**ARPA-E Quarterly Technical Report**
**Award - DE-AR0001559**
**Quarter 2 (October 1 – December 31, 2022)**

**Project Title: Quantifying the Potential and Risks of Large-Scale Macrophyte Cultivation and Purposeful Sequestration as a Viable CO2 Reduction (CDR) Strategy (SeaweedCDR)**

This is the second quarterly report for the SeaweedCDR project, covering the months October – December 2022. We have several milestones due this quarter including Q1 milestones (1.1 Refine Tasks and Milestones – complete; 4.1 Choose Initial Farm Site – complete; First Draft T2M Plan – complete) as well as the Q2 milestone (4.2 Develop Farm Scenarios for Modeling – complete and see below). We also report our activities and progress on other tasks over the past quarter.

**M2.1 - Design and Implementation of Seaweed Packaging**
Completion level - 50%

Within Task 2, we are currently planning for the first attempt at sinking kelp. For this attempt we will be filling slinky traps (Fig. 1A) with giant kelp (*Macrocystis pyrifera*) which will be harvested by The Cultured Abalone. Two mini$DO_2$T Loggers (dissolved oxygen sensors) will be attached to the kelp filled slinky trap (Fig. 1B). One of the oxygen sensors will be attached outside of the slinky trap, while the other oxygen sensor will be within the slinky trap along with the kelp. The oxygen sensor outside the slinky trap will serve as a reference of the available dissolved oxygen in seawater surrounding the kelp filled slinky trap. The second oxygen sensor within the slinky trap will provide data about the degradation of the kelp biomass as a function of the change in dissolved oxygen over time. In addition, a pressure recorder (Sensus Ultra Dive Data Recorder) will be attached to the outside of the slinky trap to record the change in pressure over time (Fig. 1C). The change in pressure over time will be used to calculate the sinking rate of the slinky trap filled with kelp as it sinks to the seafloor.


**Figure 1.** Pictures of the slinky trap to hold kelp (A), the mini$DO_2$T loggers (B), and Sensus Ultra Pressure logger (C).

**M2.2 - Seaweed Biomass Fates Methods Development**
Completion level - 25%

Recent findings from kelp dissections performed at UCSB showed that on average *Macrocystis* kelp components (stipe, blades, and pneumatocysts) are less dense than seawater and thus tend to be neutrally buoyant with the surface seawater (Fig. 2). Thus, to ensure that the kelp does sink to a water depth where pneumatocyst rupture (~60 meters) we must attach extra weight to the kelp filled slinky traps.

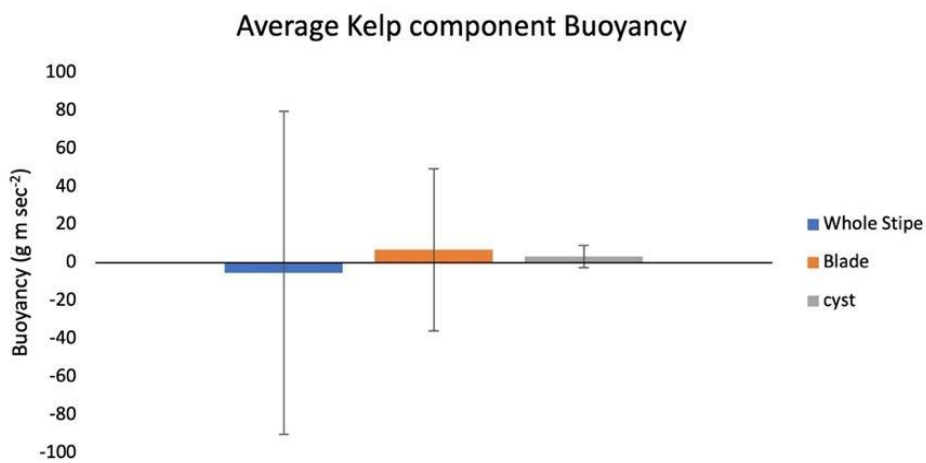


**Figure 2.** Average buoyancy of individual kelp components (stipe, blade and pneumatocyst [cyst]).

Based on the *Macrocystis* kelp components average densities, we calculated an estimate density of whole *Macrocystis* kelp frond according to Equation 1,

$$\rho_{Stipe} * R_{Stipe\ to\ frond} + \rho_{Blade} * R_{Blade\ to\ frond} + \rho_{cyst} * R_{Cyst\ to\ frond} = \rho_{Frond}, \quad [1]$$

where $\rho$ is the average density of either the stipe, blade, pneumatocysts or whole frond, and *R* is the ratio of the mass of the kelp component to the total mass of the frond. The calculated estimated density of the frond (0.9314 g/mL) was then used to calculate the volume of 1 kg of kelp biomass according to Equation 2,

$$V_{Kelp} = M_{Kelp} * \rho_{Frond}, \quad [2]$$

where *V* is the volume of 1 kg of kelp, *M* is the mass of the kelp, and $\rho$ is the density of the kelp frond calculated in Equation 1. We can then estimate the fraction of 1 kg of kelp biomass that is buoyed above the water line according to Equation 3,

$$F = \frac{\rho_{Seawater} - \rho_{Frond}}{\rho_{Seawater}}, \quad [3]$$

where *F* is the percent fraction of the 1 kg kelp parcel that is above the water line, $\rho$ is either the assumed density of seawater (1.024 g/mL) or the density of the frond (0.9314 g/mL)

calculated in Equation 1. The estimated volume (also the mass) of kelp biomass above the water line is then determined by multiplying *F* by the assumed density of seawater. Our estimates indicate for every 1 kg of kelp biomass we will need to add at least 10% of the initial weight of the kelp to the kelp package to completely submerge 1 kg of *Macrocystis* kelp below the water line. Also see task 4.2 for additional packaging experiments.

We have identified offshore areas within the Santa Barbara Channel to begin sinking *Macrocystis* kelp. Criteria that guide the location choices are 1) that sinking must occur at least 3 nautical miles away from shore, 2) must not be within a shipping lane, and 3) with water depth between 100 to 150 meters. Figure 3 is a bathymetric chart of the Santa Barbara channel, where we have identified areas that fit these criteria (blue shaded areas).

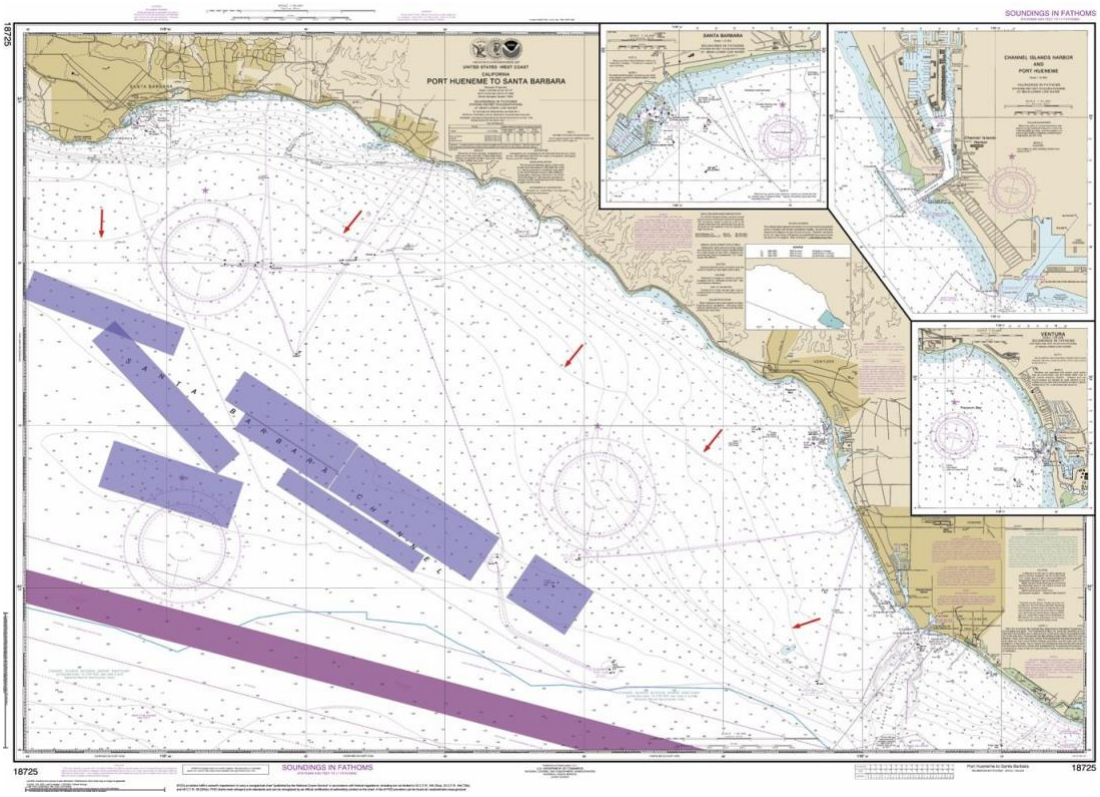


**Figure 3.** Bathymetric chart from Port Hueneme to Santa Barbara. Blue shaded regions are potential areas for kelp sinking, with water column depths between 100-150 meters (55-80 fathoms). Red arrows point to the three-mile line. The dark purple shaded areas are the shipping lanes. Chart source is from the National Oceanic and Atmospheric Administration https://www.charts.noaa.gov/OnLineViewer/18725.shtml.

The first of the kelp sinking operations is anticipated to occur in early to mid-February of 2023, pending the successful dredging of the Santa Barbara Harbor. Currently, the kelp harvesters from The Culture Abalone are not able to safely harvest kelp until the Santa Barbara harbor is dredged. The UCSB campus owns and operates a 26-ft Research Vessel *Connell* which we plan to use for deployment and recovery of the kelp filled slinky traps (Fig. 4A). The R/V *Connell* can recover the slinky traps from the seafloor using a hydraulic pump to power the

hydraulic pinch wheel attached to a davit (Fig. 4B and C). The maximum weight the hydraulic pinch wheel can hoist safely is between 150-185 lbs.

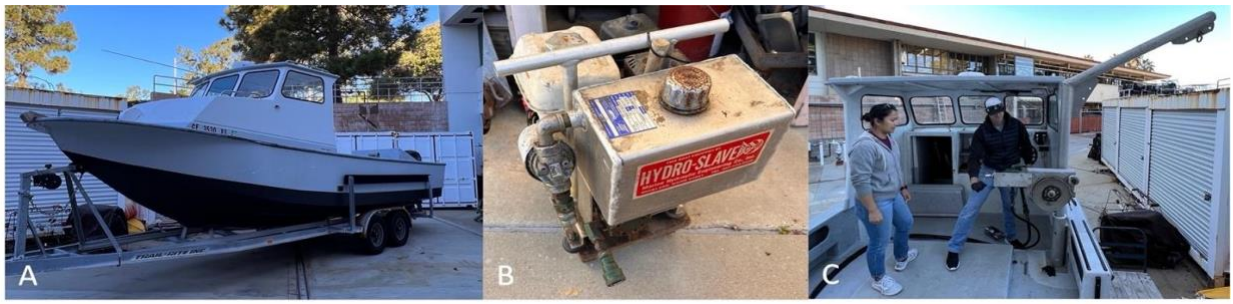


**Figure 4.** Photos of the RV *Connell* (A), hydraulic pump (B), and davit with pinch wheel (C).

The R/V *Connell* will be transported to the Santa Barbara harbor where we will meet the kelp harvesters. We plan to fill two slinky traps with kelp: one with approximately 150 lbs. and one approximately 80 lbs. The packaged kelp will then be weighed with an inline scale at the harbor to get the exact starting weight of the kelp package. Additional bundles of steel rebar will be attached to the kelp filled slinky pot to account for the positive buoyancy of the kelp (Fig. 5). A mooring line will be attached to the slinky trap on one end, followed by a subsurface float and swivel and a surface float at the very end (Fig. 5). The purpose of the dual float mooring is to reduce the chance of surface wave energy to tug and potentially move the kelp package at the sediment surface for the duration of the experiment. Kelp packages will be left on the seafloor for 5 days. Upon the recovery of the kelp packages, the remaining kelp will be weighed again using an inline scale and will provide information about how much kelp was lost over 5 days. Slinky trap sinking and decomposition rates will be calculated from the data pulled from the oxygen sensors and pressure logger.

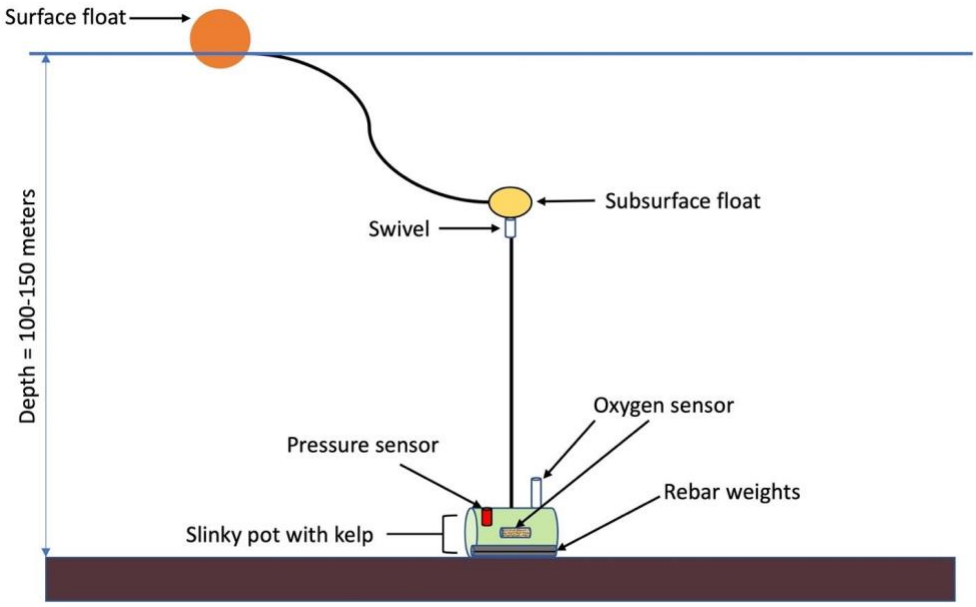


**Figure 5.** Schematic of the mooring design for the kelp sinking experiment in the Santa Barbara Channel.

**M3.1 - Seaweed DOC Fates Methods Development**
Completion level - 50%

We have begun to develop and document protocols to determine the composition and fate of DOC produced by giant kelp. To address the composition of DOC produced by giant kelp we have focused on two main compound classes: neutral sugars and polyphenols which have previously been shown to be a significant fraction of macroalgal DOC (Abdullah and Fredriksen 2004; Wada et al. 2007; Powers et al. 2019). Using the incubations described in our Q1 report, accumulated DOC are collected and characterized using High Performance Anion Exchange Chromatography with Pulsed amperometric detection (HPAEC-PAD) and the Folin-Ciocâlteu colorimetric method for neutral sugars and polyphenols, respectively. From the incubations of 9 blades, neutral sugars and polyphenols were responsible for 30 $\pm$ 21% and 24 $\pm$ 16% (54% total) of the accumulated DOC, respectively.

Neutral sugars are a relatively biologically reactive pool, fueling bacterioplankton and respiration (Skoog and Benner 1997; Goldberg et al. 2011); however, little is known about the bioavailability of macroalgal polyphenols. An important sink for polyphenols may be photooxidation due to their aromaticity (Fig. 6a) (Stubbins et al. 2008). To evaluate the role of light in the removal of macroalgal DOC we irradiated *M. pyrifera* exudates in a solar simulator to observe changes in the composition and concentration of DOC. Additionally we measured the increase in dissolved inorganic carbon which would indicate how much DOC was photooxidized to $CO_2$. Using UV-Visible spectroscopy we observe a sharp decrease in the absorption of macroalgal DOC, specifically at 270nm (Fig. 6b) which indicated the destruction of polyphenolic compounds (Powers 2020). Further we observed a loss of 10% of the original DOC concentration after 1 day of irradiation (Fig. 6c). Only 20% of the observed loss of DOC was recovered as dissolved inorganic carbon, indicating that DOC was possible partially oxidized to carbon monoxide (CO). Future work will determine if the photooxidation of macroalgal derived polyphenols is an important source of CO.

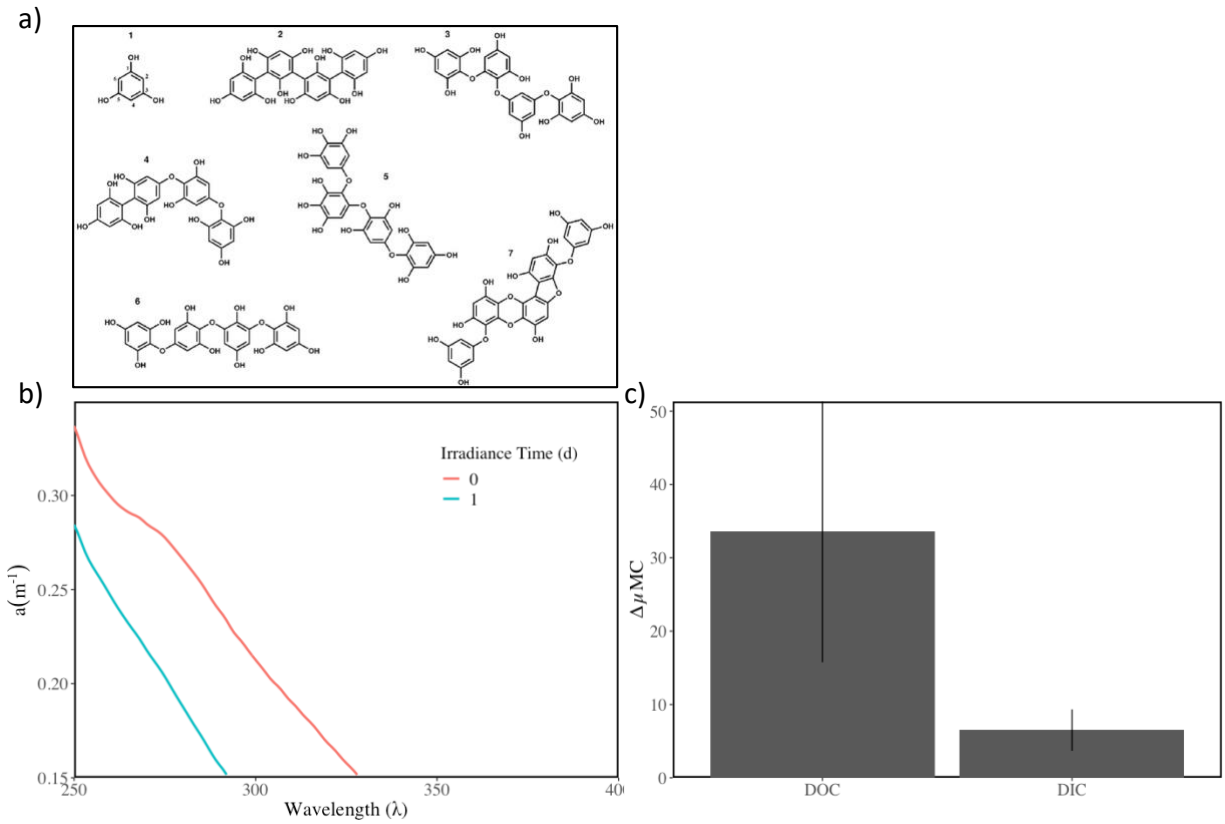


**Figure 6**. (a) Molecular structure of model macroalgal polyphenols known as phlorotannins. (b) UV-visible spectrum for *M. pyrifera* DOC before and after irradiation. The loss of the shoulder around 270nm is indicative of the destruction of polyphenol compounds. (c) The change in concentration of DOC and DIC after one day of irradiation. Loss of DOC is approximately 10% of the initial concentration.

**Task 4.1 – Choose Initial Farm / Sequestration Site**
Completion level - 100%

See Task 4.2 below.

**Task 4.2 – Develop Farm Scenarios for Modeling**
Completion level - 100%

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 kelp at the scales required to dent emissions. We can eliminate some of these considerations for the sake of the modeling exercise.

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. 7) 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 limits farm placement to primarily the Southern California Bight (SCB).

| 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 | $2.82 \times 10^6$ | 7.05 | $14.1 \times 10^6$ |
| Near-future (AOF) | 15 | 0.56 | 0.86 | $7.9 \times 10^6$ | 12.12 | $11.8 \times 10^7$ |
| Future (modeled) | 1 | 729 | 0.7 | $5.13 \times 10^{10}$ | 49.26 | $5.13 \times 10^{10}$ |

**Table 1.** 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 element $A_F$; 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$^{-1}$ (personal communication, Javier Infante). Both ORF and AOF have comparable efficiency of C yield $E_F$. 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.

We propose simulating two primary scenarios to simulate CDR in the SCB: a single-farm experiment and a multi-farm experiment (Fig. 7). The latter will allow us to cleanly diagnose ecosystem impacts and CDR potential in a controlled manner. The former represents the anticipated, required configuration to achieve CDR at relevant scales. The multi-farm experiment will allow us to diagnose farm-to-farm interactions and their aggregate impacts on SCB circulation, ecosystem functioning, and CDR potential. 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.

The single-farm location (SFE in Fig. 7) is chosen primarily based on the analyses described in the previous section. This site exhibits favorable nutrient conditions, relatively large macroalgal productivity, and less variability (nutrient stress, macroalgal productivity) than other areas with larger estimated production or lower kelp stress. Based on our back-of-the-envelope estimate, 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. 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. 7 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.

Farm scenario considerations (design, number, sizes, locations) have been detailed in a white paper that will be uploaded to an arXiv pre-print archive shortly in order for it to have its own doi.

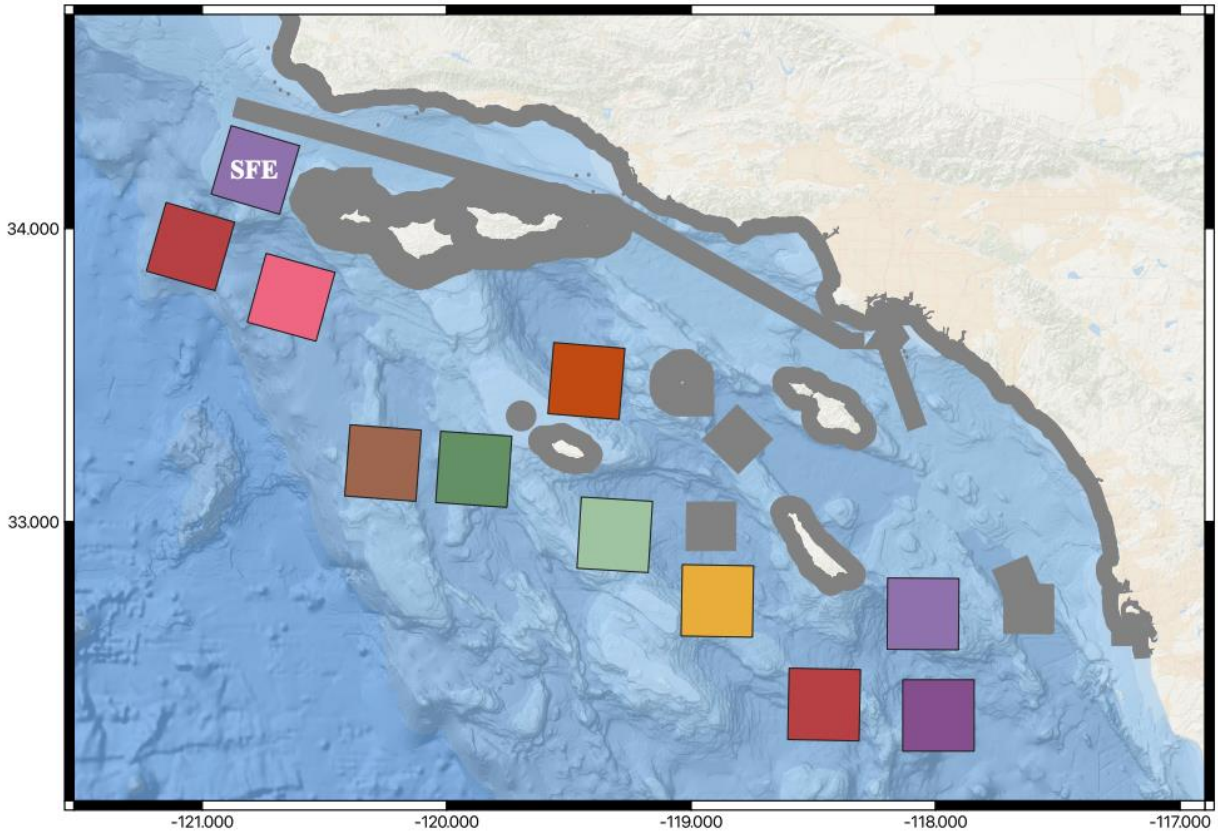


**Figure 7.** Map of 11 farm locations (colored squares) within the Southern California Bight (SCB). Farm locations are chosen based on ROMS domain boundaries, avoidance of human conflicts, and an assumption of local conveyance in deep water. Each farm is an approximately 27 km x 27 km square designed to fit on a ROMS grid with $\Delta x \approx 333$ 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. 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.

*Sinking Methods* - There are a variety of sinking methods available to convey kelp biomass to depth for the purposes of carbon sequestration. One of the challenges for using giant kelp for CDR is the fact that the biomass has positive buoyancy due to the pneumatocyst located on the proximal end of each blade. While this positive buoyancy promotes the development of a surface canopy, leading to high rates of production and a potentially easier harvest due to surface cutting, it requires additional processing before sinking can occur. For this project, we will evaluate four methods for conveying harvest giant kelp biomass to the deep ocean: 1. *Natural sinking* - where the floating biomass is released and allowed to sink on its own after degradation, 2. *Mastication* - where biomass is shredded and released to sink according to its buoyancy, 3. *Short-depth pumping* - where kelp is pumped to a shallow depth (50 - 100 m) and

pneumatocysts collapse leading to negative buoyancy, and 4. *Baling* - where kelp is baled, compressed (or weighted), and released. The optimal sinking method will minimize decomposition rate and release rate of DOC in the upper water column while maximizing sinking speed (and eventually minimize processing cost and handling time). The measured sinking rates, DOC release rates, and decomposition rates will serve as parameters for the simulated conveyance by the different sinking methods. Here, we will describe the four different sinking methods and our planned work to establish bounds for these key parameters.

**Natural sinking** - Giant kelp will naturally float due to the pneumatocyst present on each blade. If an offshore kelp farm used this sinking method, kelp would be harvested from the farm and released near the farm at the surface. Transport to depth will not occur until the kelp has partially decomposed and pneumatocysts have become ruptured, rendering the biomass negatively buoyant. The advantage of this method is that it requires no further effort after harvesting. The disadvantages of this method include the loss of carbon due to decomposition and the uncertainty of where and how much of the kelp biomass will sink. In this project we will examine the decomposition rate of these whole fronds and plants in a laboratory and/or mesocosm setting, along with DOC release and sinking rate as this biomass decomposes (Table 2). We will also examine the influence of seawater temperature on decomposition rate and timing of sinking. For the modeling framework, we will use the surface currents from ROMS simulations to understand the trajectory and fate of positively buoyant kelp and use the laboratory and mesocosm experiment results to predict the locations of sinking.

**Mastication** - Mechanized shredding of the kelp biomass may be a cost-effective method of sinking biomass to depth at, near, or at distance from the site of harvest. Mastication could be achieved with currently available agricultural machinery and act to rupture kelp pneumatocysts, leading to negative buoyancy (confirmed by experiments by Krause at UCSB). While this may be a cost-effective sinking method, cutting the kelp into smaller pieces will likely lead to slower sinking rates, meaning more carbon will be lost as sinking occurs. Additionally, cutting or breaking the kelp biomass will likely lead to greater rates of DOC release before the biomass is at depths necessary for sequestration. We will measure the change in DOC release and decomposition rate as kelp biomass is cut into progressively smaller pieces in the laboratory as well as examine the relationship between size and sinking speed. Equations derived from these experiments will be used to model the transport of carbon from the surface to depths required for sequestration activities.

**Short-depth pumping** - Pumping kelp biomass (whole or cut pieces) to a depth of ~60m should implode pneumatocysts and render the biomass negatively buoyant. This method is currently used by SOS Carbon to sink floating Sargassum collected near beaches in the Caribbean. We will complete additional work in the pressure chamber at UCSB to understand the pressure (and depth) necessary to implode pneumatocysts and render the kelp biomass negatively buoyant and examine the enhancement in sinking rate. Any rupture of the pneumatocysts will likely lead to enhanced DOC release, so we will quantify the additional DOC released that would enter the upper water column in the laboratory. Decomposition rate experiments of fronds with ruptured

pneumatocysts (simulating short-depth pumping) will occur as part of our *Baling* field experiment.

**Baling** - Compressing the kelp into bales may be an effective method for sinking harvested biomass to depths necessary for sequestration. The processing of kelp into bales could be completed at the farm site or during transport to the sequestration area. Currently, Co-PI Miller and Krause are investigating the use of 'slinky traps' to simulate the baling of kelp biomass. These bags will be filled with whole kelp fronds and compressed or weighted to sink. Critical depths for pneumatocyst collapse will be investigated in the field using pressure sensors. We may also investigate compression methods in the laboratory to establish if compression of other parts of the kelp plant leads to excess DOC release. The accordion-like bags allow for different amounts of kelp to be placed within them, so we will complete field trials for sinking and decomposition rates for multiple sizes of simulated bales and establish scaling relationships. Additionally, we will investigate the potential use of existing agricultural baling technologies.

| Sinking Method | DOC Release Rate | Sinking Rate | Decomposition Rate |
|---|---|---|---|
| Natural Sinking | Lab | Lab | Lab |
| Mastication | Lab | Lab | Lab |
| S-D pumping | Lab | Lab/Field | Lab/Field |
| Baling | Lab | Field | Field |

**Table 2**. Experimental matrix showing how we will investigate DOC release ($J^{s}_{kelp,doc}$ [mmol C $m^{-3}$ $s^{-1}$]), sinking rate ($w_{kelp}$ [m $s^{-1}$]), and decomposition rate of kelp biomass ($J^{decomp}_{kelp}$ [mmol C $m^{-3}$ $s^{-1}$]) for each sinking method. Lab indicates laboratory and/or mesocosm experiments. The translation between measured rates and model parameters will be coordinated based on the experimental design.

**Task 4.3 – Develop Macroalgae Farm Model**
Completion level - 40%

D. Bianchi, D. Dauhajre, and A. Pham recently organized and attended a workshop, in coordination with C. Frieder and K. Davis (ARPA-E MARINER) to discuss further development and sensitivity testing of the MAG code (online and offline coupled). There is presently a defined plan to update and simplify the original MAG model (Frieder et al. 2022) for coupling with ROMS-BEC. These updates include eliminating frond tracking and implementing a new vertical distribution function for biomass. Both of these updates require sensitivity tests relative to the original MAG code. These sensitivity tests will be performed in an offline MAG code in coordination with C. Frieder. In parallel, we will continue the development and testing of the fully-coupled ROMS-BEC-MAG code. The updated MAG model, and its coupling to ROMS-BEC is being detailed in a white paper that will serve as the technical guide for the ROMS-BEC-MAG user-base. This too will be uploaded to an arXiv pre-print archive in order for it to have its own doi.

**Task 4.4 – Develop and Implement Modeling System for Understanding the Environmental Impacts of Seaweed CDR**
Completion level - 15%

We have chosen an Eulerian framework for the vertical conveyance and settling model. This choice allows us to more clearly define the required information exchange between measurements (Tasks 2-3) and the model. We intend to develop and test the vertical conveyance and settling component of ROMS-BEC-MAG in an idealized simulation.

**Task 5.1 – Develop Spatial Layer of Human Use and Environmental Conflicts in Initial Domain**
Completion level - 100%

Figure 7 shows 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. All spatial layers were acquired from public sources including the NOAA Marine Cadastre.

**Task 6.4 – Website**
Completion level - 25%

A url was established for the project website (seaweedcdr.eri.ucsb.edu) and the site is currently under construction. The layout of the site has been created and most pages are complete. We expect the site to be public by the end of this coming quarter and will maintain it throughout the project. Currently, we have posted this and the previous Quarterly Reports and will post project white papers and future peer-reviewed publications.

## References


Abdullah, M. I., and S. Fredriksen. 2004. Production, respiration and exudation of dissolved organic matter by the kelp *Laminaria hyperborea* along the west coast of Norway. J. Mar. Biol. Assoc. U. K. **84**: 887–894. doi:10.1017/S002531540401015Xh

Frieder, C., Yan, C., Chamecki, M., Dauhajre, D., Mcwilliams, J. C., Infante, J., McPherson, M., Kudela, R. M., Kessouri, F., Sutula, M., Arzeno-Soltero, I. B., and Davis, K. (2022). A macroalgal cultivation modeling system (MACMODS): Evaluating the role of physical-biological coupling on nutrients and farm yield. *Frontiers in Marine Science*, 9.

Goldberg, S. J., C. A. Carlson, M. Brzezinski, N. B. Nelson, and D. A. Siegel. 2011. Systematic removal of neutral sugars within dissolved organic matter across ocean basins. Geophys. Res. Lett. **38**. doi:https://doi.org/10.1029/2011GL048620

Powers, L. C. 2020. Optical Properties and Photochemical Transformation of the Dissolved Organic Matter Released by Sargassum. Front. Mar. Sci. **7**: 17.

Powers, L. C., N. Hertkorn, N. McDonald, P. Schmitt-Kopplin, R. D. Vecchio, N. V. Blough, and M. Gonsior. 2019. Sargassum sp. Act as a Large Regional Source of Marine Dissolved Organic Carbon and Polyphenols. Glob. Biogeochem. Cycles **33**: 1423–1439. doi:10.1029/2019GB006225

Skoog, A., and R. Benner. 1997. Aldoses in various size fractions of marine organic matter: Implications for carbon cycling. Limnol. Oceanogr. **42**: 1803–1813. doi:10.4319/lo.1997.42.8.1803

Stubbins, A., V. Hubbard, G. Uher, C. S. Law, R. C. Upstill-Goddard, G. R. Aiken, and K. Mopper. 2008. Relating Carbon Monoxide Photoproduction to Dissolved Organic Matter Functionality. Environ. Sci. Technol. **42**: 3271–3276. doi:10.1021/es703014q

Wada, S., M. N. Aoki, Y. Tsuchiya, T. Sato, H. Shinagawa, and T. Hama. 2007. Quantitative and qualitative analyses of dissolved organic matter released from Ecklonia cava Kjellman, in Oura Bay, Shimoda, Izu Peninsula, Japan. J. Exp. Mar. Biol. Ecol. **349**: 344–358. doi:10.1016/j.jembe.2007.05.024