Considerations for Regional Simulations of Seaweed Carbon Dioxide Removal

ARPA-E Seaweed CDR Project (UCSB, WHOI, UCLA)

Daniel Dauhajre[1], Tom Bell[2], and David Siegel[3]

[1]Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles
[2]Department of Applied Ocean Physics & Engineering, Woods Hole Oceanographic Institution
[3]Department of Geography, University of California, Santa Barbara

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Abstract

There is a growing interest in sequestering carbon dioxide via cultivation and sinking of seaweed in the ocean. Robust quantification of the viability of this marine carbon dioxide removal (mCDR) strategy requires deployment and interrogation of computer simulations that resolve coupling between turbulent oceanic circulation, biogeochemical fluxes, and cultivated seaweed with regional granularity. This white paper describes considerations that inform the design of a virtual mCDR experiment in the Southern California Bight (SCB) that targets globally meaningful scales of CDR. For the SCB, we define an array of farm elements that share design features with present-day farms (*e.g.,* cultivation on long-lines), but are approximately O(1000) times larger in area. The simulated farm area is based on an assumption of a biomass yield that is 5× more efficient than present day farms, and the number of farms is chosen to meet a regional CDR target of approximately 0.01 Gt CO_2 / year ($\sim$ 10% of the global mCDR target). The placement of the farms in the SCB for the virtual mCDR experiment is guided by model constraints, anticipated nutrient availability, an assumption of local seaweed sinking in deep water, and avoidance of human conflict zones.

1 Introduction

The meaningful execution of marine carbon dioxide removal (mCDR) via seaweed cultivation and sinking requires massive scales that limits the capacity of in situ experiments to diagnose efficacy at the appropriate scales. Instead, simulations that resolve interactions between ocean circulation, biogeochemistry, and seaweed represent the most immediate and powerful tool to diagnose the viability of seaweed mCDR at globally relevant scales (defined below). This modeling exercise requires consideration of technological, oceanographic, and socio-economic factors to inform an appropriate experimental design.

This document defines parameters and scenarios for the purposes of designing a virtual seaweed mCDR experiment in the Southern California Bight (SCB) with a biophysically coupled modeling system. The modeling system deployed for this purpose, detailed in a companion white paper, simulates interactions between regional circulation (ROMS; Shchepetkin and McWilliams (2005)), biogeochemistry and ecosytem dynamics (BEC; Deutsch et al. (2021)), and cultivated macroalgae (MAG; Frieder et al. (2022)). Here, we provide an estimate of globally significant mCDR scales (Sec. 2) to guide choices of the size and number of macroalgal farms in the SCB modeling domain (with *Macrocystis sp.* as the target species for cultivation). Sec. 3 establishes farm element definitions based on present day farm design and defines a 'future' farm element to simulate the desired biomass yield defined in Sec. 2. Finally, we define a preliminary experimental design for the SCB (Sec. 4) based on model constraints (*e.g.*, domain boundaries and computational costs), nutrient availability, environmental stressors, and human conflict zones.

2 Required Scales for Meaningful Seaweed mCDR

The modeled regional CDR system is intended to make a meaningful contribution to global C sequestration. Chapter 5.3 of National Academies of Sciences, Engineering, and Medicine (2022) define 'meaningful contribution' as 0.1 Gt CO_2 /year (0.0273 Gt C / year) over a time scale of 100 years. National Academies of Sciences, Engineering, and Medicine (2022) also provides an estimate for the required total farm area (A_{globe}) to achieve this sequestration goal:

$$A_{globe} = \frac{NPP_{farm}}{\text{Yield} \times C_{content} \times N_{crop}} , \tag{1}$$

where NPP_{farm} is the net primary production of the farm(s), Yield the expected biomass density [g dry m^{-2}], $C_{content}$ [g C] the carbon content of the yield, and N_{crop} the number of crops per year that can be grown and sequestered. Following National Academies of Sciences, Engineering, and Medicine (2022), assume a maximum yield of 1 kg dry / m^2 and 30 percent of dry weight is carbon biomass ($C_{content}$) with 1.5 crops per year N_{crop}. These estimates give a required total farm are $A_{globe} \approx 73,000$ km^2.

We now assume that there are 10-15 regional arrays across the globe that comprise the required 73,000 km^2. This implies a single regional farm array of area $\approx 5000 - 8000$ km^2. This gives, for example, a regional array of approximately $7 - 11$ farms, each with area (27×27) km^2. However, as described below, this scale is not feasible with today's farming practices. So, we will assume that farms ~ 30 years from now can function at the scales required ($O([10 \times 10]$ km$^2))$ to make a dent in global atmospheric CO_2 levels.

3 Farm Element Definitions

We define a single farm element based on the design of present day farms (Fig. 1-2), under a heavy assumption that this design will be implemented in future, larger-scale farms. In practice, most 'farms' consists of $N_{element}$ single elements placed next to each other (*e.g.*, Fig. 2).

A single farm element is defined as an enclosed area of dimensions L_x, L_y [m] with area $A_F = L_x L_y$ [m^2]. The farm element contains n_l long-lines oriented in the same direction. The long-line orientation can extend along the longest dimension L_y (Fig. 1) or shortest L_x (Fig. 2). Each long-line is assumed to contain n_c seed (cultivation) points. Each long-line $i = 1..n_l$ sits at a cultivation depth h^i_{cult} [m], that is assumed uniform for all cultivation points $j = 1..n_c$ on that long-line. The cultivation points are separated by a distance S_c [m] and long-lines separated by a distance S_l [m].

A limiting aspect of farm placement is the required scope for mooring lines to anchor the farm (Fig. 1). We define this scope as S_m. S_m needs to be $\approx 3\times$ the water depth (H; personal communication, Javier Infante, Ocean Rainforest). The large scope required by the mooring lines restricts the placement of multiple farm elements within a confined area. The proposed Avalon Ocean Farm (AOF) has a less restrictive mooring line design (Fig. 2).

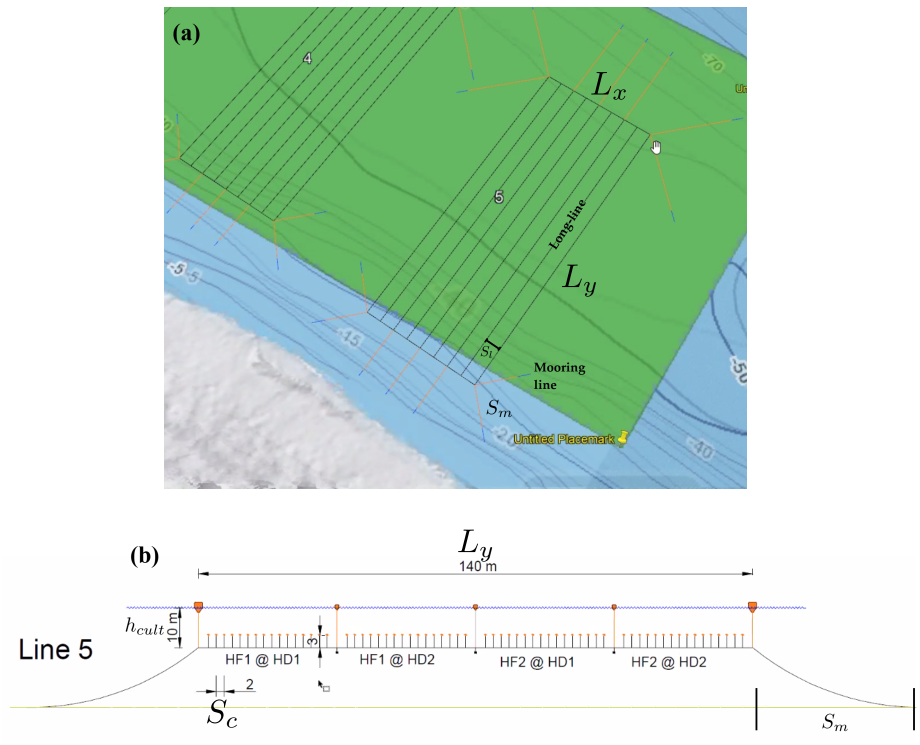

Figure 1: Example of single farm elements with dimensions indicated. (a): top view of two single farm elements with long-lines and mooring lines indicated on the right-most element. (b): cross-sectional view across a single long-line showing spacing between cultivation points S_c and cultivation depth h_{cult}. The Ocean Rainforest Farm (ORF) utilizes this design, with long-lines running parallel to the long dimension L_y. This can be contrasted with the design proposed by Avalon Ocean Farm (AOF, Fig. 2). Original schematics courtesy of Javier Infante, Ocean Rainforst.

Variable(s)	Description	Units
$N_{element}$	number of farm elements	
L_x, L_y	horizontal farm dimensions	m
A_F	farm area	m^2
n_c	number of cultivation points	
n_l	number of long-lines	
h_{cult}	cultivation depth	m
S_c	distance between cultivation points	m
S_l	distance between long-lines	m
S_m	scope for mooring lines	m
H	water depth	m
A_{tot}	farm footprint	m^2
β_x, β_y	mooring line scope coefficients	
R_F	ratio of farmed versus un-farmed area over A_{tot}	
$B_{max,line}$	maximum seaweed carrying capacity per meter of long-line	kg wet/m
$B_{max,F}$	maximum seaweed carrying capacity of a farm element	kg wet/m
$C_{content,F}$	maximum C content of a farm element	g C
E_F	farm efficiency	

Table 1: Farm element variable symbols, descriptions, and units.

An approximation of the total footprint for a single farm element A_{tot} can be given by:

$$A_{tot} = (L_x + \beta_x S_m)(L_y + \beta_y S_m) \; . \tag{2}$$

Where $\beta_x, \beta_y \in [0, 2]$ are coefficients that determine the space taken up by the mooring lines. For example, if $\beta_x = \beta_y = 2$, this implies that the mooring lines extend perpendicular from each side of the farm element.

The approximate ratio of farmed versus un-farmed area for a single farm element is then:

$$R_F = \frac{A_F}{A_{tot}} \; . \tag{3}$$

We define a maximum carrying capacity of seaweed per meter of long-line as $B_{max,line}$ [kg wet/m]. For *macrocystis p.*, this has been reported to be $\approx$ 25 [kg wet/m], and can reach as high as $\approx$ 80 [kg wet/m] (personal communication, Javier Infante, Ocean Rainforest).

The maximum carrying-capacity of a single farm element is then:

$$B_{max,F} = B_{max,line} L_y n_l \; , \tag{4}$$

if the long-lines run parallel to L_y (Fig. 1), or

$$B_{max,F} = B_{max,line} L_x n_l \; , \tag{5}$$

if the long-lines run parallel to L_x (Fig. 2). Assuming that the long-lines fill the farm end-to-end, the maxium carrying capacity is more generally defined for either long-line orientation as:

$$B_{max,F} = B_{max,line} \frac{L_x L_x}{S_l} \; . \tag{6}$$

The definition of $B_{max,F}$ assumes that the reported $B_{max,line} \approx 25$ kg wet/m stands for some small spacing between cultivation points ($S_c \approx 1 - 2$ m). That is, we expect $B_{max,line}$ to decrease for larger S_c. For now, we do not consider S_c in estimates of farm yield (Table 2).

We can define the maximum C content $C_{content,F}$ [g C] of the farm as

$$C_{content,F} = B_{max,F} \times 0.094 \times 0.3 \,, \tag{7}$$

where we assume a wet to dry conversion of 0.094 and 30 percent of dry weight is carbon biomass (Rassweiler et al., 2018; National Academies of Sciences, Engineering, and Medicine, 2022). Finally, we define a 'farm efficiency' of maximum C yield E_F [g C m^{-2}] relative to the total farm footprint:

$$E_F = \frac{C_{content,F}}{A_{tot}} = \frac{R_F C_{content,F}}{A_F} \,. \tag{8}$$

By construction, R_F and E_F are the same when considering a single farm element or an area of multiple farm elements (multiply $A_{tot}, A_F, C_{content,F}$ by $N_{elements}$).

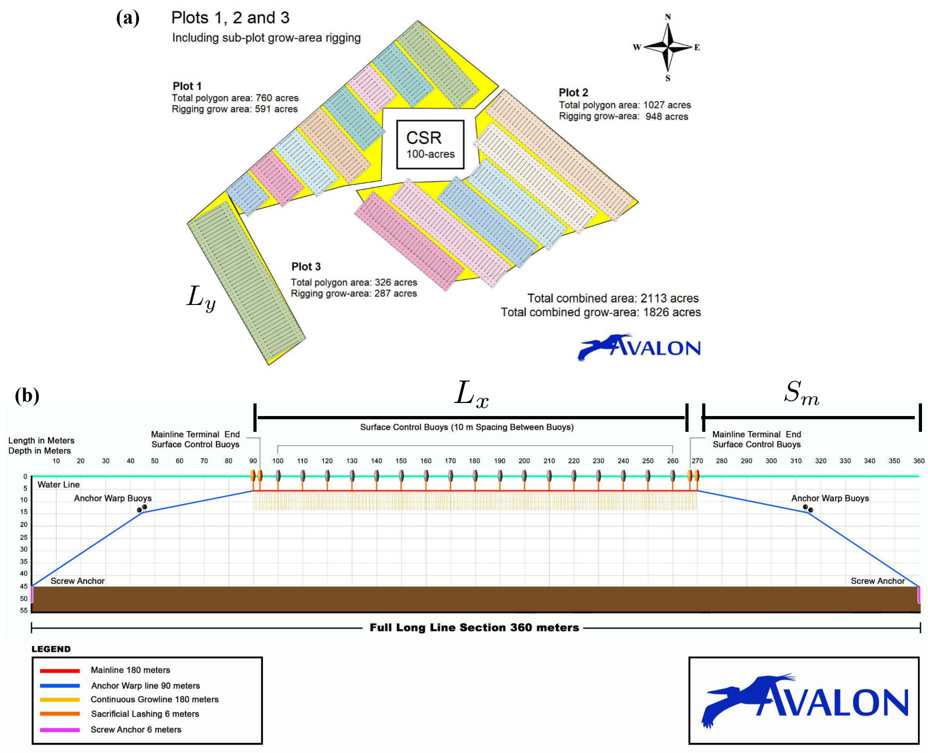

Figure 2: Proposed layout of Avalon Ocean Farm (AOF), intended to grow shellfish and kelp. (a) top view of the entire farmed region with 15 single farm elements. (b) cross-sectional view of a long-line that runs parallel to the shortest single element dimension (L_x, opposite the ORF design (Fig. 1)). The entire farm array covers a total area of ≈ 8.4 km^2. Figure from U.S. Army Corps of Engineers (2020)

3.1 Farm sizes

Farm Type	$N_{elements}$	A_F [km^2]	R_F	$C_{content,F}$ [g C]	E_F [g C/m^2]	$N_{elements} \times C_{content,F}$ [g C]
Present (ORF)	5	0.1	0.25	2.82×10^6	7.05	14.1×10^6
Near-future (AOF)	15	0.56	0.86	7.9×10^6	12.12	11.8×10^7
Future (modeled)	1	729	0.7	5.13×10^{10}	49.26	5.13×10^{10}

Table 2: Single farm element parameters for present, near-future, and future farms: $N_{elements}$ the number of individual farm elements in a farm array; area of an elelment A_F; ratio of farmed versus un-farmed area $R_F = A_F / A_{tot}$, where A_{tot} is the total farm footprint that accounts for *e.g.*, mooring line scope; the maximum yield of C or a single element $C_{contentF}$; the efficiency of C production E_F (defined in the previous section); and the total C yield (assuming no loss) of a multi-element farm array. The carrying capacity assumes a maximum of 25 kg wet /m on a long-line. Both ORF and AOF have comparable efficiency (E_F) of C yield. This is not by design here (*i.e.,*carefully tuning free parameters), but more likely indicates a ceiling on present farm technology. We intend to model large-scale seaweed CDR with the future farm parameters, which are assumed more efficient than present (E_F). This assumed increase in efficiency relies on heavy assumptions about technological development.

3.1.1 Present day and near-future farm parameters

Here, we give parameters for the Ocean Rainforest farm (ORF) in Santa Barbara and the proposed Avalon Ocean Farm (AOF, Fig. 2). Presently, real-world farms consist of multiple single farm elements, each with a typical areas of 300-500 m $\times$ 200-300 m. A 700 m x 300 m farm has been developed, but is presently considered too dense (personal communication, Javier Infante, Ocean Rainforest). The proposed AOF consists of 15 elements that take up a total area of $\approx$ 8.41 km^2.

Ocean Rainforest Farm (ORF)
The planned Ocean Rainforest farm on the Santa Barbara Channel shelf will consist of 5 farm elements and the following parameters:

$$N_{elements} = 5 \ , \ \ L_x = 200 \text{ m} \ , \quad \mathrm{L_y} = 500 \text{ m} \ , \tag{9}$$

$$H = 60 \text{ m} \ , \ \ \mathrm{S_m} = 180 \tag{10}$$

$$\beta_x = 1.5 \quad \beta_y = 2 \tag{11}$$

$$S_l = 1 - 25 \text{ m} \ , \ \ \mathrm{S_c} = 1.5 \text{ m} \ , \ \ \mathrm{h_{cult}} = 10 - 20 \text{ m} \tag{12}$$

Where a range for the space between the long-lines S_l is given. We assume a depth of $H = 60$ m ($S_m = 180$ m) for this farm, noting that Javier Infante has said the maximal depth for present farms is approximately 100 m. Based on the schematic in Fig. 1a, we assume $\beta_x = 1.5 \quad \beta_y = 2$, noting that this is a rough approximation. The total farm footprint is then $A_{tot} = 0.4$ km^2 with $R_F = 0.25$, indicating that a large portion of this footprint is un-farmed area.

Assuming $S_l = 25$ m, the maximum carrying capacity for an ORF element is

$$B_{max,F} = 25 \times 10^3 \text{ g wet/m} \times 500 \text{ m} \frac{200 \text{ m}}{25 \text{ m}} = 1 \times 10^8 \text{ g wet} \tag{13}$$

With a maximum C content:

$$C_{content,F} = 1 \times 10^8 \text{ g wet} \times 0.094 \times 0.3 = 2.82 \times 10^6 \text{ g C} \ . \tag{14}$$

The maximum C yield for the multi-farm element is then:

$$C_{content,array} = N_{elements} \times C_{content,F} = 14.1 \times 10^6 \text{ g C} . \quad (15)$$

Avalon Ocean Farm (AOF)

The proposed AOF (Fig. 2) consists of 15 farm elements placed in 3 'sub-plots' (polygons) to grow kelp and shellfish. Here, to give comparative scales we assume only kelp is grown in all of the sub-plots. The total area taken up by all elements is approximately (2.9×2.9) km^2. The permitting document (U.S. Army Corps of Engineers, 2020) shows that $S_m = 90$ m (where mooring line is referred to as 'anchor wrap line') and that this line is only attached to one end. According to the acreage given in Fig. 2a, $R_F = 0.86$, which is much greater than our estimates for ORF. This implies a very small β_x, β_y, which we do not define here.

For simplicity in deriving anticipated yield, we assume the 15 farm elements are split evenly (unlike Fig. 2) in rectangles of area ≈ 0.56 km^2 at a constant depth of 45 m; we assume $L_x = 180$ m as in Fig. 2b. Notably, the long-line spacing for AOF is larger ($S_l = 50$ m) than what is reported for ORF. The farm parameters are then

$$N_{elements} = 15 \ , \ \ R_F = 0.86 \ , \quad (16)$$

$$L_x = 180 \text{ m} \ , \ \ \mathrm{L_y} = 3111 \text{ m} \ , \quad (17)$$

$$H = 45 \text{ m} \ , \ \ \mathrm{S_m} = 90 \text{ m} \quad (18)$$

$$S_l = 50 \text{ m} \ , \ \ \mathrm{S_c} = 1.5 \text{ m} \ , \ \ \mathrm{h_{cult}} = 10 - 20 \text{ m} \quad (19)$$

The maximum carrying capacity for the single AOF element is then

$$B_{max,F} = 25 \times 10^3 \text{ g wet/m} \times 180 \text{ m} \frac{3111 \text{ m}}{50 \text{ m}} = 2.8 \times 10^8 \text{ g wet} \quad (20)$$

With a maximum C content:

$$C_{content,F} = 2.8 \times 10^8 \text{ g wet} \times 0.094 \times 0.3 = 7.9 \times 10^6 \text{ g C} . \quad (21)$$

The maximum C yield for the multi-element farm is then:

$$C_{content,array} = N_{elements} \times C_{content,F} = 11.8 \times 10^7 \text{ g C} . \quad (22)$$

3.1.2 Future (simulated) farm parameters

As stated before, the horizontal scope of the mooring line places a heavy limitation on the farm location, specifically in the context of the required *farmed* area for a single farm element at the scales required for significant mCDR (27×27 km^2, Sec. 2). The required area of these farms rule out the possibility of placing them within the continental shelf, with cross-shore widths $\approx 5 - 10$ km. We assume that these future farms will sit in federal waters (greater than 3 nautical miles offshore) in the open-ocean, defined here as total depth $H \geq 500$ m. The deep water also allows for local conveyance. For simplicity, we assume that this future farm consists of 1 element ($N_{elements} = 1$).

To model CDR at relevant scales (Sec. 2), we will have to assume that the mooring line limitation is not as constraining as present and that farms can function at large H. Instead of defining S_m, β_x, β_y, we assume $R_F = 0.7$ for future farms, which is larger than ORF (Table 1). This R_F value assumes technological advancements but still accounts for engineering and logistics that may be impossible to overcome (*e.g.*, $S_m = 0$).

We define parameters for a future farm we intend to model:

$$N_{elements} = 1\ ,\ \ R_F = 0.7\ , \tag{23}$$

$$L_x = 27 \times 10^3\ \mathrm{m}\ ,\ \ \mathrm{L_y} = 27 \times 10^3\ \mathrm{m}\ , \tag{24}$$

$$H = 500 - 2000\ \mathrm{m}\ ,\ \ \mathrm{S_l} = 10\ \mathrm{m}\ ,\ \ \mathrm{S_c} = 1.5\ \mathrm{m}\ , \tag{25}$$

$$h_{cult} = 10 - 20\ \mathrm{m}\ . \tag{26}$$

We assume a marginal reduction in long-line spacing($S_l = 10$ m) relative to present farms. This gives a maximum carrying capacity

$$B_{max,farm} = 25 \times 10^3\ \mathrm{g/m} \times 27 \times 10^3\ \mathrm{m}\frac{27 \times 10^3\ \mathrm{m}}{10\ \mathrm{m}} = 1.82 \times 10^{12}\ \mathrm{g\ wet} \tag{27}$$

With a maximum C content

$$C_{content,F} = 1.82 \times 10^{12}\ \mathrm{g\ wet} \times 0.094 \times 0.3 = 5.13 \times 10^{10}\ \mathrm{g\ C} \tag{28}$$

To give a sense of scale relative to the required 0.0273 Gt C / year sequestration goal (Sec. 2), we can give a rough estimate how many farms in the regional array it will take to sequester 10% of the global requirement (0.00273 Gt C / year), assuming 1.5 crops per year and 20% loss of C content from harvest and sequestration:

$$N_{farms,region} = \frac{0.00273\ \mathrm{Gt\ C/year}}{5.13 \times 10^{-5}\ \frac{\mathrm{Gt\ C}}{\mathrm{farm}} \times 1.5 \times 0.8} \approx 44\ \mathrm{farms} \tag{29}$$

The required number of farms can be reduced by assuming a larger $B_{max,line}$ or smaller S_l.

4 Farm Location Considerations

There are many factors that will inform farm placement in both the real-world and the model: logistical feasibility and costs, distance to conveyance locations, nutrient availability and environmental stress, marine use conflicts, and modeling domain boundaries. Our target is to model CDR efficacy assuming that farms will grow giant kelp in the SCB at the meaningful scales defined in Sec. 2. We can eliminate some of these considerations for the sake of the modeling exercise.

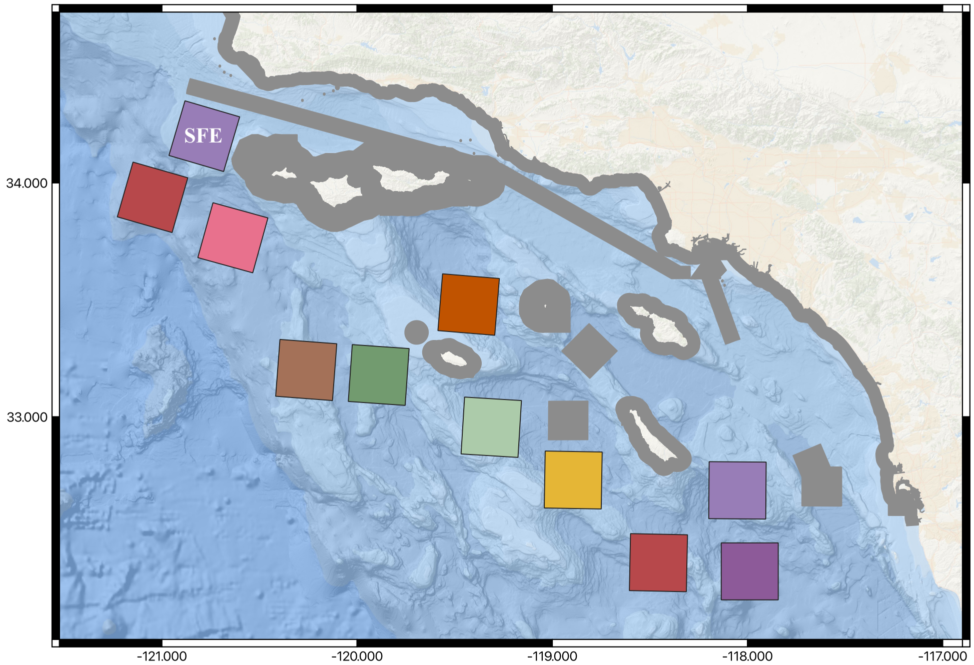

Figure 3: Map of 11 farm locations (colored squares) within the Southern California Bight (SCB). Farm locations are chosen based on ROMS domain boundaries, avoidance of human conflicts, and an assumption of local conveyance in deep water. Each farm is an approximately 27 km x 27 km square designed to fit on a ROMS grid with horizontal resolution $\Delta x \approx 333$ m. The northernmost farm (labeled SFE - 'single farm experiment') represents our *a priori* assumption of an optimal SCB farm, primarily based on favorable nutrient fluxes (Fig. 5). Gray areas show potential human conflicts including marine sanctuaries and protected areas, state waters, shipping lanes, oil and gas extraction areas, military zones, and unexploited ordinance areas. Additionally, AIS vessel traffic was assessed and high activity areas were avoided.

Here, we do not strongly consider logistical feasibility and costs as a limiting factor; we assume technological developments will allow farms to operate in deep water, at larger scales (Table 1) in the next 30-50 years. We also temporarily assume that conveyance is done locally at the farm. As a starting point for modeling, we define one single-farm experiment and one multi-farm experiment (Fig. 3) to assess regional CDR efficacy and ecosystem impacts. Apart from model domain constraints, our primary considerations are nutrient availability and avoiding marine use conflicts. In line with our heavy assumptions of developments in future farm technology, we do not strongly constrain the farm sites relative to mechanical stress (large waves and winds). The present ROMS-BEC-MAG model domain (Fig. 4) limits farm placement to primarily the Southern California Bight. Expansion of the modeling domain upcoast of Pt. Conception, where nutrients are more readily available but waves and winds are larger, is trivial but comes with increased computational costs.

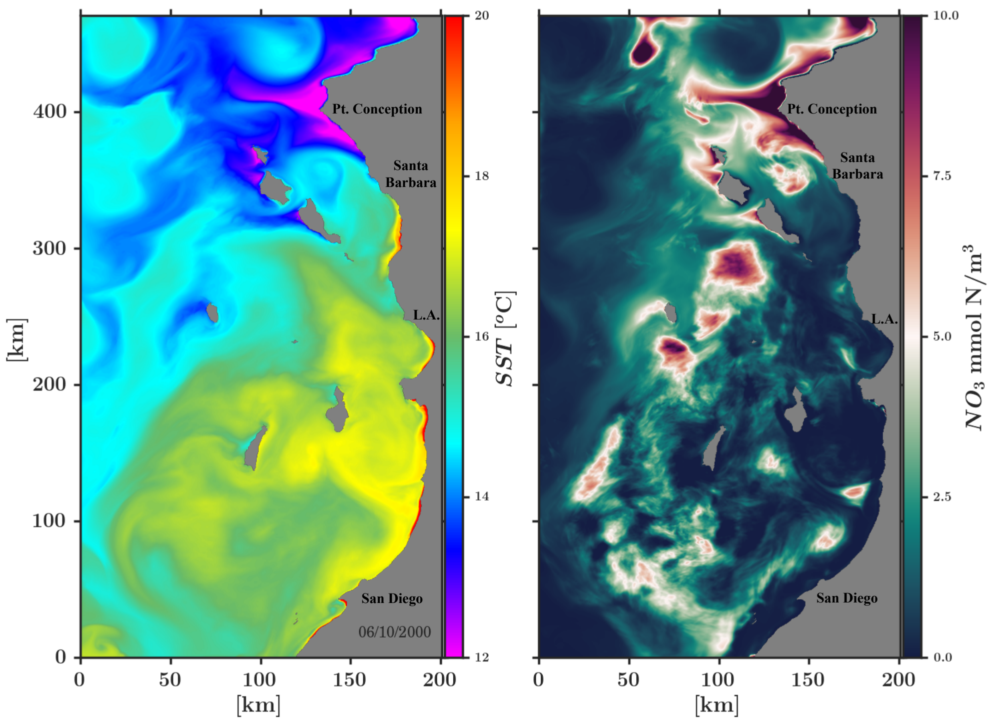

Figure 4: Snapshot (June 10, 2000) of daily averaged sea-surface temperature (left) and near-surface nitrate (right) from a multiply-nested, realistically forced, ROMS-BEC hindcast (simulation by Fayçal Kessouri). The domain has a horizontal resolution $\Delta x \approx 333$ m with initial and boundary conditions provided by a parent solution with $\Delta x \approx 1$ km. The domain boundaries guide the farm configurations in Fig. 3. We note that CDR simulations may be run in a different SCB domain (with similar Δx) that extends further up-coast of Pt. Conception in order to take advantage of the larger, ambient nutrient concentrations.

4.1 Nutrient availability and expected macroalgal production

We primarily rely on the results of Snyder et al. (2020) (shown in Fig. 5 here) and un-published analysis by Christina Frieder (SCCWRP) to give an approximate map of 'hot spots' of farmed kelp production. Snyder et al. (2020) demonstrate that the western portion of the Southern California Bight exhibits persistent, low kelp stress (high nutrient flux; Fig. 5a). The present conception for this pattern is that this area is continually exposed to nutrient fluxes that originate upcoast (Fig. 4 right panel, Fig. 5a).

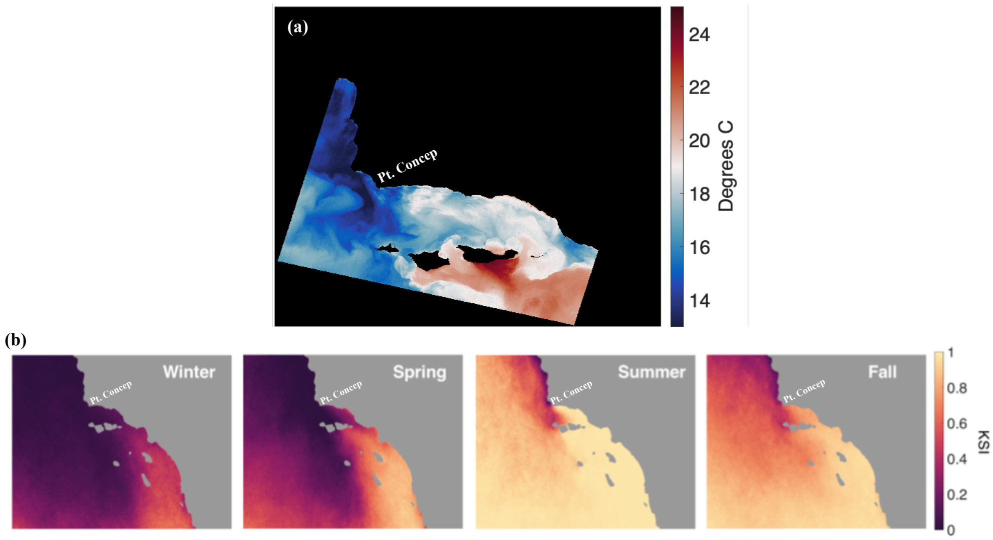

Figure 5: Environmental considerations for farm siting. (a): snapshot of SST from LANDSAT (source: Tom Bell) in the Southern California Bight. The snapshot illustrates the advection of cold (nutrient rich) water from the northwest to the western Santa Barbara Channel (SBC). (b): map of Kelp Stress Index (KSI) taken from Snyder et al. (2020). Low (high) KSI values correspond to low (high) nutrient stress. Note the persistence of low KSI in the western SBC relative to further inside the Bight.

Christina Frieder's analysis runs the macroalgal-growth (MAG; (Frieder et al., 2022)) 'offline' in the ROMS domain at every grid-point using the circulation and nutrient fields for a 1997-2008 hindcast simulation (with no feedback from the macroalgae on the nutrients). The results (not shown here at the request of C. Frieder) show multiple 'hot spots' for production (quantified as average annual harvest): (1) on the shelf, most strongly in Santa Monica and San Pedro Bays, (2) in the SB channel, (3) between the SB channel islands and San Nicolas island, and (4) west of the SB channel. The variability of average annual harvest is strongest in (1), (2), and (3), and less so in (4).

The larger values on the shelf are thought to be due to anthropogenic nutrient fluxes on the Santa Monica and San Pedro Bay shelves. These nutrients can be swept up and down the coast or trapped on the shelf by bathymetry. However, these mechanisms remains to be confirmed. There is an expectation of lower-frequency variability (>10 years) for the biomass production absent in the offline MAG analysis. Christina has also noted that the result is sensitive to the cultivation depth, *e.g.*, $h_{cult} < 10$ m strongly decreases production in the SB channel. The analysis by Snyder et al. (2020) only considers kelp stress as a function of surface nitrate (via SST).

4.2 Proposed farm configurations

We propose two primary scenarios to simulate seaweed mCDR in the SCB: a single-farm experiment and a multi-farm experiment (Fig. 3). The latter will allow us to cleanly diagnose ecosystem impacts and mCDR potential in a controlled manner. The former represents the anticipated, required configuration to achieve mCDR at relevant scales (Sec. 2). The multi-farm experiement will allow us to diagnose farm-to-farm interactions and their aggregate impacts on SCB circulation, ecosystem functioning, and mCDR viability. All farm locations (assumed to have

$A_F \approx (27 \times 27)$ km^2) have been chosen to sit away from ROMS-BEC domain boundaries, away from marine use zones, in federal waters, and in large depth ($H > 1000$ m) that favors local C conveyance.

4.2.1 Single farm scenario

The single-farm location (SFE in Fig. 3) is chosen primarily based on the analyses described in the previous section. This site exhibits favorable nutrient conditions (Fig. 5), relatively large macroalgal productivity, and less variability (nutrient stress, macroalgal productivity) than other areas with larger estimated production or lower kelp stress.

4.2.2 Multi-farm scenario

Based on the back-of-the-envelope estimate in Eq. (29), we estimate that an array of O(10) farms with area (27×27) km^2 is required for CDR at a globally significant scale. The exact number of farms will depend on assumed line spacing and maximum biomass per meter of line (Sec. 3).

The ideal location for additional farms is likely up-coast of the SFE site to take advantage of large nutrient fluxes and deeper waters. However, the present ROMS-BEC nested solution has domain boundaries very close to these possible locations. Fig. 3 shows a multi-farm array of 10 farms that extend primarily southeast of the SFE site (11 total with SFE site). These locations can be re-defined based on the ROMS-BEC-MAG modeling domain we choose for 'production' simulations. This would involve creating a new $\Delta x \approx 300$ m nested grid.

5 Summary

This white paper defines scenarios to simulate seaweed mCDR at a globally relevant scale in the Southern California Bight utilizing a biophysically coupled, regional modeling system (ROMS-BEC-MAG). The details of the modeling system, seaweed sinking methods, and other parameters for this modeling exercise are discussed separately in companion white papers as part of the ARPA-E Seaweed CDR Project.

A global mCDR target of 0.1 Gt CO_2/year (Sec. 2) guides the design of the SCB regional farm array (Fig. 3) that is assumed to account for $\sim 10\%$ of the global mCDR target. A non-exhaustive survey of present day farm design makes clear that simulating mCDR at the desired scales is not possible with present-day farm technology (Sec. 3). Mainly, present-day farms must sit in shallow-water (away from optimal sinking sites in deep water) and no present-day farm configurations can operate at a large enough scale (O(10x10) km of farmed area) to produce biomass at meaningful CDR scales. We define 'future' (*i.e.,*simulated) farm elements partially based on present-day farm design, but make assumptions about increases in efficiency (biomass production per square meter of farm) and technological advancements that will allow for cultivation in deep water ($H > 1000$ m). A single future farm element comprises a 27 km x 27km square (~ 7000 times the area of present-day farms) with an estimated production efficiency of 49.26 g C m^{-2} ($\sim$7 times the estimated efficiency of present-day farms). We note these efficiency estimates are based on an assumed carrying capacity per meter of long-line, chosen here to be 25 kg wet / m after discussion with Javier Infante (Ocean Rainforest).

We define two scenarios for the virtual mCDR experiment (Fig. 3) in the SCB modeling domain: a single-farm experiment and a multi-farm experiment. For both experiments, farm placement is constrained by model domain boundaries (Fig. 4) as well as avoidance of human conflict zones (gray areas Fig. 3). All farms locations are chosen anticipating local sinking in deep-water (approximately 1000 m or deeper). The single farm experiment (SFE, Fig. 3) places one farm in an 'optimal' location relative to anticipated nutrient availability based on previous studies (*e.g.*, Snyder et al. (2020)). However, we note that no studies have resolved the combined interactions between seaweed farms, regional ocean circulation, and nutrient cycling. A goal of the proposed SCB mCDR simulations is to inform future, real-world deployment of seaweed mCDR at large-scales.

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