ARPA-E Quarterly Technical Report
Award - DE-AR0001559
Quarter 1 (July 29 – September 30, 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 first quarterly report for the SeaweedCDR project, covering the first three months of the project timeline (July 29 – September 30, 2022). As this timeframe did not cover a full quarter of work on this project, we did not have any milestones to achieve in this quarterly report. We do however report our activities since the July 29 start date and our progress on first quarter milestones and other aspects of the project.

M2.1 - Design and Implementation of Seaweed Packaging
Completion level - 10%

Within Task 2 (*Quantification of the fates of seaweed biomass*)**,** we are investigating different package designs for packaging giant kelp (*Macrocystis*). The first design we are investigating is adopting fishing pot technology known as slinky pots or traps (Fig. 1A) used in commercial fishing of black cod at deep depths (up to ~300m). The slinky pots range in size and consist of metal coils surrounded by mesh netting. The slinky pot can be loaded with *Macrocystis* as whole fronds or pieces of cut up (macerated) kelp.

There are some advantages to use the slinky pots to meet the objectives in this project. First the slinky pots can be large and flexible enough to pack large quantities of kelp while maintaining some rigidity. The range in size and dimensions enables us to test this packaging method in field with varying surface area and volume ratios. The ability to attach the slinky pots to a line will enable us to repeatedly deploy and recover slinky pots in the marine environment as we plan to do in milestone M2.3 (*Validation of seaweed biomass fates methods*). The slinky pot frame also allows us to equip various sensors (e.g., oxygen and temperature) to the packages of kelp. This will allow us to monitor changes to seawater chemistry that inform us on kelp degradation and local environment change. We have obtained five slinky pots for testing and are ordering the remaining mooring gear and oxygen sensors for the first test deployment planned for the coming quarter.

Macrocystis will be purchased from The Cultured Abalone, a local abalone farm that is permitted to harvest kelp. The Culture Abalone farm has on its premises a kelp cutter (Fig. 1B), the use of which we are exploring for macerating the kelp.

We are also been chatting with seaweed CDR startups to learn how they see the packaging problem, along with other issues. So far, we have talked with Phykos (https://www.phykos.co) and have Running Tide (https://www.runningtide.com) on the schedule for the following week. It is interesting to note that both of these companies plan to sink macroalgae as whole plants.

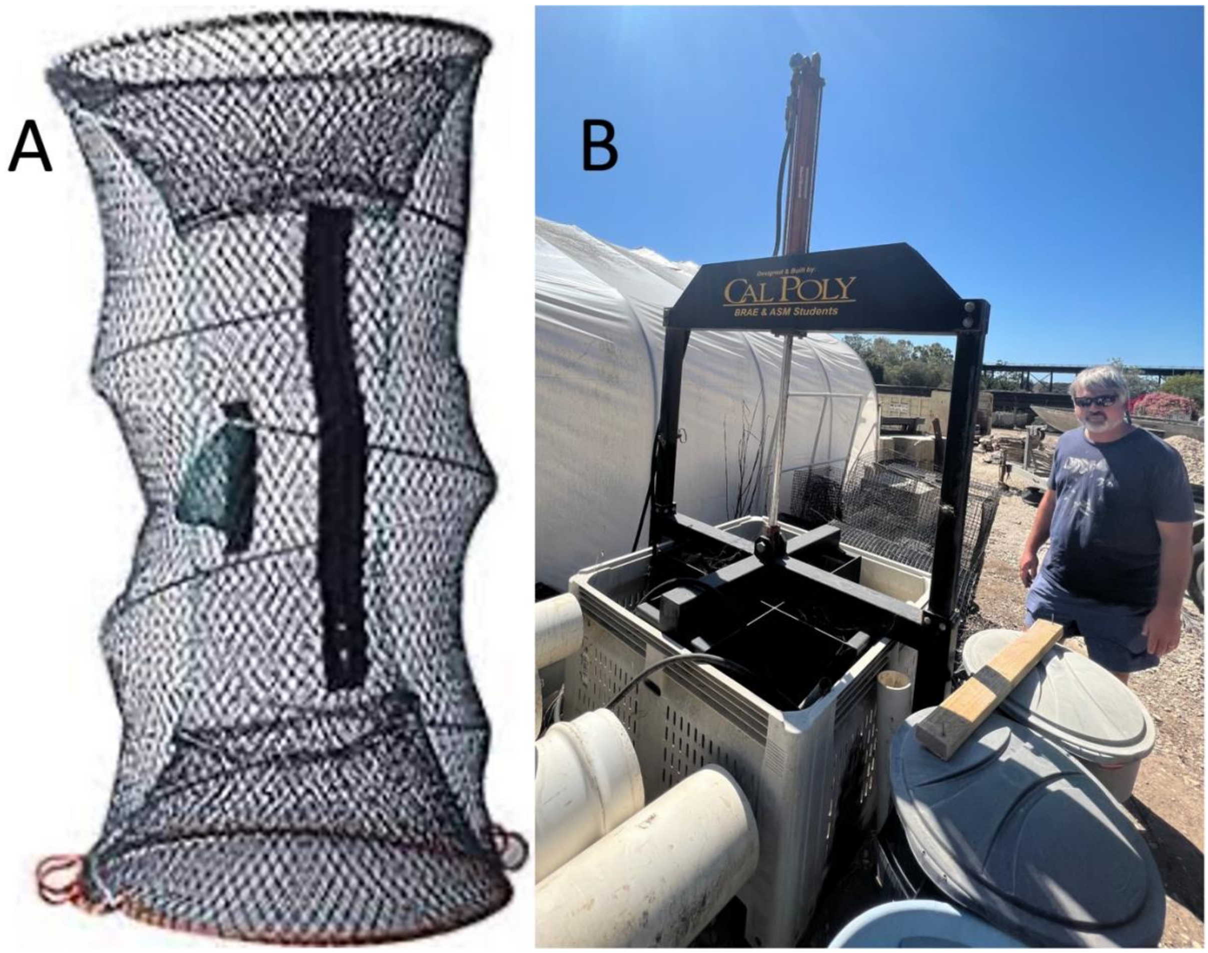

Figure 1. Picture of slicky pot as a proposed method to deliver and recover macrocystis kelp to and from the seafloor (A). Picture of the kelp cutter on the premises of The Cultured Abalone (B).

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

Sinking kelp requires consideration of its buoyancy and sinking rate (M2.4; *Measure / Model Seaweed Sinking Rates*). *Macrocystis* has pneumatocysts (gas filled bladders) that make the fronds positively buoyant. As the kelp sinks. the pneumatocysts will fail under increasing pressure. To measure buoyancy and sinking rates, we are quantifying the biomass density and sinking rates of *Macrocystis* components (stipe, pneumatocysts and blade) in the lab (Fig. 2A). We are also quantifying the average contribution of these components to the biomass of fronds in order to scale the component measurements to estimate density, buoyancy and sinking rates of large parcels of kelp. To estimate the failure pressure of pneumatocysts, we pressure tested pneumatocysts of varying sizes using a hydrostatic pressure chamber (Fig. 2B). Preliminary data show that the pneumatocysts are crushed or ruptured between 45 – 60 meters seawater depth (Fig. 2C).

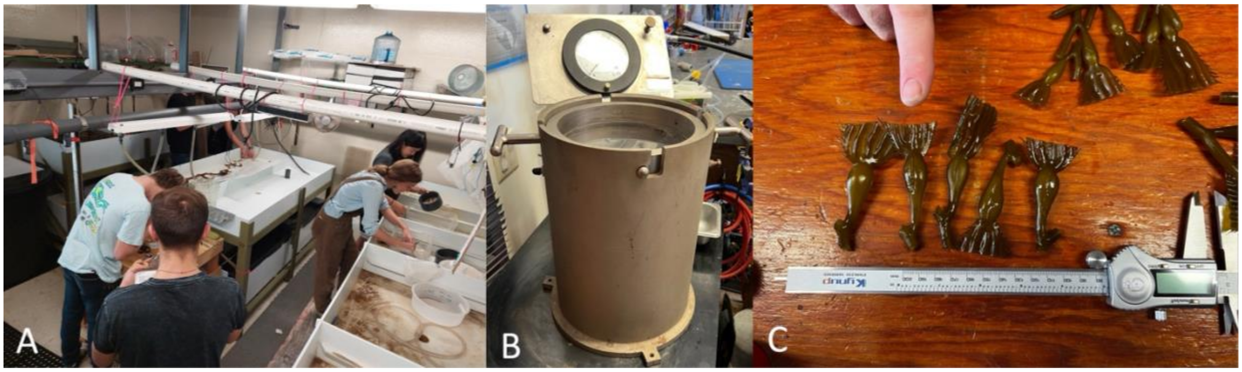

Figure 2. Picture of kelp dissection and data collection of kelp characteristics (A). Picture of pressure chamber (B) and ruptured pneumatocysts after exposure to pressure (C).

We further seized an opportunity to perform proof of concept respiration incubation experiments to constrain the rate at which fresh kelp was respired during deposition to the deep ocean. This is work needed for achieving milestone M2.5 (*Measure / Model the Seaweed Decomposition Rates*). These incubations were performed while on a research expedition in the Gulf of Mexico in September-October, 2022. The incubations were set up headspace-free in the dark at in-situ deep water temperature with local seaweed (Sargassum) and freshly collected seawater from 500 and 1000m seawater depth. Preliminary results of oxygen consumption from whole frond and macerated kelp indicate there is multiple phases or modes of remineralization that occur over the potential timescale of deposition. These phases may include Sargassum's own respiration, monotonic respiration coupled to remineralization, and a bacterial bloom phase (Fig. 3A and B).

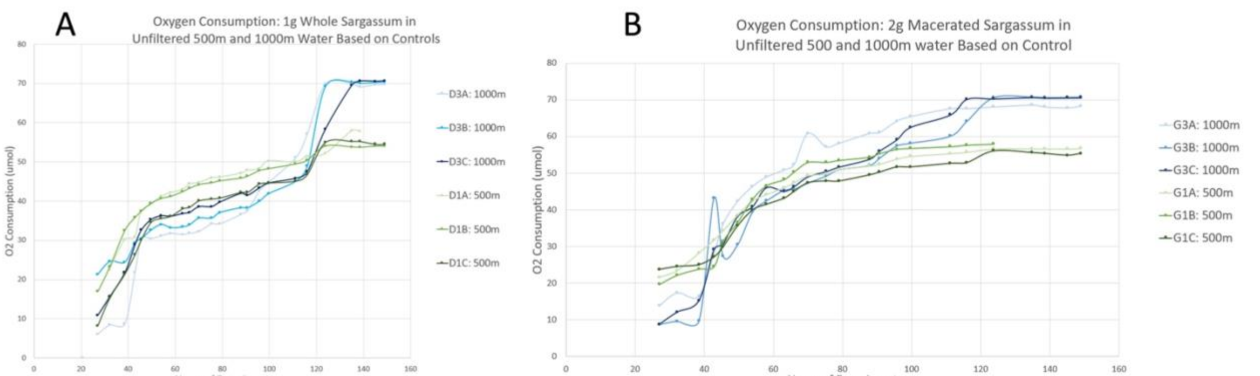

Figure 3. Respiration incubation results as a function of oxygen consumption with whole frond (A) and macerated Sargassum (B) incubated with seawater collected from 500- and 1000-meter seawater depth.

M3.1 - Seaweed DOC Fates Methods Development
Completion level - 10%

As part of milestone 3.1 (*Seaweed DOC Fates Methods Development*), we have begun testing incubation methods to constrain the magnitude of *M. pyrifera* NPP released as dissolved organic carbon (DOC). We have developed an incubation procedure which allows for the simultaneous determination of whole blade net primary production, measured as the net change in total dissolved inorganic carbon concentrations (DIC), and DOC release. Whole blades are clipped between the pneumatocyst and stipe and incubated in acrylic tanks in temperature-controlled water baths. Preliminary results demonstrate a decrease in NPP with blade age (measured as distance from the tip of the frond; Figure 4a) which is consistent with previous studies of giant kelp (Rodriguez et al. 2016; *Oecologia*). Additionally, a negative trend between percent extracellular release (the percentage of NPP released as DOC) and NPP was observed (Figure 1b), however variability in the small sample set was observed (Figure 4b: encircled data points) and the negative relationship was not significant (Model II regression; r^2 = 0.06, p = 0.25). Exclusion of these outliers similarly showed a negative relationship between PER and NPP and was significant (Model II regression; r^2 = 0.81, p <0.01). More intensive sampling of this relationship will be pursued as per milestone 3.2 (*validation of methods*) and 3.3 (*measuring / modeling DOM release rates*).

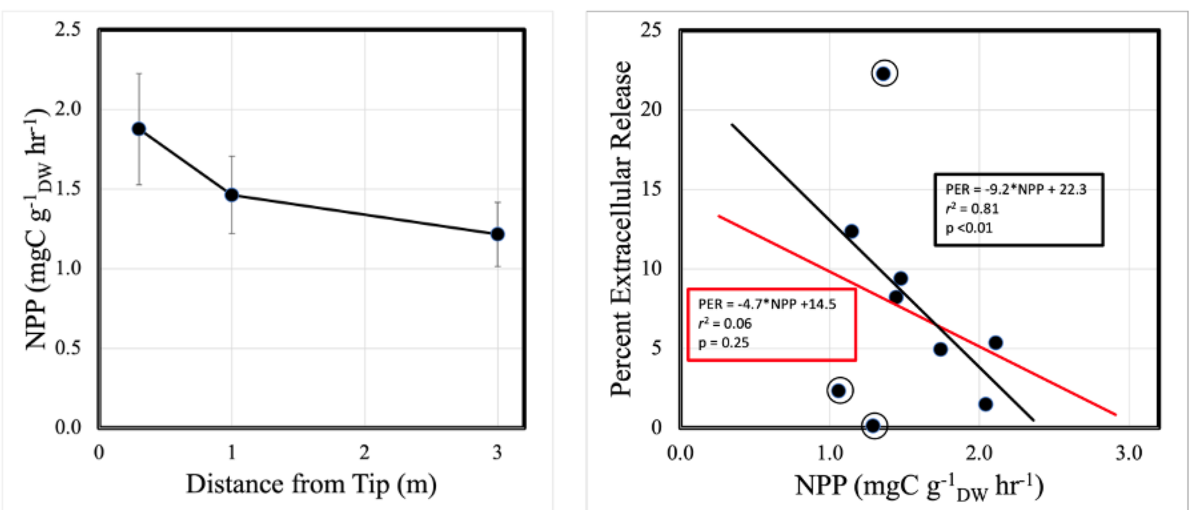

Figure 4: *M. pyrifera* carbon fluxes. (a) NPP measured from single blades at three different lengths from the growing tip of a frond: 0.3, 1, and 3 meters. A longer distance indicates an older blade. Points and error bars are the mean ± 1SD of triplicate incubations (b) Relationship between NPP and percent extracellular release (PER). The red line indicates the model II regression slope of all the data. The black line indicates the model II regression line after excluding the 3 outlier points (encircled points). The inset boxes are the model II summary statistics for each regression analysis and are color coded with their respective regression line.

Tasks 4.0 - Modeling the environmental impacts of seaweed cultivation and sequestration

We have chosen the Southern California Bight (SCB) as the initial region to model the environmental impacts of seaweed CDR (M4.1; *Choose Initial Farm / Sequestration Site*; 100%

complete). This choice is guided by (1) the pre-existing suite of coupled circulation-biogeochemical simulations (ROMS-BEC) for this region developed and maintained by the McWilliams and Bianchi groups at UCLA and (2) the historical and planned observations in the same region (e.g., SBC LTER). We are in the process of defining farm scenarios (single and multi-farm experiment, see Figure 5) for the modeling (M4.2; *Develop Farm Scenarios for Modeling*, 50% complete). The considerations for these scenarios (e.g., nutrient availability, farm technology, intended CDR scales, marine use conflicts) have been detailed in a white paper that is in preparation.

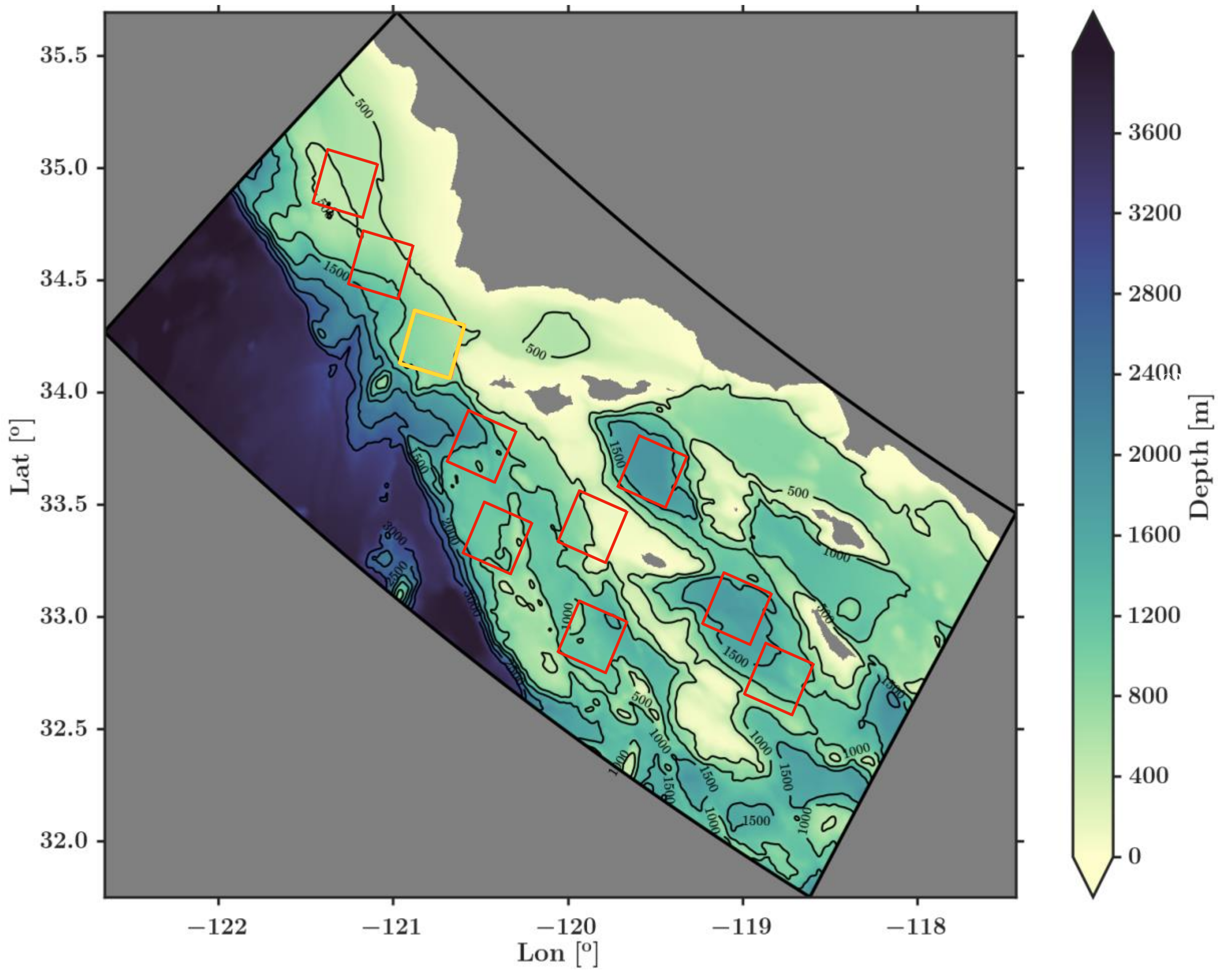

Figure 5: Farm scenarios in the Southern California Bight (SCB) modeling domain. The red and yellow squares indicate 27 km x 27 km farms. We intend to perform two initial experiments: single-farm (yellow) and multi-farm (red and yellow). The single-farm location is chosen to approximately optimize nutrient uptake, avoid marine use conflicts, and sit away from modeling domain boundaries. The scale of these farms was chosen large enough so that they could, in principle, remove 0.01 Gt CO_2 per year assuming that there are 10 other locations globally where these activities are occurring. The scale of these modeled farms is not feasible with present-day technology and logistical constraints, although they may be in the year 2050 given investment and interest.

The present model development is focused on (1) developing a seaweed farm (growth) model for *M. Pyrifera* (Task 4.3; *Develop Macroalgae Farm Model*, 30% complete), (2) developing the vertical conveyance and settling model (Task 4.4; *Develop & Implement Modeling System*; 5% complete) and (3) coupling the farm and conveyance and settling models to ROMS-BEC in realistically forced simulations (also part of Task 4.4, 20% complete). We are presently developing a simplified version of a macroalgal growth (MAG) model (Task 4.3) originally developed via MARINER (Frieder et al. 2022; *Frontiers in Marine Science*). Through this project and ongoing MARINER work, the code infrastructure for coupling MAG to ROMS-BEC is 85% complete. The testbed for this coupling is a realistically forced SCB simulation. The ROMS-BEC-MAG coupled modeling system includes physical interaction of kelp and currents (drag, mixing) and feedbacks with biogeochemistry (competition for nutrient uptake, modulation of photosynthetically active radiation). The implementation of the simplified MAG model for the CDR modeling should be trivial. In future quarters, we intend to test the upper-ocean kelp coupling in ROMS-BEC-MAG simulations and further develop the vertical conveyance and settling model.