Regional Seaweed Services Model
Technical documentation

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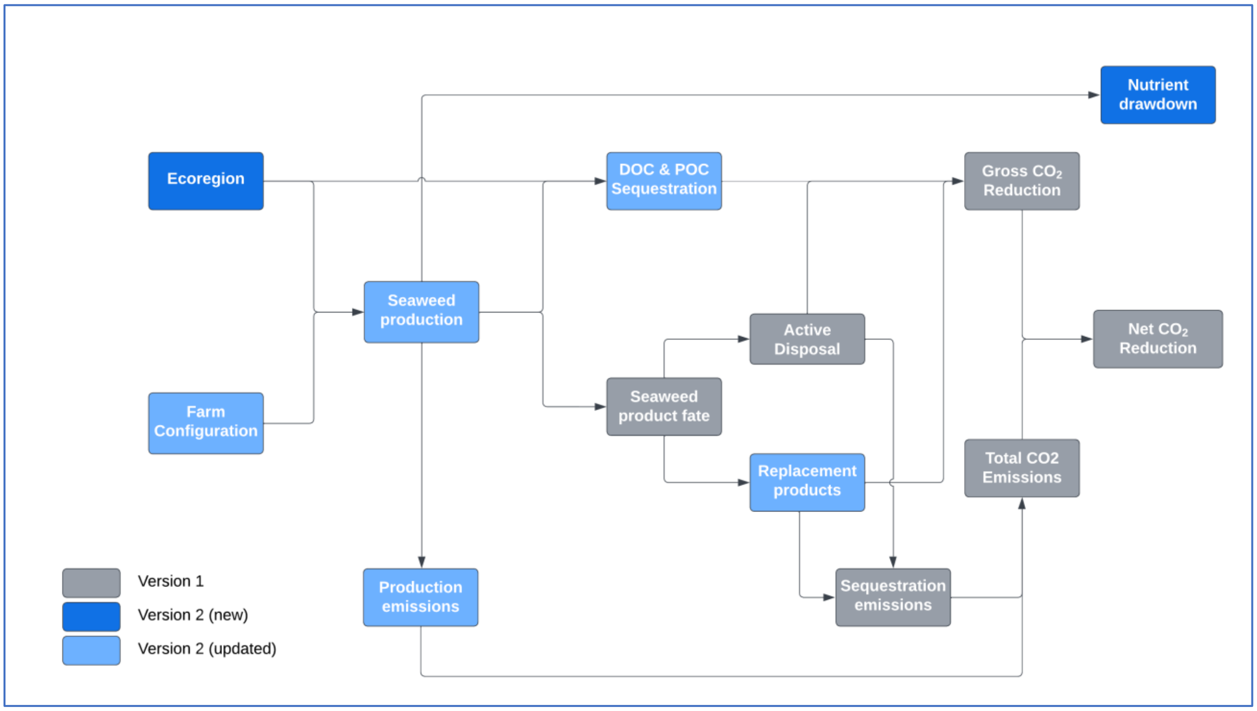

Figure 1: Schematic showing the high-level design of the original model (version 1) and the updates included as part of this Regional Seaweed Services Model update (version 2).

1 Summary

This document describes the objectives, design, structure, and updated parameters of the Regional Seaweed Services Model (RSSM). This second version of the tool for estimating carbon sequestration potential from seaweed aquaculture generalizes the original model to make it more broadly applicable, in terms of geography, farmed species, and seaweed products. The RSSM can now be applied in any ecoregion of the world, with local seaweed cultivation methods and replacement products. We have also included the potential drawdown of anthropogenic nitrogen and phosphorous to estimate the effectiveness of seaweed aquaculture at providing this ecosystem service. The RSSM thus provides important insights into the regional benefits of seaweed farming, despite being constrained by a lack of data on differences between locations, cultivation methods, and seaweed products. Estimating potential ocean sequestration of seaweed biomass has high uncertainty because it is very dependent on local conditions. However, as it represents a small fraction of the carbon reduction potential of product replacement, a focus on product replacement is a better natural carbon solution.

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3 Overview and objectives

Seaweed growth, oceanic and atmospheric carbon cycling, and product life cycles are complex and interconnected areas of study. Our mathematical model integrates these dynamics using values from the literature to create a simple and user-friendly tool, providing first-order estimates that may be of use to farmers, regulators, and other interested parties globally.

The first version of this model (described in Bullen et al. 2023) represents the potential climate benefits from seaweed aquaculture in BC, Canada. This version aims to improve and extend the original model by generalizing the analysis to make it more transferable and adding important new functionality (Figure 1). The goals for the RSSM include:

- Enabling the application of the model to coastal regions around the world
- Accounting for the influence of seaweed farming on water quality
- Enhancing the pathways for replacement products
- Improving estimates of the contribution of detrital pathways to sequestration
- Refining emission parameters.

The main operational change to support these objectives was to support user-specified farm configurations. The original model relied on pre-defined ‘scenarios’ and required several assumptions about the extent of seaweed aquaculture, the species cultivated, and the fate of harvested biomass to meet the objective of estimating the feasibility of seaweed aquaculture as a natural climate solution for British Columbia, Canada. The changes implemented in the RSSM now support a more flexible model easily applied to different geographies, with user-defined farm configurations for their region of interest.

4 Design of RSSM upgrades

4.1 Geographic transferability

The RSSM addresses the reality that the geographic setting (i.e., context) of the seaweed farm(s) will influence seaweed species selection, farming methods, productivity, carbon sequestration pathways and any associated emissions, and the provision of ecosystem services (i.e., nutrient drawdown). The geographic setting is therefore key to determining how effective the farm(s) will be at providing climate, ecological, economic, and social benefits.

4.1.1 Extents and resolution

To support a globally applicable, regional seaweed model, we represent geographic processes at the scale of marine ecoregions. These 232 ecoregions are defined according to ecological and oceanographic similarities (Spalding et al. 2007 - Fig. 2) and have been widely used as a basis for understanding large-scale spatial processes.

To support users with the ability to assess the carbon removal potential of seaweed farms within their area of interest, we have pre-processed available global data into relevant parameters for each ecoregion. For users with suitable local data, the open architecture of the RSSM allows users to update these prepared parameters with local biophysical, production, or emission data, to the extent such data are available (see the User Manual).

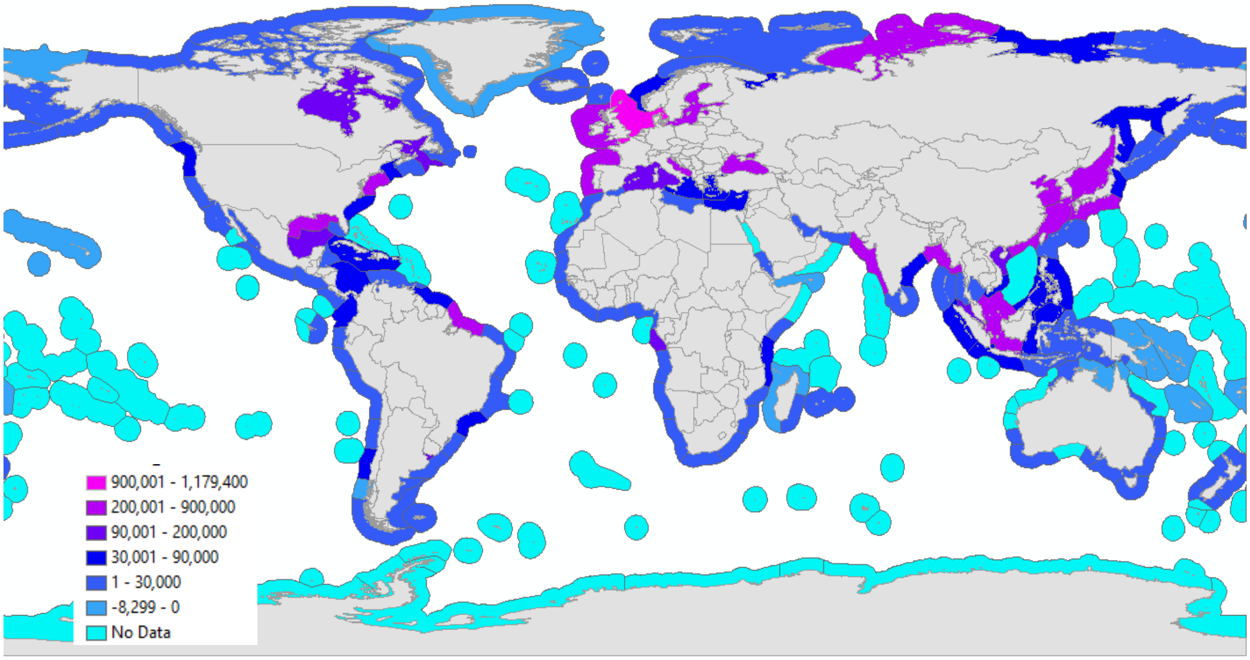

Figure 2: Global map showing regional marine ecosystems (Spalding et al. 2007) shaded according to anthropogenic nutrient loadings (Tg/year) from Green et al. (2004).

The RSSM uses ecoregions as a unit of analysis to improve model accuracy at the regional scale over global averages. We have calculated ecoregion-specific averages and standard deviations from available global data sets (Table 1) to define defensible regional parameters to inform seaweed productivity, sequestration potential, and nutrient drawdown. We describe the spatial layers and their intended use in the following section.

Table 1: Spatial layers used to characterize the seaweed farming potential of 232 global marine ecoregions and their role in the analysis.

Layer	**Description/source**	**Role**
Bathymetry	Global bathymetry (GEBCO 2015)	Allow conditioning of other spatial layers to relevant depth classes.
Seaweed growth potential	Seaweed growth model output (Arzeno-Soltero et al. 2023)	Relative ecoregion productivity.
Nitrogen loadings	Anthropogenic loadings from landscape (Green et al. 2004).	Relative value of nutrient mitigation by seaweed farms.
Marine sequestration	Fraction sunk carbon sequestered (DeAngelo et al. 2023, Siegel et al. 2021)	Estimating active and passive potential sequestration rates.
Mangroves	From global mangrove watch (Bunting et al. 2022). Obtained the 2020 coverage.	Estimating potential sequestration rates for Carbon Functional Units (see below).
Seagrasses	UNEP-WCMC global distribution of seagrasses as polygons (Short 2021).	Estimating potential sequestration rates for Carbon Functional Units (see below).
Estuaries	Global data presented as polygons (Watson et al. 2003), not comprehensive, includes some lagoons and fjords, sources have different resolutions.	Estimating potential sequestration rates for Carbon Functional Units (see below).
Distance to port	Created by DeAngelo et al. (2023), original data interpolated to 1/12th degree (5 nm or ~10 km) resolution.	Inform emissions from marine transport.

4.2 Spatial parameters

In this section we describe how we use each of the spatial layers in the RSSM in general terms. For the technical description please see Section 5, *Model Equations*.

Bathymetry

Using the General Bathymetric Chart of the Oceans (GEBCO) layer of global elevations at 30 arc second (~1 km) resolution, we classified ocean depths into seven classes (Table 2) to inform both sequestration and artisanal aquaculture potential. We use the relative amount of abyssal vs. shallow depths in each ecoregion to condition sequestration rates, and the proportion of shallow bottom in each ecoregion as an indication of the feasibility for on-bottom farming.

Table 2: Spatial layers used to characterize the seaweed farming potential of 232 global marine ecoregions.

Class	Depth range (m)	Farm interactions
0	0 – 3	On bottom farm potential
1	3 – 10	Floating line region
2	10 – 30	Shallow floating rafts
3	30 – 50	Commercial floating rafts
4	50 – 200	Industrial floating rafts
5	200 – 500	Slope and deep on shelf areas
6	500 – 10977	Abyssal depths

Seaweed growth potential

Seaweed production at potential aquaculture sites depends on local environmental factors. We use global estimates of annual productivity for temperate brown, temperate red, tropical brown, and tropical red algae developed by Arzeno-Soltero et al. (2023). The model developed by Arzeno-Soltero et al. (2023) considers salinity, nutrient concentrations, temperature, and light availability among other factors to predict potential seaweed productivity in the global ocean at a resolution of 1/12th degree (5 nm or ~10 km).

To estimate productivity for each ecoregion, we calculated the average and standard deviation of the values for each species-group for each marine ecoregion and use these values to scale the growth rates of our species groups. For species not captured by the species groups (i.e., green seaweeds such as Ulva) growth rates were not scaled.

Nutrient loadings

We obtained anthropogenic nutrient loading data used by Theuerkauf et al. (2019) from the Data Basins website. This layer was developed by TNC using data from Green et al. (2004). We calculated the average and standard deviation of annual nutrient loadings within each ecoregion, and use this to quantify the potential annual drawdown by seaweed farms.

Sequestration

In their exploration of the limits to seaweed as a natural carbon solution, DeAngelo et al. (2023) explore the costs and benefits of actively sinking seaweed biomass to the deep ocean. For their analysis, they prepared spatial layers describing sequestration times at different depths based on the work of Siegal et al (2021). We obtained the layer describing the proportion of carbon sequestered for > 100 years from seaweed actively sunk to the seafloor below depths of 500 m, and combined it with depth classes from the global bathymetry to estimate the relative potential for sequestration from the intentional (deep) sinking of seaweed biomass across ecoregions. We did this by first estimating the proportion of deep shelf areas and abyssal depths for each ecoregion (Table 2), and then using the deviance of each ecoregion sequestration fraction from the global mean to scale the widely used DOC and POC passive export estimate from Krause-Jensen and Duarte (2016). To complete the calculation, we use an estimate of the emissions from intentional sinking of seaweed, and a user-specified distance from the farm(s) to nearest suitable location (i.e., with depths > 500 m).

In addition to estimating potential ecoregion-specific deep-ocean sequestration rates, we also estimate carbon sequestered in shallow coastal areas from passive (in situ) biomass loss according to the ecological functions within each ecoregion (see following section).

It must be noted that our sequestration rates are estimates of potential only, and that any actual seaweed sequestered will depend largely on the effectiveness of the very local conditions (e.g., currents, sediment type) where the seaweed biomass ends up.

Carbon functional units

Using the ecological functional groups defined by Keith et al. (2022), we defined 5 carbon functional units (CFUs, Table 3) to represent areas with distinct sequestration and ecosystem service potentials in each ecoregion. We presume the CFUs will have different nutrient dynamics based on their geophysical characteristics. Thus, farms in different CFUs will have different passive sequestration rates (i.e., Fraction DOC sequestered, fraction POC sequestered) and intentional sequestration potential (both at the farm site and in the deep ocean).

As the ecological functional groups (EFGs) proposed by Keith et al. (2022) are poorly delineated at regional extents, we defined them using available global maps of coastal vegetation (see below), estuaries, and estimates of bottom type. We obtained polygons (Table 1) describing the global distribution of mangrove, seagrass, and estuary data from the UN Environmental program data portal (https://data.unep-wcmc.org/). We used these data to measure the extents of the CFUs within each ecoregion. We then estimate the passive sequestration of POC and DOC for the specified farm based on the CFU where the farm is located, and the size of the CFUs in the ecoregion (see equations 7 through 12).

Bottom type

Bottom type is important to both farm siting and to coastal sequestration. However, global estimates of bottom type are both inaccurate and imprecise. For example, we examined the data made available by Frazier (2019) to support global assessments of cumulative impacts (Halpern et al. 2019). Through visual inspection we found the layers specified as rocky intertidal and intertidal mud to be identical. Nevertheless, the resolution of global layers is perhaps the greatest challenge for bottom type maps, as 10 km pixels will typically misrepresent bottom type close to shore, as they cannot capture the local influence of depth on substrate in coastal areas (Gregr et al. 2021). Users are thus asked to estimate the proportions of hard and soft substrate in the area of their farm, or their ecoregion of interest.

Table 3: Carbon functional units (CFUs) created by combining ecological function groups (EFGs) defined by Keith et al. (2022). We combined EFGs with similar carbon sequestration and inorganic nutrient and phosphorous drawdown characteristics in the context of seaweed farming and associated ecosystem services.

CFU	**Description/ relevant characteristics**	**Contained EFGs**
Estuaries and deltas	Subset of soft substrates with potential high nutrient loadings and human use. A common location for many seaweed farms around the world.	Open estuaries & bays River deltas[1]
Coastal vegetation	Areas of high potential detritus sequestration.	Seagrass meadows Intertidal forests & shrublands Saltmarshes & reedbeds
Soft subtidal substrates	Suitable for seaweed farm anchoring, with no impact on natural kelp forests. Higher potential for in situ carbon storage.	Subtidal sand beds Subtidal mud plains
Hard subtidal substrates	Areas more challenging for anchoring kelp farms, and that may have local, natural seaweeds potentially impacted by aquaculture.	Subtidal rocky reefs
Deep inlets and canyons	Areas of enhanced carbon sequestration potential, both on and off shelf, deeper than 500 m.	Deepwater inlets

1. While Keith et al. (2022) combine bays and estuaries into a single EFG, we note these two features can be quite distinct, particularly in arid areas (e.g., northern Australia). We suggest reviewing our assumptions about the role of estuaries when applying the RSSM in these contexts.

Distance to port

We used distance to port data from DeAngelo et al (2023), who generated port distances for a 10 km grid of the global ocean with data from Global Fishing Watch. We use the average and standard deviation of distance to port for each ecoregion to inform emissions from vessel travel and material or seaweed transport.

4.3 Seaweed production

Seaweed growth is a complex, dynamic process driven by numerous interacting factors including nutrients, light, temperature, salinity, and ocean currents. Production is therefore variable between species, locations, and times, in response to dynamic local conditions. This variability in productivity is challenging to represent in a global model, however its representation is important for generating realistic estimates of the potential yield from seaweed aquaculture.

Depending on the goal of any seaweed aquaculture study, two approaches for modelling growth are common in the literature. Several seaweed aquaculture models (including the first version of this model) treat seaweed productivity in a simplified way using fixed rates of production (e.g., Racine et al. 2021, Seghetta et al. 2016) or an annual harvest (e.g., Gao et al. 2021). In these models, seaweed production is not related to environmental conditions such as nutrient concentrations. Rather, seaweed growth is treated as uniform across the modelled area using species-specific values (or a distribution of values) obtained from the literature. While this approach allows for the use of productivity rates based in empirical data, and may account for general variability if a distribution is used, it cannot consider how this average productivity differs across space or time.

At the other end of the spectrum, complex seaweed growth models have been developed to represent seaweed growth in response to various interacting environmental conditions (Frieder et al. 2022, Hadley et al. 2015, Strong-Wright and Taylor 2022). These models consider changes in nutrient availability, temperature, irradiance, water flow, shading, and other factors. These complex models generally consider just a single species, operate on hourly or daily timesteps (allowing consideration of both diurnal and seasonal effects), and typically range in extent from a single individual to a defined geographic location (e.g., a bay or stretch of coastline).

Recent work also includes global estimates of potential productivity of temperate and tropical brown and red algae (Arzeno-Soltero et al. 2023) based on a global macroalgae growth model, and a habitat suitability approach to estimate the total global suitable area to seaweed cultivation (Liu et al. 2023).

4.3.1 Our approach

Working at an ecoregion scale means developing an approach to estimate average productivity in an ecoregion. Since building a global growth model is an ambitious undertaking beyond the scope of this project, we chose to proceed with the productivity estimates from Arzeno-Soltero et al. (2023). As the results of a well-developed growth model, we believed these productivity predictions to be more credible than the suitabilities calculated by Liu et al. (2023) where a single mean productivity value for each species was used globally.

We matched the taxonomic algal resolution (i.e., temperate brown, temperate red, tropical brown and tropical red) of the Arzeno-Soltero et al. (2023) productivities with specific seaweed species by classifying commonly cultivated species into larger taxonomic groups (Table 4), assuming similar growth characteristics. We then developed an approach that combined mean seaweed productivity (kg ww / m^2) for our species groups from the literature with average growth potential for each ecoregion calculated from Arzeno-Soltero et al. (2023).

Where multiple production values were available for a species group we defined a distribution to capture the inherent variability in productivity. To represent spatial differences in habitat suitability and growth conditions between ecoregions we scaled the literature-based productivity values using the relative growth potential from Arzeno-Soltero et al. (2023) (see *Model Parameters* for more information).

Although we recognize that substantial variability in seaweed productivity in response to local conditions within ecoregion will remain, the local variability cannot be captured using our approach. Nevertheless, we expect that the variability we have built in to the productivity and growth potential estimates captures much of this variability, although further investigation is warranted (see *Future Considerations*).

4.4 Nutrient drawdown

This ecosystem service was chosen as a prototype, to begin developing the model pathways for the wider range of services provided by seaweed farms. Our implementation focuses on the removal of anthropogenic nutrients (especially nitrogen but also phosphorous) and does not currently consider the role of natural nutrient loadings and re-circulation.

To estimate annual nitrogen drawdown, we used literature values of the proportion of N and P in farmed species and back-calculated drawdown from biomass harvested, yielding the mass of nitrogen extracted as part of the harvested biomass of the farmed species. The RSSM then reports the estimated nitrogen and phosphorus removed by farms, and the proportion of annual anthropogenic loadings removed (based on earlier work on anthropogenic loadings from the landscape by Green et al. (2004)).

Table 4: Commonly farmed species and their assignment to productivity groups defined by Arzeno-Soltero (2023). We used these groups to scale productivity according to predicted potential productivity values averaged for each ecoregion. Descriptions includes common names (also known as – aka) for some species.

Group	**Description**	**Productivity Group**
Eucheuma	e.g., *Kappaphycus alvarezii*, a species from a genus in the same family as Eucheuma. Aka lkhorn sea moss.	Tropical Red
Gracilaria	Aka agarophytes for their high agar content.	Tropical Red
Laminaria	Aka kombu, this group includes the Saccharina family ("sugar kelp") but we treat Macrocystis and Nereocystis separately.	Temperate Brown
Pyropia	Genus also called Porphyra. Aka nori. Found in intertidal and shallow waters.	Temperate Red
Sargassum	e.g., *Sargassum fusiforme*, aka hiziki. A sea vegetable native to rocky coastlines of East Asia.	Temperate Brown
Ulva	A marine and brackish water green algae, aka sea lettuce. Appears to be uniquely productive and is the most diverse in terms of farming methods.	Not scaled
Undaria	e.g., *Undaria pinnatifida*, aka wakame. Native to cold, temperate coasts of the northwest Pacific.	Temperate Brown
Macrocystis	While not common cultivars on a global scale, these canopy-forming species are of increasing interest for large-scale cultivation.	Temperate Brown
Nereocystis		Temperate Brown

4.5 Sequestration and the fate of seaweed

The topic of carbon sequestration is of increasing scientific and political interest in the face of anthropogenically forced climate change, and the emerging carbon credit economy. Sequestration (i.e., the storage of carbon in the ocean, either in sediments at depth or under farms) is an aspirational goal for many proponents of blue carbon seeking carbon credits for coastal communities. However, recent work (Bullen et al. 2023) suggests that the processing of seaweeds into replacements for traditional, more carbon intensive products may provide a much greater climate benefit by reducing future emissions. This approach also side-steps the challenging scientific questions of how much atmospheric carbon is drawn down and sequestered – that is removed from the atmosphere and stored for more than 100 years – by seaweed farming, the risks of extensive seaweed farming competing with phytoplankton for nutrients, and the potential for local impacts on coastal ecosystems (Berger et al. 2022, Wu et al. 2022).

Given the rapid evolution of seaweed farming, particularly in the developed North, we included a wide range of potential fates in the RSSM (Table 5). The fates include both existing and potential replacement products, reflecting the diversity of future seaweed products (e.g., Farghali et al. 2023). While the carbon and ecosystem service accounting for most of these products has yet to be completed, we include them and align the outputs and discussion in the model with “potential sequestration” in anticipation of the relevant data being available in the future.

Table 5: A description of the seaweed fates available in the model.

Model fate	**Description**
Food	Categories include not only foods for direct consumption such as protein and pulses and legumes (Blikra et al. 2021), but also as additives (e.g., emulsifiers and stabilizers - Leandro et al. 2020).
Feed	Seaweeds have the potential to be used in feed for ruminants (Morais et al. 2020), poultry (Michalak and Mahrose 2020) and aquaculture (Emblemsvåg et al. 2020).
Agriculture	Fertilizer and biostimulants (crop additives to promote health and productivity - Mukherjee and Patel 2020).
Biochar	As a form of charcoal, seaweed biochar is suitable for soil amelioration (Roberts et al. 2015) and wastewater treatment (Dang et al. 2023).
Biofuels	Seaweeds are increasingly considered suitable for the production of biogas and bioethanol (Nagula et al. 2022, Sharmila et al. 2021).
Plastics and food packaging	Seaweed alternatives to plastic coatings for food packaging, and as a replacement for pulp paper products (Carina et al. 2021, Perera et al. 2021, Shravya et al. 2021).
Cosmetics	Various compounds from seaweeds have been adopted by the cosmetic and skin care industries (López-Hortas et al. 2021).
Intentional sinking	The widely promoted idea of transporting kelp to the deep ocean.

Biomass left in situ	The biomass that is intentionally left at or near the farm, for sequestration and ecosystem nourishment.

4.6 The role of detritus

The role of detritus and the amount available for sequestration is sensitive to the distinction between natural and farmed systems, as it intersects with natural seaweed productivity and the re-cycling of particulate and dissolved carbon and nutrients by the associated invertebrate communities. Some of these associated species are largely absent from farmed systems, making farmed systems more closely connected to ambient nutrient concentrations. This means that the sequestration parameters estimated for natural systems are likely to underestimate the CO_2 and nutrient drawdown by aquaculture sites.

On the other hand, aquaculture systems typically harvest biomass following periods of high growth prior to senescence, while the life cycle for natural seaweeds includes periods of low growth and decomposition, potentially resulting in more detritus from natural systems. We therefore use the widely cited estimates from Krause-Jensen and Duarte (2016) for aquaculture export and sequestration rates with caution, as these do not consider of how seaweed farm siting, nutrient cycling, or biomass harvest may influence the reported rates.

While the potential contribution of DOC and POC to overall CO_2 sequestration is relatively small, these pathways are important for assessing the ecosystem services provided by seaweed aquaculture. The seemingly low importance and complexity of these detrital pathways have led to them being ignored or generalized by global models. However, the bioavailable forms of carbon and nitrogen in marine systems do determine the benefits and costs of a variety of ecosystem services. We therefore argue that a more explicit treatment of these pathways is warranted. Our approach is described along with the equations in the following section.

5 Model equations

5.1 Seaweed production

The model estimates production using a combination of literature-based production (i.e., harvest) rates (kg / m^2) and the results of a global seaweed growth and harvest model (Arzeno-Soltero et al. 2023).

We estimated global harvest rates for each seaweed group and farm type by aggregating values on reported farm growth rates from the literature. While we sought to distinguish growth rates by different farm types, the data were limited to the most common form of cultivation for each species (See *6. Model parameters* for details). Nevertheless, the model parameters distinguish the biomass available by species and farm type (e.g., Ba_Eucheuma_bottom).

This seaweed productivity (B_A) includes a standard deviation (B_{Asd}), and an uncertainty that follows a truncated normal distribution (constrained to be positive). To bound the regional scaling (described below) with reasonable values, we defined minimum and maximum values for (B_A) as (B_{Amin}) and (B_{Amax}). If data were unavailable we used the minimum and maximum values set at 3 standard deviations from the mean (roughly approximating a 99% confidence interval). (B_{Amin}) is constrained to be positive. All parameters are available on the editable parameter sheet accessible through the model interface.

This provides us with a truncated normal distribution of potential harvest defined in R as :

$$Tnorm(\,mean = \,B_A,\ \mathrm{sd} = \,B_{Asd}, \mathrm{min} = \,B_{Amin}, \mathrm{max} = B_{Amax}) \qquad \text{Equation 1}$$

We then calculate a scaling factor from harvest rates (tonnes DW / km^2) predicted by Arzeno Soltero et al. (2023) for each of the four seaweed groups (Table S2). Arzeno Soltero et al. calculated a mean and standard deviation for productivity for each group on a roughly 10 x 10 km^2 grid as a function of sea surface temperature, light availability, current velocities, and nitrate concentrations using a seaweed growth model (G-MACMODS). The biomass produced by the growth model was harvested using group-specific harvesting schemes, and potential harvest was then calculated for each pixel.

For each ecoregion we calculated a mean potential harvest (PH_E) and used this information to understand how 'good' an ecoregion is for growing seaweed of each type. For this, we extracted the global mean harvest (the mean of ecoregion means, PH_{Mean}) and the minimum and maximum mean harvest across all ecoregions (PH_{min} and PH_{max} respectively), excluding outlier ecoregions from the Arctic and Antarctic (Southern Ocean).

We then calculate, for each ecoregion, it’s productivity relative to the global maximum potential harvest (PH_{Quant}):

$$PH_{Quant} = \frac{PH_E}{PH_{Max}} \qquad \text{Equation 2}$$

We then scale the production rate of a given seaweed species according to the relative productivity of that ecoregion. Using the distribution defined in (Eq. S1), we ask what is the value associated with PH_{Quant}’s position in the distribution of literature-based values? For example, if PH_{Quant} is 0.6, then we look up the value for the 60th quantile in the truncated normal distribution defined by equation 1. We define this value as the scaled productivity rate (B_{A_scaled}), and use it to represent the mean productivity rate for the species group in that specific ecoregion.

Using this scaled value as the mean, we finally define a new distribution from which we sample the harvest:

$$Tnorm(\,mean = \,B_{A\_scaled},\ \mathrm{sd} = \,B_{Asd},\ \mathrm{min} = \,B_{Amin},\ \mathrm{max} = B_{Amax}) \qquad \text{Equation 3}$$

The standard deviation, minimum, and maximum values are unchanged from Equation 1. Note that the model also includes an option to ignore this ecoregion scaling and use provided parameter values as they are. Using this option is likely preferable when local values are available, as scaling would not be needed.

This approach, while somewhat complex, offers several advantages.

1. It is grounded in literature values rather than relying on coarse-scale, modelled harvest rates.
2. Harvest is allowed to vary within the min and max of the literature values according to estimates of relative global productivity.
3. Because the Arzeno-Soltero estimates have high variability, scaling relative to the maximum harvest predicted by Arzeno-Soltero et al. rather than the mean constrains the scaling multipliers to reasonable values.

5.2 Seaweed harvest

For a specific model configuration, the model samples a harvest rate for each species and farm type from the ecoregion-specific distribution (Equation 3) as:

$$B_{S,F} = B_{E,S,F} * A_{E,S,F} * H_{N,E,S,F} \qquad \text{Equation 4}$$

Where $B_{S,F}$ is the harvested seaweed biomass (kg ww / year) for a specified species and farm type, $B_{E,S,F}$ is the scaled, ecoregion-specific harvest rate (kg ww/m^2); $A_{E,S,F}$ is the total area farmed (m^2); and H_N is the number of harvests per year. Subscripts E, S, and F denote ecoregion, species, and farm type specific parameter values.

5.3 Detrital production and export

We begin with global carbon budget estimates from natural algal beds (Krause-Jensen and Duarte 2016). We adjust these global values using more specific data where available, and condition the values according to the Carbon Functional Unit (CFU) where the farm is located, and the amount of each CFU in the ecoregion (see Table 6 for a summary of the relevant equation parameters, Table 3 for details on CFUs, and Section 6.2 for the estimation of the CFU adjustment values).

Table 6: We estimate sequestration from detritus in two steps. First, we export the POC and DOC components from the farm and partition them into deep and on-shelf components. We then estimate sequestered proportions based on global sequestration rates, adjusted according to the proportion of different Carbon Functional Units within the ecoregion. Estimates from Krause-Jensen and Duarte (KJD) (2016) and others are used as noted.

Parameter	Description	KJD value	CFU scaling
$fPOC_{export}$	The fraction of POC and DOC lost from the algal bed by natural processes.	0.212	Unchanged from KJD
$fDOC_{export}$		0.233	Unchanged from KJD
$fPOC_{deep}$	The fraction of exported POC and DOC transported to the deep ocean by natural processes.	0.11	Unchanged from KJD, but scaled relative to the amount of the ecoregion that is > 500 m deep.
$fDOC_{deep}$		0.3	
$fPOC_{shelf}$	The fraction of exported POC that remains on the shelf.	0.189	Calculated for each simulation (1-$fDOC_{deep}$), then scaled relative to the amount of the ecoregion that is shallower than 500 m.
$fSeq\_POC_{sediment}$	The fraction of NPP sequestered as POC under the algal bed.	0.004	We replaced this KJD estimate with values based the CFU where farm is sited.
$fSeq\_POC_{shelf,CFU}$	The fraction of exported POC sequestered on the shelf, by CFU.	0.43	We replaced this KJD estimate with CFU-specific values based on the areal proportion of each CFU and its sequestration potential.
$fSeq_{deep}$	The fraction of biomass that, when sunk, is sequestered for at least 100 years, adjusted for each ecoregion.	0.10	We replaced this KJD estimate by the average sequestration value from Siegel et al. (2021) for the ecoregion.

5.4 Assumptions about seaweed sequestration pathways

Various assumptions were necessary to represent seaweed growth and sequestration pathways within the model. These assumptions apply to both detrital sequestration and intentional, passive sequestration.

We assume that the published estimates for seaweed harvest are net, and thus do not include detritus lost to DOC and POC during the growing period. We therefore calculate NPP as the sum of the harvested biomass and total detritus (DOC export, POC export, and POC sequestered in farm sediments).

We also use detrital export and sequestration rates from the literature, applying these rates from wild seaweed systems to aquaculture. This means assuming that farmed seaweeds prior to harvest lose the same proportion of DOC and POC as a natural system does over the course of a year. This ignores potential differences from farm siting, timing of harvest, and the potential for detritus recycling in natural systems. Further, we assume passive sequestration entails the release of seaweed biomass as only POC, thus ignoring the DOC pathway.

We base the spatial adjustments of the Krause-Jensen and Duarte (2016) numbers on the proportion of each CFU within an ecoregion. This assumes uniform mixing, and that detrital deposition in each CFU is primarily a function of the CFU's size. It also assumes that all areas within a CFU are equivalent in terms of sequestration potential. We believe these assumptions are nevertheless more tenable than those required for using global average values.

For sequestration in deep areas (> 500 m), we use the sequestration fraction from Siegel et al., (2021) made available by DeAngelo et al. (2023) and averaged for each ecoregion. It represents the proportion of biomass that is sequestered for > 100 years if sunk to the seafloor. This is somewhat different to detrital sequestration in deep water, which isn't necessarily sunk to the seafloor, but is assumed to be a good proxy.

5.5 Detrital pathways

Because our seaweed production is expressed as harvest rather than net productivity, we first back-calculated net primary productivity (NPP) as the sum of the harvested biomass, the DOC exported, the POC exported, and the POC buried:

$$NPP = \frac{B_{S,F} * DW_S * fC_S}{1-(fDOC_{export}+fPOC_{export}+fSeq\_POC_{sediment})} \qquad \text{Equation 5}$$

Where NPP is in kg C; and $B_{S,F}$ is the harvested wet weight biomass for a given seaweed species (S) and farm type (F) . DW_S and fC_S are species-specific conversion factors for wet to dry weight and dry weight to carbon, respectively, used to convert seaweed biomass to units of carbon. The denominators are defined in Table 6.

Detrital sequestration in farm sediments

We then calculate drawdown of atmospheric carbon from the POC sequestration in farm sediments as

$$Seq_{sediment} = NPP * fSeq\_POC_{sediment} * K_{C.CO2} * K_c \qquad \text{Equation 6}$$

Where $Seq_{sediment}$ is in kg CO_2; $K_{C.CO2}$ is the carbon to CO_2 conversion factor (kg CO_2/kg C); and K_c relates carbon sequestered to atmospheric drawdown of CO_2. $fSeq\_POC_{sediment}$ is defined in Table 6 and varies by CFU.

Detrital sequestration in the deep sea

We estimate the proportion of exported DOC and POC sequestered in the deep sea by considering the proportion of the ecoregion classified as deep (below 500 m). This approach, common with global models, assumes uniform mixing of global oceans. We first calculate the DOC and POC exported to the deep sea as:

$$DOC_{deep} = NPP * fDOC_{export} * fDOC_{deep} * \frac{fDeep_{Ecoregion}}{fDeep_{Global}} \qquad \text{Equation 7}$$

$$POC_{deep} = NPP * fPOC_{export} * fPOC_{deep} * \frac{fDeep_{Ecoregion}}{fDeep_{Global}} \qquad \text{Equation 8}$$

Where DOC_{deep} and POC_{deep} are in kg C; $fDeep_{Ecoregion}$ is the fraction of the ecoregion area that is deep sea; and $fDeep_{Global}$ is the average fraction of all ecoregions (globally) that is deep sea. This ratio scales the export of DOC and POC to the deep sea according to the proportion of the ecoregion that is deep. $fDOC_{export}$, $fPOC_{export}$, $fDOC_{deep}$ and $fPOC_{deep}$ are defined in Table 6. DOC_{deep} and POC_{deep} are constrained such that they are not allowed to be greater than the exported DOC and POC (e.g., $NPP * fDOC_{export}$)

We then calculate the atmospheric carbon removed by DOC and POC sequestration in deep waters and sediments as:

$$SeqDOC_{deep} = DOC_{deep} * fSeq * K_{C.CO2} * K_c \qquad \text{Equation 9}$$

$$SeqPOC_{deep} = POC_{deep} * fSeq * K_{C.CO2} * K_c \qquad \text{Equation 10}$$

Where $SeqDOC_{deep}$ and $SeqPOC_{deep}$ are in kg CO_2; $fSeq$ is the average fraction of carbon that is sequestered for > 100 years in deep waters; $K_{C.CO2}$ and K_c are defined for Equation 6; and DOC_{deep} and POC_{deep} are as calculated in Equation 7 and 8.

$fSeq$ is a spatially explicit value from Siegel et al. (2021) describing the fraction of carbon sequestered when organic biomass is sunk to the seafloor. We calculated the average and standard deviation of this fraction for each ecoregion to allow this variable to vary spatially.

Detrital sequestration on the shelf

We estimate the POC remaining on the shelf as the exported POC that did not make it to the deep sea:

$$POC_{shelf} = \left(NPP * fPOC_{export}\right) - POC_{deep} \qquad \text{Equation 11}$$

Where POC_{shelf} is in kg C. All other parameters are defined above.

We then calculate the atmospheric carbon sequestered by POC on the shelf as:

$$SeqPOC_{shelf} = (\sum_{i=1}^{4} POC_{shelf} * fCFU_i * fSeq_{CFU}) * K_{C.CO2} * K_c \qquad \text{Equation 12}$$

Where $SeqPOC_{shelf}$ is in kg CO_2 and the sequestration within each CFU in the ecoregion are calculated separately with $fCFU$ being the proportion of each of the 4 shelf CFUs (Vegetated, Estuaries, Soft, and Hard) within the ecoregion, and $fSeq_{CFU}$ the fraction of carbon sequestered by each shelf CFU. POC_{deep}, $K_{C.CO2}$, and K_c are defined above.

5.6 Intentional sequestration and product replacement

These pathways relate to the fate of harvested biomass and are split into active sequestration, passive sequestration, and replacement products. All sequestration and product replacement values are calculated in units of kg CO_2.

Active sequestration

$$C_{Seq.A} = \sum_i (B_s * DW_S * fC_S) * fSeq * K_{C.CO2} * K_c \qquad \text{Equation 13}$$

Where B_s is the harvested biomass of each species directed towards active sequestration (kg /year); DW_s is the wet-weight to dry-weight conversion of species s (kg dw / kg ww); and fC_s is the carbon content of species s (kg C / kg dw). $fSeq$, $K_{C.CO2}$, and K_c are defined above.

Passive sequestration

Passive sequestration is calculated according to the detrital sequestration pathways described above (equations 6 through 12). We assume here that all seaweed biomass for passive sequestration is released as POC. It is thus distinct from detritus as it does not include DOC.

Replacement products

The use of seaweed products as alternatives to traditional products such as food, animal feed, or fuels results in the avoidance of carbon emissions associated with the production of these traditional products. We calculated these avoided emissions as:

$$C_{Avoid} = \sum_{s,j} B_s * DW_s * fRep_{s,j} \qquad \text{Equation 14}$$

Where $FRep_{s,j}$ is a carbon replacement factor relating the carbon emissions avoided for each kg DW of seaweed species s and product j (kg CO_2/kg dw). B_s and DW_s are defined above.

5.7 Emission pathways

All emissions values are calculated in units of kg CO_2.

Nursery

This pathway captures the emissions from the operation of a nursery to produce seeded line or other forms of propagules for seaweed production. We assume that the majority of these emissions are due to energy use, thus:

$$E_{Nurs} = NRG_{Nurs} * A * E_{Nrg} \quad \text{Equation 15}$$

Where NRG_{Nurs} is the annual energy required to run the nursery to produce propagules for a given area (GWh / km^2 / year); A is the total area used for seaweed production (km^2); and E_{Nrg} is the emissions from energy production (kg CO_2 / GWh). E_{Nrg} varies depending on the energy source specified by the user, and some forms of aquaculture may not require nursery emissions.

Capital infrastructure

We calculated capital emissions from the production of the materials needed as part of the capital investment in a seaweed farming operation as:

$$E_{Cap} = E_{Mat} * A \quad \text{Equation 16}$$

Where E_{Mat} is the average emissions associated with the material required by a square kilometre of seaweed aquaculture (kg CO_2 / km^2); A is the total area used for seaweed production (km^2). E_{Mat} is allowed to vary by farm type.

Material transport

We calculated emissions from the transport of material (e.g., ropes, anchors, buoys, etc.) to and from the site of seaweed aquaculture from the nearest port as:

$$E_{Mat.Trans} = M_{Mat} * H_N * A * E_{Barge} * 2 * D_{Port} \quad \text{Equation 17}$$

Where M_{Mat} is the mass of equipment required for each km^2 of seaweed harvested (kg / km^2); H_N is the number of harvests per year; A is the total area used for seaweed production (km^2); E_{Barge} is the emissions from transporting one kg of equipment one kilometre by barge (kg CO_2 / kg / km); and D_{Port} is the distance from the port to the site of farming (km). Some forms of aquaculture (e.g., intertidal or shallow subtidal farm types) may not require any material transport.

Maintenance

We calculated emissions due to maintenance of the seaweed farm as:

$$E_{Maint} = \left(\left(2 * D_{Port} * E_{Ves} * \frac{A}{A_{Maint}}\right) + (A * D_{Maint} * E_{Ves})\right) * N_{Maint} * H_N \qquad \text{Equation 18}$$

Where D_{Port} is the distance from the port to the site of farming (km); E_{Ves} is the emissions from a maintenance vessel travelling one kilometer (kg CO_2 / km); A_{Maint} is the area maintained per trip (km^2); A is the total farmed area (km^2); D_{Maint} is the distance travelled per km^2 maintained (km / km^2); N_{Maint} is the number of maintenance trips required per harvest; and H_N is the number of harvests per year. In this equation the first part calculates the travel to and from the farm, the second portion calculates the travel at the farm, and the third portion scales this with the number of maintenance trips and harvests per year. As with material transport, this may not be required by some types of farms.

Active sequestration

Emissions from active sequestration of seaweed include emissions due to transporting seaweed to the optimal sinking location and the sinking process itself. We calculated this as:

$$E_{Seq} = (B_S * E_{Barge} * D_{Sink}) + (B_H * E_{Sink}) \qquad \text{Equation 19}$$

Where B_S is the harvested seaweed biomass directed to active sequestration (kg ww / year); E_{Barge} is the emissions from transporting one kg of equipment one kilometer by barge (kg CO_2 / kg ww / km); D_{Sink} is the distance from the farm to the location of sinking (km); and E_{Sink} is the emissions generated during the process of sinking the seaweed (kg CO_2 / kg ww).

Seaweed transport

To produce seaweed products the harvested seaweed must be transported to the nearest port or processing location. We calculated these transport emissions as:

$$E_{SW.trans} = B_S * E_{Barge} * D_{Port} \qquad \text{Equation 20}$$

Where B_S is the harvested seaweed biomass directed towards processing (kg ww/ year); E_{Barge} is the emissions from transporting one kg of equipment one kilometre by barge (kg CO_2 / kg ww / km); and D_{Port} is the distance from the port to the site of farming (km). As with material transport, some types of aquaculture may not produce these emissions.

Seaweed processing

Once at port the processing of seaweed into products will also entail greenhouse gas emissions. In the absence of data on emissions associated with different potential products, we calculated these emissions simply as:

$$E_{Proc} = \sum_j B_S * E_{Conv} \qquad \text{Equation 21}$$

Where B_S is the harvested seaweed biomass directed towards product j (kg ww/year); and E_{Conv} is the emissions released from converting seaweed into product j (kg CO_2 / kg ww).

5.8 Nutrient removal

Using data on the nitrogen and phosphorous content of commonly farmed seaweed species, we estimate the mass of nitrogen and phosphorous that would be removed by the specified seaweed aquaculture scenario. We also calculate the portion of annual loadings within the ecoregion that would be mitigated by the aquaculture scenario. This nutrient removal potential is based on earlier work on global anthropogenic loadings from the (Green et al. 2004). For those ecoregions where the change in loadings (from pre-industrial fluxes) are reported as negative or were not assessed due to insufficient data, we treat them as 0.

The effects of increased nutrients on seaweed growth are accounted for by the seaweed growth model (Arzeno-Soltero et al. 2023) we use to adjust the productivity in each ecoregion. We do not consider how nutrient depletion by aquaculture may influence growth rates.

We calculate the removal of nitrogen and phosphorus from water as:

$$N_{Removed} = \sum_s B_S * DW_S * fN_S \qquad \text{Equation 22}$$

$$P_{Removed} = \sum_s B_S * DW_S * fP_S \qquad \text{Equation 23}$$

Where $N_{Removed}$ and $P_{Removed}$ are in units of kg. B_S is the harvested biomass of each species (kg ww / year); and fN and fP are the content of nitrogen and phosphorus in seaweed (kg N or P / kg DW). DW is defined above. DW, fN, and fP vary by species group.

The total amount of nitrogen removed is also reported as a percentage of the annual anthropogenic nutrient loading for the selected ecoregion.

6 Model parameters

We updated model parameters for nutrient content and production with additional information found by TNC (Ruff 2023). These are described below. The majority of model parameters, including downstream product emissions and replacement products, were updated as part of this work, and used in the BC version of the model (Bullen et al. (2023).

6.1 Nutrient content and production

Seaweed nutrient content data were collected by Ruff (2023) from 27 sources across the seven most commonly harvested species groups (Eucheuma, Gracilaria, Laminaria, Pyropia, Sargassum, Ulva, and Undaria). We calculated a mean and standard deviation for groups with sufficient sample size (Table 7) and used the grand means for Macrocystis and Nereocystis.

Table 7: Updated nutrient content parameters (as % content) for the 9 species groups in version 2 of the model including mean Carbon (C), Nitrogen (N), Phosphorus (P) and wet-to-dry ratio (WTD) values and their standard deviations (SD), where sufficient data were available.

Group	**C**	**SD**	**N**	**SD**	**P**	**SD**	**WTD**	**SD**
Eucheuma	30.66	4.62	0.66	0.16	1.4475	1.80	--	--
Gracilaria	29.82	1.74	3.67	0.69	0.3775	0.31	7.18	1.72
Laminaria	28.91	4.44	2.57	1.21	0.35	0.23	7.71	3.07
Pyropia	33.18	5.31	5.11	1.52	0.57	0.29	4.07	3.60
Sargassum	31.06	3.22	2.49	0.93	0.20	0.09	8.50	0
Ulva	36.29	8.38	3.18	0.87	0.33	0.23	4.50	0
Undaria	29.16	1.53	3.01	0.83	0.28	0.28	5.00	0
Macrocystis	31.33	4.18	2.96	0.887	0.508	0.461	6.16	1.40
Nereocystis	31.33	4.18	2.96	0.887	0.508	0.461	6.16	1.40

For production rates we sought information on our six different farm types but only found parameters for submerged lines (Ruff 2023), for four species groups (Table 8). We therefore used the submerged lines parameters for all farm types. We retained the global value for Nereocystis for both Nereocystis and Macrocystis (floating lines) from Bullen et al. (2023), and used the Laminaria values for the remaining species groups.

Table 8: Production data found for four species groups farmed using submerged lines, and values retained from Bullen et al. (2023) for Macrocystis and Nereocystis (floating lines).

Group	**Kg DW/ m^2**	**SD**	**# of harvests**	**Source**
Eucheuma	0.34	0	5	Ruff 2023
Gracilaria	4.54	1.04	--	Ruff 2023
Laminaria	1.28	1.77	1	Ruff 2023
Pyropia	0.00164	0	--	Ruff 2023
Sargassum	1.28	1.77	1	Laminaria used
Ulva	1.28	1.77	1	Laminaria used
Undaria	1.28	1.77	1	Laminaria used
Macrocystis	8.3	5.9	1	Bullen et al. 2023
Nereocystis	8.3	5.9	1	Bullen et al. 2023

6.2 Carbon functional unit scaling

The numbers from Krause Jensen and Duarte (2016) provide global average for natural systems. Regionally, it is reasonable to expect these numbers to deviate from this global mean according to the local ecosystems. For example, we expect farms located in or near highly depositional environments like the Coastal Vegetation CFU (which includes seagrasses, mangroves, and saltmarshes) to sequester more, and farms sited in hard-bottom environments to sequester less than the global average. These adjustments are described below.

$fSeq\_POC_{sediment}$

This parameter describes the fraction of POC released from the farm that is sequestered at or near the farm site. Measured as a proportion of NPP, Krause Jensen and Duarte (2016) estimated that 0.4% of NPP from wild macroalgae is sequestered under the kelp bed. Additional information (Duarte et al. 2023) allowed us to estimate sequestration rates for the **Soft Subtidal substrates** and **Hard subtidal substrates** CFUs. Duarte et al. (2023) examined 20 operating farms and found CO_2 sequestration under the farms to be highly variable. Using the ratio of reported excess CO_2 removal and farm yield, we calculated a mean under-farm sequestration of 1.2%, with farms ranging from 0 to 6.8% of the NPP. We found the farms identified to be over coarse substrate (N=2) to have had a mean sequestration rate of 0.23% (N=2), while farms over soft sediments sequestered on average 1.6% harvested biomass (N=7).

To bridge the gap between unrealistic global averages and undescribed local sequestration processes, we combine the above data with the characteristics of the CFUs to generate estimates around the Krause-Jensen and Duarte (2016) baseline (Table 9).

Table 9: Fractional sequestration rates for sediments under farms, and for exported, on-shelf sequestration for coastal Carbon Functional Units (CFUs). Krause Jensen and Duarte (2016) (KJD) estimates are shown for reference. The triplet values represent the minimum, mean, and maximum values.

CFU	$fSeq\_POC_{sediment}$	$fSeq\_POC_{shelf}$
KJD	0.004	0.049
Soft subtidal substrates	0.004, 0.012, 0.016	0.04, 0.12, 0.16
Hard subtidal substrates	0.0023, 0.004, 0.006	0.023, 0.04, 0.06
Estuaries and deltas	0.004, 0.012, 0.016	0.04, 0.12, 0.16
Deep inlets and canyons	0.002, 0.006, 0.008	Ecoregion specific
Coastal vegetation	0.016, 0.024, 0.033	0.16, 0.24, 0.33

For **Soft Subtidal substrates** we constructed a triangular distribution using the Krause-Jensen and Duarte (2016) baseline (0.004) as the minimum, the Duartes et al. (2023) overall mean (0.012) as our mean, and their average farm sequestration over soft substrates (0.016) as our maximum. For **Hard Subtidal substrates** we used Duartes et al.'s (2023) mean farm sequestration over hard substrates (0.0023) as the minimum, the Krause-Jensen and Duarte (2016) baseline (0.004) as the mean, and 1.5 x this value as the maximum.

Work on tidal flats and estuaries shows that the considerable carbon stored in these areas is mostly from terrestrial detritus (Krauss et al. 2018). However, to allow for some increased deposition in these often vegetated, soft-bottom ecosystems, we assigned the **Estuaries and deltas** CFU the same values as the Soft Subtidal sediments CFU. With no specific data on the sequestration of POC from seaweed farms over **Deep Inlets and canyons**, we assumed farms in this CFU would sequester half as much POC as farms over Soft subtidal substrates (Table 9).

$\boldsymbol{fSeq\_POC_{shelf}}$

Krause Jensen and Duarte (2016) estimated that 4.9% of the POC exported beyond the farm but retained on the shelf was sequestered on the shelf. This number is supported by Queros et al. (2019) who reported that 4-9% of the macroalgal POC lost as detritus from coastal kelp forests was deposited in soft sediments at a depth of 48 m, 13 km from shore. The estimate of 4.9% from Krause Jensen and Duarte (2016) is about 12 times their estimate of what is sequestered under kelp forests. This difference between under-farm and on-shelf sequestration is a reflection of the much larger size of the shelf compared to the typical extents of kelp forests.

To estimate the sequestered fraction of seaweed exported from farms but retained on-shelf, we multiplied the under-farm estimates for the **Soft and Hard subtidal substrates**, and the **Estuaries and Deltas** CFUs by a factor of 10 to reflect the difference reported by Krause Jensen and Duarte (2016). For the **Deep inlets and canyons** CFU we used the sequestration value calculated for the ecoregion based on work by Seigel et al. (2021) (see 4.2 *Spatial Parameters*).

Coastal Vegetation CFU

Macrophyte contributions to sediments in the ecosystems within the **Coastal vegetation** CFU are likely much higher than those in other ecosystems, as the vegetation appears to be very effective at retaining POC. For example, Ortega et al. (2020) found that in seagrass meadows and mangrove forests, macrophytes were found to comprise 33% of the sediment eDNA. Our assumption of uniform mixing on the shelf thus allowed us to assume that as much as 33% of the seaweed exported from farms, retained on-shelf, and transported to this CFU would be sequestered (in the seagrass or mangrove standing stock).

We thus used this value (0.33) as the maximum of our triangular distribution for our estimate of $fSeq\_POC_{shelf}$ in this CFU. We used the maximum value from the Soft subtidal substrate CFU (0.16) as the minimum value, and the midpoint between them (0.24) as the median value. In keeping with our approach of using the ratio of Krause Jensen and Duarte (2016) under-farm and on-shelf estimates, we reduced these values by one-tenth to define our triangular distribution for under-farm sequestration ($fSeq\_POC_{sediment}$) for farms in this CFU (Table 9).

7 Model performance and testing

As an initial test of the performance of the RSSM, we compared it to the well-validated version 1 of the model (Bullen et al. 2023). We did this by configuring three scenarios in the RSSM that mimicked the Local-No Harvest, Expanded, and Techo-industrial scenarios used the assess the feasibility of seaweed farming as a natural climate solution in British Columbia, Canada.

We found that across the three scenarios, harvested biomass matched well between the two models, as did our estimates of net primary productivity (after we ensured correspondence of several parameters including the dry weight and carbon content of the harvested species). As the first model version did not include ecoregion productivity scaling, it was also necessary to run the second model with this functionality turned off.

Examining the correspondence of total detrital sequestration (termed passive sequestration in version 1) was more challenging as the treatment of DOC and POC has been revised substantially. Specifically, detrital sequestration is now more appropriately divided between below-farm sediments, on-shelf deposition, and export to the deep ocean. Additionally, we scale the first two pathways by CFU, and use a value from Siegel et al. (2021) to estimate the proportion of exported detritus sequestered in the deep ocean. This is particularly relevant for the BC model for which we used the Puget Trough/Georgia Basin ecoregion, for which the fraction that is deep is very small. By reconfiguring the RSSM to mimic how version 1 treated detrital sequestration (including setting the farm and deep sequestration to 0), the shelf sequestration from the RSSM was comparable to that from v1. Notably, the RSSM only sequestered POC (not DOC) on the shelf (under the assumption that shelf DOC is remineralized), meaning that version 2 sequesters about 50% of the carbon as version 1.

We found generally good agreement in the emissions numbers, with differences attributable to how transport-related emissions are handled in the two models: in versions 1 we used a weighted average of all ports in the region, while the RSSM uses the average ecoregion value from the global spatial layer. Carbon sequestration also showed generally good agreement with the exception of biomass left in-situ because of the same challenges as detrital sequestration described above. We found the avoided emissions from products to be very similar, as these pathways were not materially changed between the model versions.

This performance assessment gives confidence that the refinements made to the RSSM maintained the credible performance of version 1 with a more realistic model structure. Recommended next steps for model validation include a formal testing program with a collection of farms in different ecoregions, with different farmed configurations and species.

8 Future considerations

A critical next step is the field testing of the RSSM to see how well the predictions match available observations. We hope to work with the TNC seaweed community to develop a robust testing plan, which will also lead to improved model parameterization.

The model is configured to allow for differences between species, farm types, and replacement products. However, in practice a lack of data means these differences have not been parameterized and the model thus does not distinguish between these factors. As new information becomes available it will be important to regularly update the model parameters to improve the accuracy of the model estimates.

For industrial-scale operations, details on the emissions arising from the different energy sources are likely to influence the carbon budget and should probably be considered.

We obtained all coastal vegetation data from https://data.unep-wcmc.org/. Additional relevant global data (e.g., tidal flats, kelp forests) may also be available and should be considered for future upgrades.

The Estuaries CFU includes embayments that may not be captured by global data of estuaries and deltas, particularly in more arid regions (e.g., Marlborough Sound, New Zealand). Suitable layers describing such features would improve the representativity of this CFU.

Production rates could be scaled based on the CFU in which a farm is located. As most seaweed growth is nutrient limited (Duarte 1992), seaweed grown in areas with higher nutrient loadings such as estuaries may have higher productivity. Exploring the relationship between nutrient loadings (Green et al. 2004) and productivity potential (Arzeno-Soltero et al. 2023) could provide some insight. For large-scale operations, it will also be important to consider the competition of seaweed farms with natural systems including phytoplankton.

The role of depth on farm type could be used to constrain the suitability of ecoregions to different types of seaweed cultivation (e.g., on-bottom farming is limited to the 0 to 3 m depth range). This will become increasingly important as production increases.

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