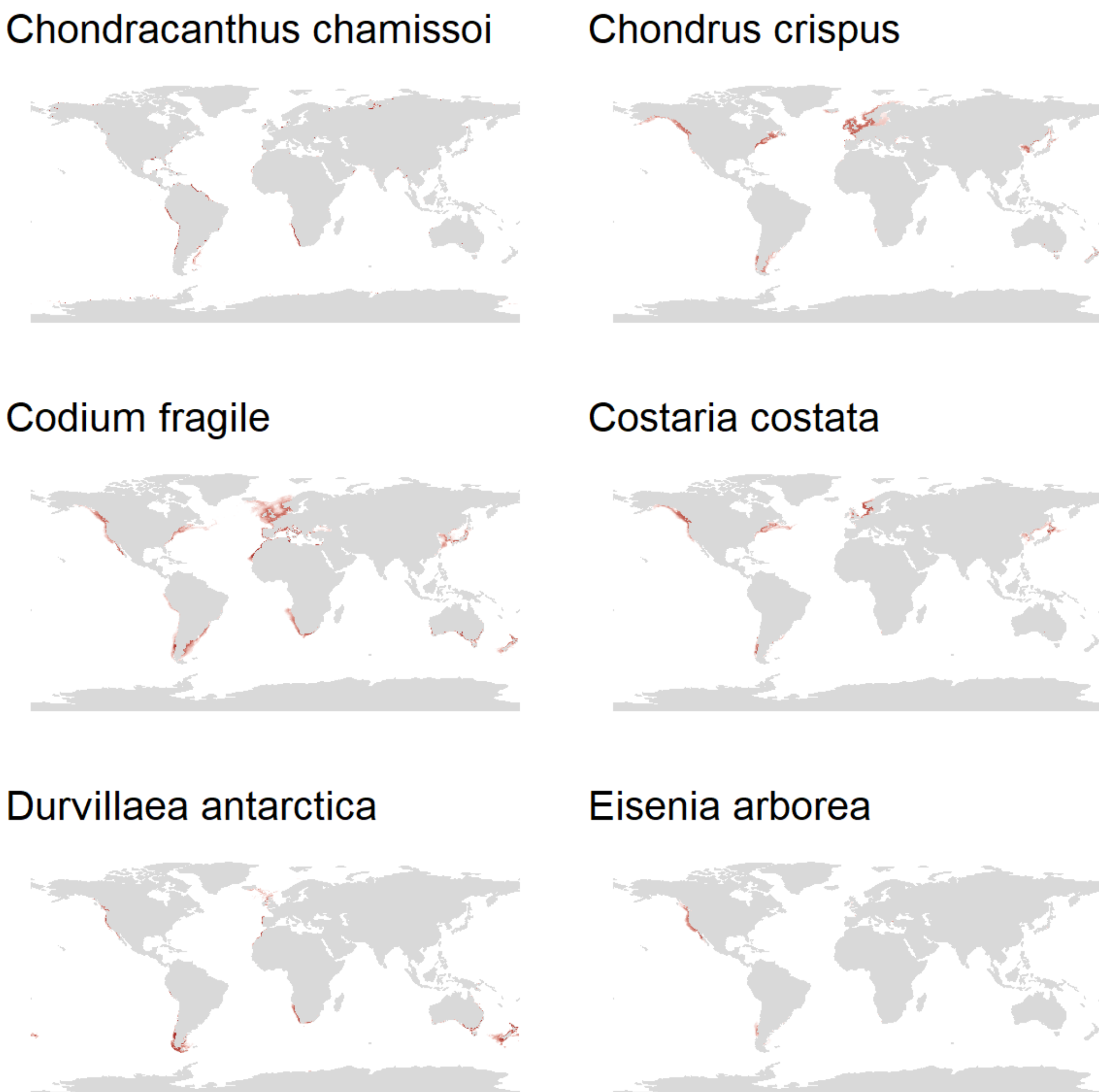

Figure S3: Global Potential for C.chamissoi, C.crispus, C.fragile, C.costata, D.antarctica, E.arborea.

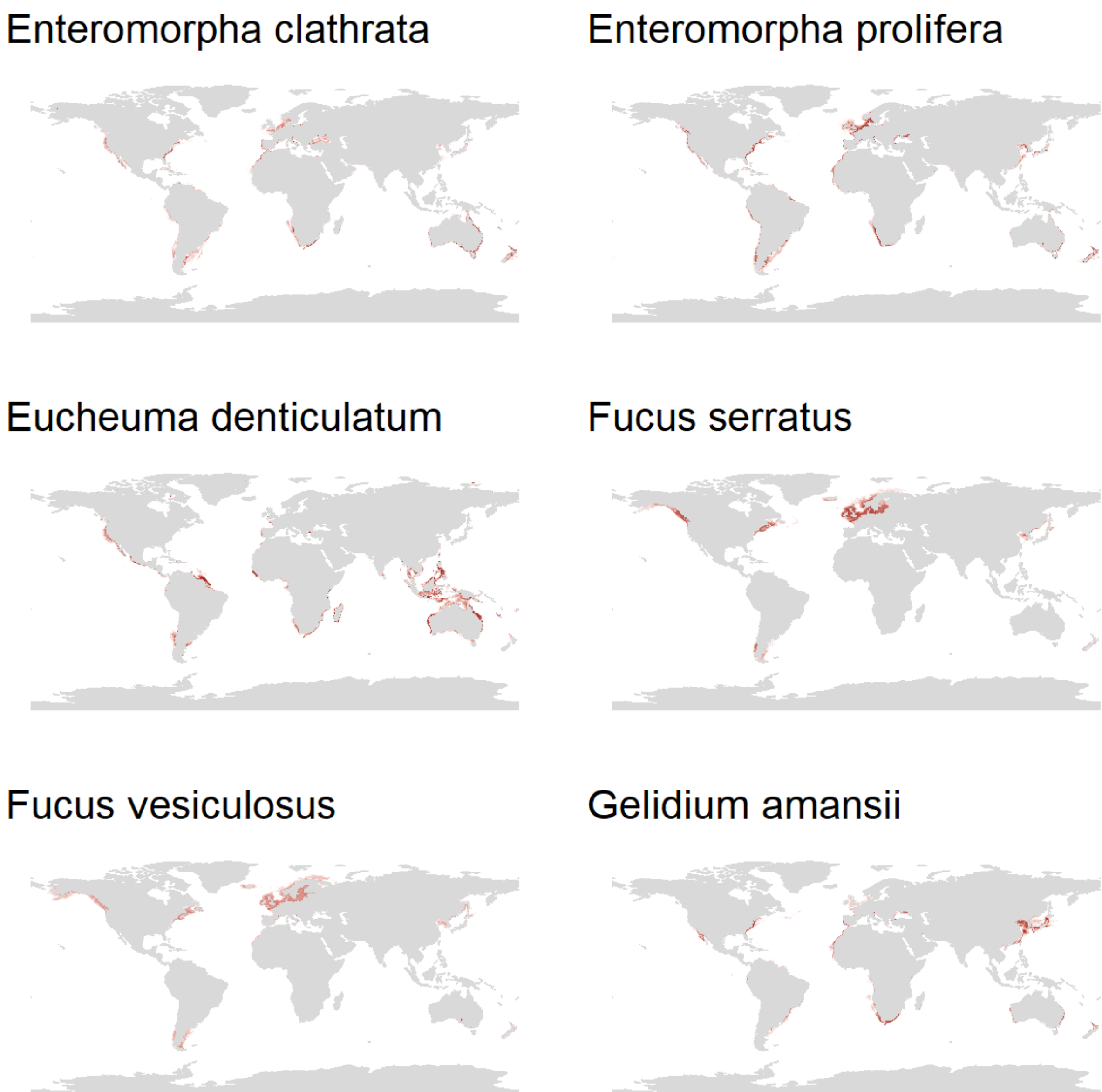

Figure S4: Global Potential for E.clathrata, E.prolifera, E.denticulatum, F.serratus, F.vesiculosus, G.amansii.

Figure S5: Global Potential for G.skottsbergii, G.chilensis, G.gracilis, G.verrucosa, K.alvarezii, L.digitata

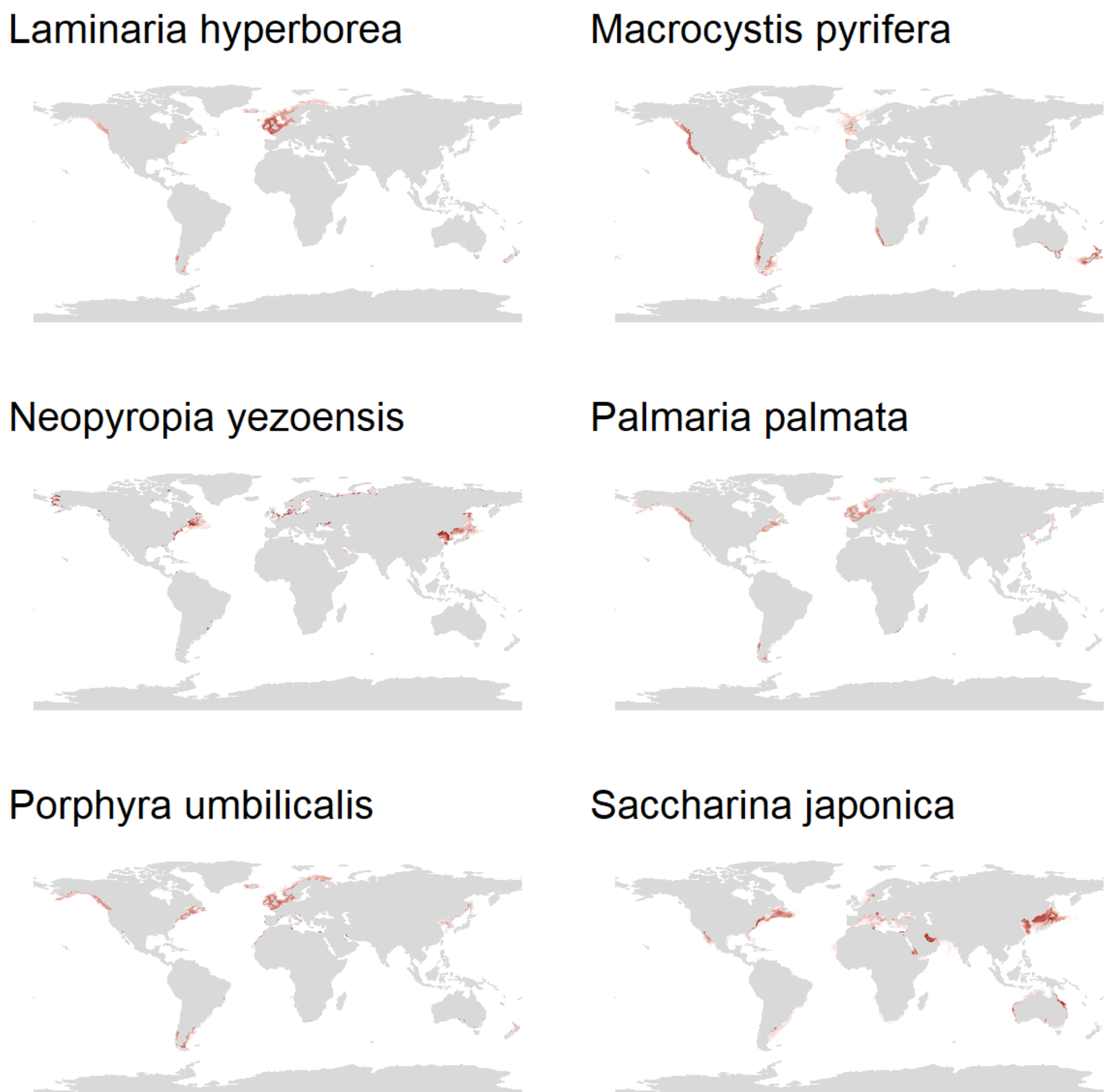

Figure S6: Global Potential for L.hyperborea, M.pyrifera, N.yezoensis, P.palmata, P.umbilicalis, S.japonica.

Figure S7: Global Potential for S.latissima, U.lactuca, U.pertusa, U.reticulata, U.pinnatifida.

Level of Constraints

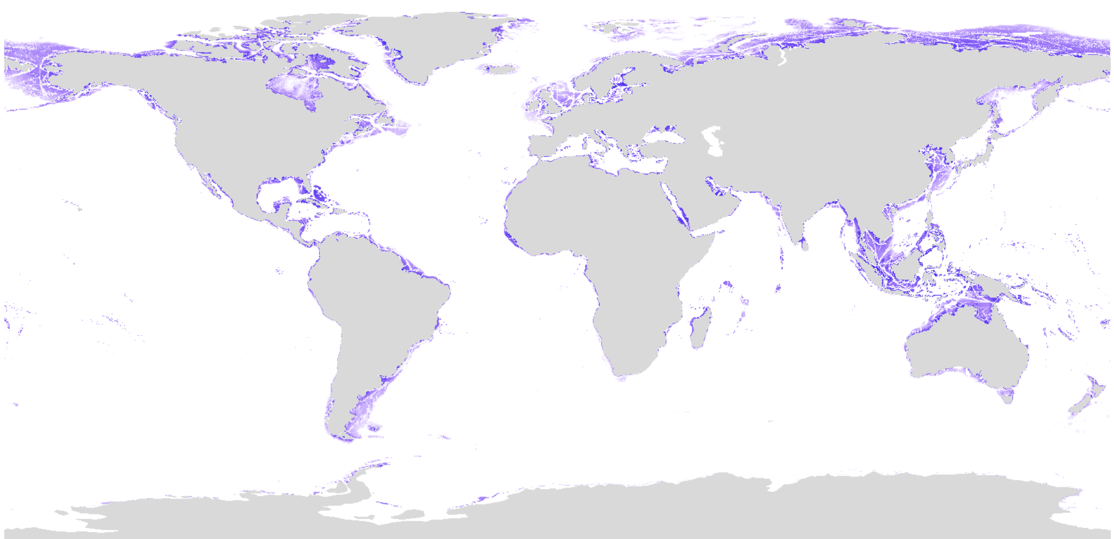

Figure S8

Table S3: Production potential of in tonnes of dry matter per hectare per year reported in the literature. For species for which estimates could not be found an average for their class is reported.

Taxa	**Production min (t DM / ha)**	**(t DM / ha)**	**Class**	**Source**
Alaria esculenta	19	30	Phaeophyceae	[136, 65]
Ascophyllum nodosum	9.6	11.8	Phaeophyceae	[137]
Asparagopsis armata	14.4	38.1	Florideophyceae	*Mean of Florideophyceae
Asparagopsis taxiformis	14.4	38.1	Florideophyceae	*Mean of Florideophyceae
Caulerpa lentillifera	7.1	34.7	Ulvophyceae	*Mean of Ulvophyceae
Caulerpa racemosa	7.1	34.7	Ulvophyceae	*Mean of Ulvophyceae
Chondracanthus chamissoi	14.4	38.1	Florideophyceae	*Mean of Florideophyceae
Chondrus crispus	14.4	38.1	Florideophyceae	*Mean of Florideophyceae
Codium fragile	7.1	34.7	Ulvophyceae	*Mean of Ulvophyceae
Costaria costata	18	43.5	Phaeophyceae	*Mean of Phaeophyceae
Durvillaea antarctica	18	43.5	Phaeophyceae	*Mean of Phaeophyceae
Eisenia arborea	18	43.5	Phaeophyceae	*Mean of Phaeophyceae
Enteromorpha clathrata	7.1	34.7	Ulvophyceae	*Mean of Ulvophyceae
Enteromorpha prolifera	7.1	34.7	Ulvophyceae	*Mean of Ulvophyceae
Eucheuma denticulatum	14.4	38.1	Florideophyceae	*Mean of Florideophyceae
Fucus serratus	18	43.5	Phaeophyceae	*Mean of Phaeophyceae
Fucus vesiculosus	18	43.5	Phaeophyceae	*Mean of Phaeophyceae
Gelidium amansii	14.4	38.1	Florideophyceae	*Mean of Florideophyceae
Gracilaria chilensis	7.6	18	Florideophyceae	[85, 137]
Gracilaria gracilis	14.4	38.1	Florideophyceae	*Mean of Florideophyceae
Gracilaria verrucosa	2.7	9.4	Florideophyceae	[**?**]
Kappaphycus alvarezii	8.3	95.9	Florideophyceae	[138]
Laminaria digitata	2.9	2.9	Phaeophyceae	[65, 139]
Laminaria hyperborea	30	90	Phaeophyceae	[65]
Lessonia nigrescens	18	43.5	Phaeophyceae	*Mean of Phaeophyceae
Macrocystis pyrifera	16.5	50	Phaeophyceae	[103, 65]
Neopyropia yezoensis	0.8	0.8	Bangiophyceae	[140]
Palmaria palmata	14.4	38.1	Florideophyceae	*Mean of Florideophyceae
Porphyra umbilicalis	0.8	0.8	Bangiophyceae	*Mean of Bangiophyceae
Saccharina japonica	31	93.9	Phaeophyceae	[65, 141, 142]
Saccharina latissima	1.5	36	Phaeophyceae	[136, 65, 143, 139]
Ulva lactuca	7.1	34.7	Ulvophyceae	[65]
Ulva pertusa	7.1	34.7	Ulvophyceae	*Mean of Ulvophyceae
Ulva reticulata	7.1	34.7	Ulvophyceae	*Mean of Ulvophyceae
Undaria pinnatifida	18	43.5	Phaeophyceae	*Mean of Phaeophyceae

Table S4: Fuel Conversion Potential of Commercially Viable Seaweed Species.

Taxa	Fuel Type	Fuel Energy (MJ/kg)	Source
Enteromorpha clathrata	Biooil	40.9	[85]
Enteromorpha prolifera	Biooil	40.9	[85]
Neopyropia yezoensis	Biooil	46.7	[85]
Saccharina japonica	Biooil	36	[87, 85, 12, 86, 87, 85]
Saccharina latissima	Biooil	36	[65, 144, 145]
Ulva lactuca	Biooil	22.3	[65, 85]
Ulva pertusa	Biooil	25.1	[86]
Gelidium amansii	Ethanol	19.2	[87]
Gracilaria chilensis	Ethanol	1.5	[103]
Gracilaria gracilis	Ethanol	14.3	[85]
Gracilaria verrucosa	Ethanol	21.1	[86, 87]
Kappaphycus alvarezii	Ethanol	13.4	[87]
Laminaria digitata	Ethanol	18.6	[65, 144, 145, 12]
Laminaria hyperborea	Ethanol	18.6	[86]
Macrocystis pyrifera	Ethanol	3	[103]
Palmaria palmata	Ethanol	8.5	[86]
Saccharina japonica	Ethanol	19	[87, 85, 12, 86, 87, 85]
Saccharina latissima	Ethanol	19	[65, 144, 145]
Ulva lactuca	Ethanol	23	[65, 85]
Ulva pertusa	Ethanol	22.8	[86]
Undaria pinnatifida	Ethanol	7	[12, 85]

Table S5: GLOBIOM Product Definitions

Vegetable products	
WHEA	Wheat and products
RICE	Rice and products
CORN	Corn grain and products
CORO	Corn oil
SOYA	Soybean seed
SOYO	Soybean oil
RAPE	Rape seed
RAPO	Rape oil
BARL	Barley and products (excl. beer)
BEER	Beer
CASS	Cassava and products
SUNF	Sunflower seed
SUNO	Sunflower oil
MILL	Millet and products
SRGH	Sorghum and products
SUGR_C	Sugar from sugar cane
BEAN	Beans and products*
COTO	Cotton oil
PLSN	Other pulses*
SWPO	Sweet potatoes and products
POTA	Potatoes and products
GNUT	Groundnuts
GNUO	Groundnut oil
PLMO	Palm oil
PKRO	Palmkernel oil
Livestock products	
BVMEAT	Bovine meat
SGMEAT	Small ruminant meat
PGMEAT	Pigmeat
PTMEAT	Poultry meat
PTEGGS	Poultry eggs
ALMILK	Ruminant milk
*products with consumption definition broader than the production definition in FAOSTAT	
Other products within aggregates not present on GLOBIOM production side	
CEREALS+	Other cereals
OILSEEDS+	Other oilseeds
PULSES+	Other pulses
ROOTS+	Other roots
SUGAR+	Other sugar (incl. from sugar beet)
VEGOIL+	Other vegetable oils
VEGET+	Other vegetables (all)
FRUITS+	Other fruits (all)
TNUTS+	Other tree nuts (all)
AQUAFOOD+	Other aquatic products (all)
OTMEAT+	Other animal meat
ANIMOTH+	Other animal products
ALCOOL+	Other alcools
OTHER+	Other food

Table S6: GLOBIOM Region Definitions

GLOBIOM Region	Country	GLOBIOM Region	Country	GLOBIOM Region	Country
ArgentinaReg	Argentina	MiddleEast	Lebanon	RSAS	Pakistan
AustraliaReg	Australia	MiddleEast	Oman	RSAS	SriLanka
BrazilReg	Brazil	MiddleEast	Palestin	RSEA_OPA	BruneiDarsm
CanadaReg	Canada	MiddleEast	Qatar	RSEA_OPA	Myanmar
ChinaReg	China	MiddleEast	SaudiArabia	RSEA_OPA	Philippines
CongoBasin	Cameroon	MiddleEast	Syria	RSEA_OPA	Singapore
CongoBasin	CentAfrRep	MiddleEast	UntdArabEm	RSEA_OPA	Thailand
CongoBasin	CongoDemR	MiddleEast	Yemen	RSEA_OPA	TimorLeste
CongoBasin	CongoRep	NewZealandReg	NewZealand	RSEA_PAC	Cambodia
CongoBasin	EqGuinea	NorthernAf	Algeria	RSEA_PAC	KoreaDPRp
CongoBasin	Gabon	NorthernAf	Egypt	RSEA_PAC	Laos
EU_Baltic	Estonia	NorthernAf	Libya	RSEA_PAC	Mongolia
EU_Baltic	Latvia	NorthernAf	Morocco	RSEA_PAC	VietNam
EU_Baltic	Lithuania	NorthernAf	Tunisia	RussiaReg	RussianFed
EU_CentralEast	Bulgaria	NorthernAf	WestSahara	SouthAfrReg	SouthAfrica
EU_CentralEast	Croatia	Pacific_Islands	FijiIslands	SouthKorea	KoreaRep
EU_CentralEast	CzechRep	Pacific_Islands	FrPolynesia	EasternAf	Burundi
EU_CentralEast	Hungary	Pacific_Islands	NewCaledonia	EasternAf	Ethiopia
EU_CentralEast	Poland	Pacific_Islands	PapuaNGuin	EasternAf	Kenya
EU_CentralEast	Romania	Pacific_Islands	Samoa	EasternAf	Rwanda
EU_CentralEast	Slovakia	Pacific_Islands	SolomonIs	EasternAf	Tanzania
EU_CentralEast	Slovenia	Pacific_Islands	Vanuatu	EasternAf	Uganda
EU_MidWest	Austria	RCAM	Bahamas	SouthernAf	Angola
EU_MidWest	Belgium	RCAM	Belize	SouthernAf	Botswana
EU_MidWest	France	RCAM	CostaRica	SouthernAf	Comoros
EU_MidWest	Germany	RCAM	Cuba	SouthernAf	Lesotho
EU_MidWest	Luxembourg	RCAM	DominicanRp	SouthernAf	Madagascar
EU_MidWest	Netherlands	RCAM	ElSalvador	SouthernAf	Malawi
EU_North	Denmark	RCAM	Guadeloupe	SouthernAf	Mauritius
EU_North	Finland	RCAM	Guatemala	SouthernAf	Mozambique
EU_North	Ireland	RCAM	Haiti	SouthernAf	Namibia
EU_North	Sweden	RCAM	Honduras	SouthernAf	Reunion
EU_North	UK	RCAM	Jamaica	SouthernAf	Swaziland
EU_South	Cyprus	RCAM	Nicaragua	SouthernAf	Zambia
EU_South	Greece	RCAM	Panama	SouthernAf	Zimbabwe
EU_South	Italy	RCAM	TrinidadTob	WesternAf	Benin
EU_South	Malta	RCEU	Albania	WesternAf	BurkinaFaso
EU_South	Portugal	RCEU	BosniaHerzg	WesternAf	CapeVerde
EU_South	Spain	RCEU	Macedonia	WesternAf	Chad
Former_USSR	Armenia	RCEU	Serbia-Monte	WesternAf	CotedIvoire
Former_USSR	Azerbaijan	ROWE	Greenland	WesternAf	Djibouti
Former_USSR	Belarus	ROWE	Iceland	WesternAf	Eritrea
Former_USSR	Georgia	ROWE	Norway	WesternAf	Gambia
Former_USSR	Kazakhstan	ROWE	Switzerland	WesternAf	Ghana
Former_USSR	Kyrgyzstan	RSAM	Bolivia	WesternAf	Guinea
Former_USSR	MoldovaRep	RSAM	Chile	WesternAf	GuineaBissau
Former_USSR	Tajikistan	RSAM	Colombia	WesternAf	Liberia
Former_USSR	Turkmenistan	RSAM	Ecuador	WesternAf	Mali
Former_USSR	Uzbekistan	RSAM	FalklandIs	WesternAf	Mauritania
IndiaReg	India	RSAM	FrGuiana	WesternAf	Niger
IndonesiaReg	Indonesia	RSAM	Guyana	WesternAf	Nigeria
JapanReg	Japan	RSAM	Paraguay	WesternAf	Senegal
MalaysiaReg	Malaysia	RSAM	Peru	WesternAf	SierraLeone
MexicoReg	Mexico	RSAM	Suriname	WesternAf	Somalia
MiddleEast	Bahrain	RSAM	Uruguay	WesternAf	Sudan
MiddleEast	Iran	RSAM	Venezuela	WesternAf	Togo
MiddleEast	Iraq	RSAS	Afghanistan	TurkeyReg	Turkey
MiddleEast	Israel	RSAS	Bangladesh	UkraineReg	Ukraine
MiddleEast	Jordan	RSAS	Bhutan	USAReg	PuertoRico
MiddleEast	Kuwait	RSAS	Nepal	USAReg	USA