ARPA-E Quarterly Technical Report
Award - DE-AR0001559
Quarter 6 (February 1, 2024 – April 30, 2024)

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 sixth quarterly report for the SeaweedCDR project, covering the period February 1, 2024 to April 30, 2024. The two deliverables proposed for this quarter are M2.3 (Validation of Biomass Fate Methods - a go/no go milestone) and M3.5 (DOM Remineralization Rate Measurements and Modeling). We have made considerable progress on Task M2.3 (now at 90% completion), which is documented below. We expect this milestone to be 100% completed before our presentation on this QR on June 18.

We will not be able to complete M3.5 (DOM Remineralization Rate Measurements and Modeling) as proposed in the SOPO. The experiments needed for M3.5 require many months to perform and, although we have many experiments underway, we only have scant preliminary results at this time. We do have excellent results for kelp DOM production rates (M3.3) and kelp DOM composition (M3.4) and are very far along with each of these at this time. Hence, we will present these milestone results here. In reflection, we should set the due date for M3.5 behind the other two.

We also have exciting new results for modeling mCDR sequestration time scales (M4.6). The new modeling includes finite time CO_2 gas transfer physics and demonstrates much longer sequestration time scales for seaweed CDR than determinations made without properly accounting for the physics of CO_2 gas exchange, as well as Measurement, Report and Verification (MRV) challenges looming for any mCDR approach.

Last, we several T2M milestones to report out on; namely, Publication of Method Protocols (M6.6) and Scientific Outreach and Publications (M6.7).

Task 2 – Quantification of Seaweed Biomass Fates
M2.3 – Validation of biomass fates methods - Completion level – 90%

The goal for task M2.3 is to validate the precision of methods used to assess the fate of kelp biomass through a series of laboratory and field-based experiments that were outlined in the previous quarter (see Krause et al., 2023b). Task M2.3 aims to quantify the precision of the methods used to quantify the fate of kelp biomass. The goal is to assess measurements from at least three replicates that the biomass decomposition and sinking rates can be determined within 20% of the average value and the product partitioning fraction (DIC vs. DOC vs. POC) within 10%. This is a Go/NoGo milestone. We have made considerable progress has been made in both our laboratory and field-based experimental methods, which are discussed below.

Laboratory Experiments

Precision of POC, DOC and DIC measurements

Our incubations thus far have included 5 treatments (seawater control, pneumatocysts, stipes, blades, and whole kelp segments), each with three technical replicates, under two redox conditions (anoxic and oxic). Analysis for SPOC (suspended POC in the seawater during our incubations) was done by the automated organic elemental analyzer at the UCSB Marine Science Institute Analytical lab, which has a precision of ± 0.3%. Analysis for DOC was done by the Carlson lab on the UCSB campus using high-temperature combustion method using a TOC-V or TOC-L analyzer (Shimadzu, Kyoto, Japan) with a 25 µmol per liter C detection limit. Analysis for DIC was also done in the Carlson lab at UCSB using an Autonomous Infra-Red Inorganic Carbon Analyzer (AIRICA) with 2 µmol C/L detection limit.

Part of task M2.3 is to demonstrate the precision of our methods. As an outcome of the previous report meeting, we were requested to provide the number of timepoints where our data fall within our target precision goal of 10%. From our anoxic incubation, performed at sea on a recent 2023 research cruise, SPOC, DOC, and DIC was collected. We calculated averages, standard deviations, and the precision (average values across technical replicates divided by the standard deviation and made into %) of all collected data. SPOC had two timepoints ($T_{initial}$ and T_{final}) where out of the two measurements for the 5 treatments, only 3 out of 10 (30%) SPOC averages had precisions at or below the target range of 10%. For DOC in the anoxic incubation, out of the 5 time points per treatment, 2 out of 25 (8%) DOC averages had precisions at or below the target range of 10%. For DIC in the anoxic incubation, out of the 5 time points per treatment, 16 out of 25 (64%) DIC averages had precisions at or below the target range of 10%.

From our oxic incubation, which was done at UCSB in the laboratory, precisions were also calculated similar to the anoxic incubations described above. For SPOC in the oxic incubation, out of 3 time points per treatment, 10 out of 15 (66%) SPOC averages had precisions at or below the target range of 10%. For DOC, out of the 8 time points per treatment, 19 out of 32 (59%) DOC averages had precisions at or below 10%. For DIC, out of the 5 time points per treatment, 27 out of 30 (90%) DIC averages had precisions at or below our target range of 10%.

We believe the variation we see in the data is explained by two main reasons. 1) Particularly in our anoxic incubations, conducting this experiment on a moving research vessel in summer of 2023 posed challenges such as obtaining precise weights of kelp biomass and seawater volumes. Additionally, we can attribute some of the error to unforeseen challenges in our protocols as this incubation was our first attempt at using our developed protocols. However, as shown in our precision from the oxic experiments, we were able to apply what we learned in the first anoxic incubation to our second oxic incubation, which was performed at UCSB in a much more controlled environment where we showed improved robustness of method(s) precision. As we continue to do more incubations, we are also optimizing our methods to reduce the amount of variability and demonstrate robustness. 2) We also attribute the variation in the precision to the natural variation associated with the biological processes (i.e., kelp and microbial respiration) across the technical replicates, which do not interact with each other. There is little that we can do about the natural variability associated with biological processes occurring during our incubations. But we believe more incubations and obtaining more comparable results will aid discussion in environmental variability versus error.

Within the last quarter we have conducted another kelp degradation incubation. This incubation was conducted in the dark but at a slightly higher temperature of 14 °C. In these incubations we sampled for bulk POC, SPOC, DOC and DIC. Currently analysis of these samples are underway through the methods outlined in Krause et al., (2023b) and preliminary results and interpretations of this analysis will be shown in the quarterly report meeting in June.

Kelp degradation rate constants

Another component of task M2.3 is to determine the kelp degradation rate constants and demonstrate the precision to be within 20%. Kelp degradation rate constants were quantified only in the oxic incubations (both 4 and 14 °C) that were conducted in the lab at UCSB. Rate constants were determined by the grams of wet weight biomass lost per total grams of wet weight, per day. Generally, our results show that kelp biomass degrades slower in colder temperatures. Kelp degradation rate constants of pneumatocysts, stipes, blades and whole segments during the 4 °C incubation were on average 0.003 ± 0.004, 0.016 ± 0.0001, 0.012 ± 0.002, and 0.01 ± 0.0006, respectively. Kelp degradation rate constants of pneumatocysts, stipes, blades and whole segments during the 14 °C incubation were on average (n = 3) 0.017 ± 0.001, 0.022 ± 0.001, 0.115 ± 0.01, and 0.102 ± 0.014, respectively. Generally, the precision of the kelp degradation rate constants was lower in the incubations at 4 °C than the rate constants determined in the 14 °C incubation. With the exception of the pneumatocysts in 4°C, the precision in determining the kelp degradation rate constants is at or below our target precision cap of 20%. Rate constant precision in the 4°C incubation for the pneumatocysts, stipes, blades, and whole segments were 133%, 0.6%, 0.2%, and 6%, respectively. Rate constant precision in the 14°C incubation for the pneumatocysts, stipes, blades, and whole segments were 6%, 4.5%, 8.7%, and 13.7%, respectively. Our results demonstrate that temperature appears to be an important parameter to consider with degrading kelp. Moreover, at lower temperatures, more macerated stipes have higher degradation rate constants than an intact whole frond which could highlight the importance of sinking less macerated kelp biomass, but more results are necessary before a firm conclusion is drawn.

Field Experiments

Field-based sinking rates

For field-based kelp sinking rate experiments, we collected a total of 6 fresh kelp fronds ranging in mass between 0.4 to 2 kg from Mohawk Reef off-shore of Santa Barbara, Ca. Off Santa Cruz Island, a surface buoy and a line (with depth markings) was dropped in ~ 30 m (~100 ft) of water. Because kelp fronds naturally float, we constructed a 1 X 1 meter platform made from a PVC frame and polycarbonate mesh to keep the kelp fronds from floating to the surface and guide the kelp fronds as it sinks (Fig.1). Two sinking rate experiments were performed (2 dives) 1) unaltered kelp fronds with intact pneumatocysts; 2) altered kelp fronds with popped pneumatocysts. During each dive, three kelp fronds were placed underneath the platform. With the assistance of scuba divers, the platform with kelp fronds were lowered slowly along the drop line. A diver with a camera filmed the descent of the kelp. The sinking rate of the kelp fronds would only be determined when the kelp fronds separated from the platform and start sinking on their own without the aid of the divers or the platform.

Unalerted kelp fronds with intact pneumatocysts were never observed to separate from the PVC platform and sink on their own throughout the 30 m descent. However, divers observed the pneumatocysts popping just before 30 m and at 30 m. Kelp fronds with popped pneumatocysts in the second dive behaved similarly to the unaltered kelp fronds. However, in the last 2-2.5 meters the divers observed the bunched-up kelp fronds sinking on their own. Due to subsurface surge, bunching-up of individual kelp fronds and turbidity, it is difficult to provide precise in situ sinking rates of individual fronds. Nevertheless, from our available video footage, we can provide an estimated sinking rate of a kelp raft consisting of three fronds with a combined mass of ~2.5 kg. The sinking rate of a kelp raft with popped pneumatocysts ranged between 0.077 and 0.053 m s^{-1}, where the former rate is calculated at the moment when the kelp first touched the seafloor and the ladder rate is when the full kelp raft settled on the seafloor. These rates are similar to what was measured in the laboratory of masticated kelp biomass averaging 0.087 m s^{-1} ± 0.531 (n = 28) for stipes, 0.033 m s^{-1} ± 0.028 (n= 30) for blades and 0.053 m s^{-1} ± 0.22 (n = 20) for the pneumatocysts.

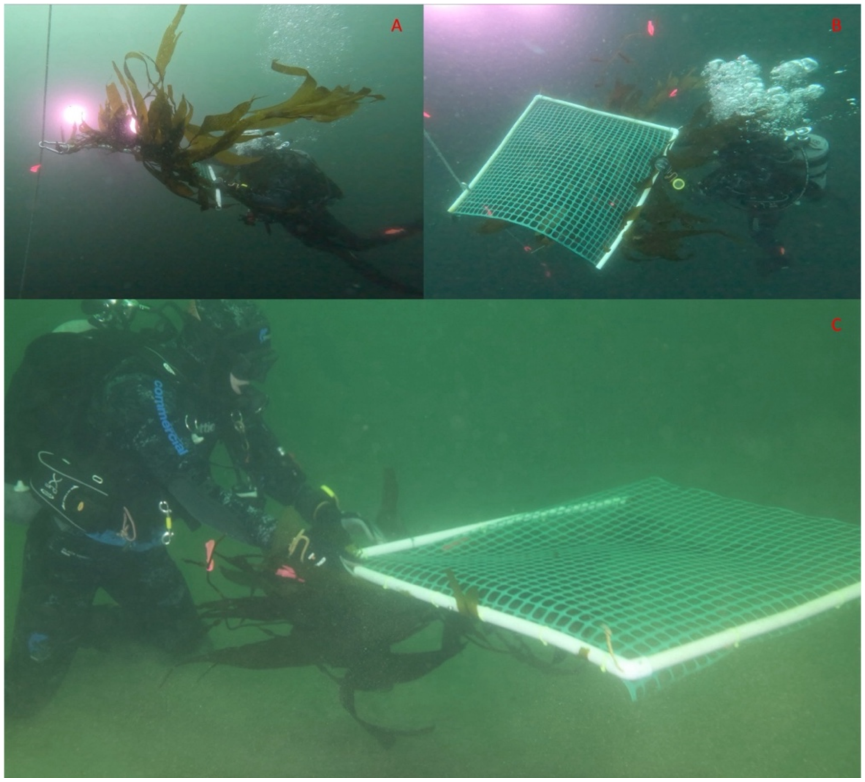

Figure 1. Images from the kelp sinking rate experiments. A) Divers lowering kelp using PVC platform at ~15 meters; B) top view of divers lowering platform with kelp underneath at ~ 20 meters; C) divers with kelp still being held down by PVC platform nearly on the seafloor at ~30 meters.

The findings from the sinking rate experiments in the field suggests that for rapid conveyance of kelp biomass to the seafloor, there will need to be some mechanism that aids the sinking of kelp biomass to depths > 30 meters. Conveyance techniques like short-depth pumping of masticated or whole fronds described by Krause et al. (2023a) to depths > 30 meters would have the greatest potential to convey kelp to the seafloor.

Filed-based Kelp Degradation Experiments

At the time of writing this report, we are actively conducting field-based kelp degradation experiments. We are prioritizing experiments in shallower depths (5-30 meters) but will also conduct deeper experiments with moorings (> 100 meters). For the shallow kelp degradation experiments, SCUBA divers will be placing kelp on the seafloor across 4 stations across a depth transect with depths ranging between ~5 and ~30 meters. Kelp will be packaged in onion and spat bags which have varying mesh sizes to either permit or limit macrofaunal interactions on the kelp. These packages will be anchored and left on the seafloor and checked every 5-7 days for up to two weeks. Kelp degradation rates in these experiments will be determined using the wet weight of the kelp biomass before and after the experiment. Any macrofaunal interactions will also be recorded.

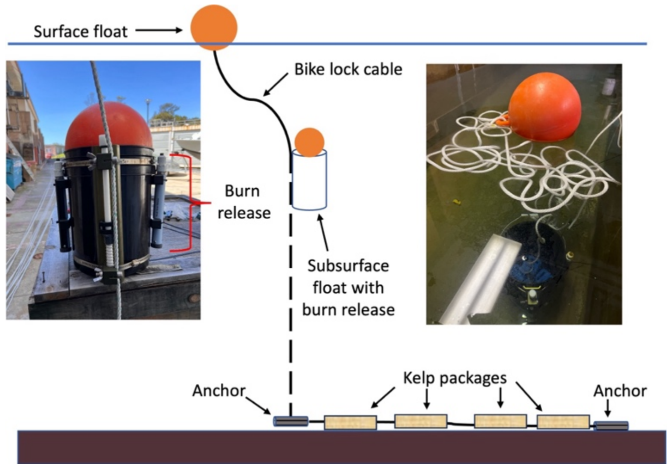

Figure 2. Schematic of modified mooring line with coated bike lock cables and subsurface float with burn release systems.

For deeper deployments of kelp packages (>100 meters), we will be using moorings similar to what we have used previously. However, we will be modifying these moorings to be more durable to reduce loss from ship strikes and have contingencies to increase our chances of recovery. Figure 2 shows a schematic of our modified mooring setup. We will be adding 3-meter coated bike lock cables below the surface buoy to reduce damage and severance of the mooring lines due to ship strikes. Additionally, we will add a subsurface buoy with a timed-release system, which will be positioned at a shallower depth (~10 meters). This system is designed to release a subsurface buoy at a set time such that in the event the surface buoy is lost, we would still have a secondary buoy to recover our package. We plan to have these out as soon as possible after the shallow water kelp deployments described above.

We have also ordered acoustic release systems from Desert Star Systems. These are made to order and are currently being constructed by the company. As soon as we receive these acoustic release systems, we will be able to perform deeper deployments.

Task 3 – Quantify Fates of Seaweed Dissolved Organic Matter (DOM)

Deliverable – M3.5 - We are asking to postpone the M3.5 deliverable to Quarter 10. M3.3 (Kelp DOM production) and M3.4 (Kelp DOM composition) are 75% complete and will be presented here.

Leads: Chance English and Craig Carlson (UCSB)

As mentioned above, work is on-going to measure the DOC remineralization rates and the proportion that is recalcitrant to heterotrophic remineralization (M3.5). However, remineralization experiments are done using batch cultures of natural bacterioplankton communities from nearby kelp forests and each one takes ~3 months to complete. Several experiments are currently on-going and will be completed during quarters 8 and 9. As a result, we request that our deadline for M3.5 be moved from Quarter 7 to Quarter 10.

Here, we highlight results from M3.3 (Kelp DOM production) and M3.4 (Kelp DOM composition). Each are presently 75% complete. We expect to complete these milestones earlier than proposed. Methods for our approach can be found as a preprint in (English and Carlson, 2023; DOI:10.31223/X5167F). To summarize, we find that key regulating parameters for DOC release rates are net primary production and age-related kelp physiological decline. When mature kelp blades were <50 days old, DOC production was found to be a small and constant fraction (~3 ± 2.7%) of kelp net primary production (NPP). Following a decline in kelp physiological condition after 50 days, DOC release became uncoupled from NPP and the daily release of DOC exceeded that of daily NPP, suggesting loss of previously fixed carbon to the dissolved pool. We refer to this loss of biomass carbon to the DOC as solubilization. Rates of solubilization ranged from <1-8% d^{-1} and increased exponentially with the decline of blade physiological condition. Using a simple model for kelp solubilization, we estimate that for the average lifespan of a blade (~100 days), solubilization can produce DOC equivalent to almost 70% of kelp biomass carbon. Following similar trends in *M. pyrifera* DOC release, we found that DOC composition was significantly related to kelp physiological condition. DOC transitioned from fucose-rich polysaccharides to mannuronic acid-rich polysaccharides. Mannuronic acid is one of alginate's two main sugar monomers, an important structural polysaccharide in kelps. Its release into the surrounding seawater as DOC further confirms that kelp tissue was being solubilized following a decline in physiological condition with age.

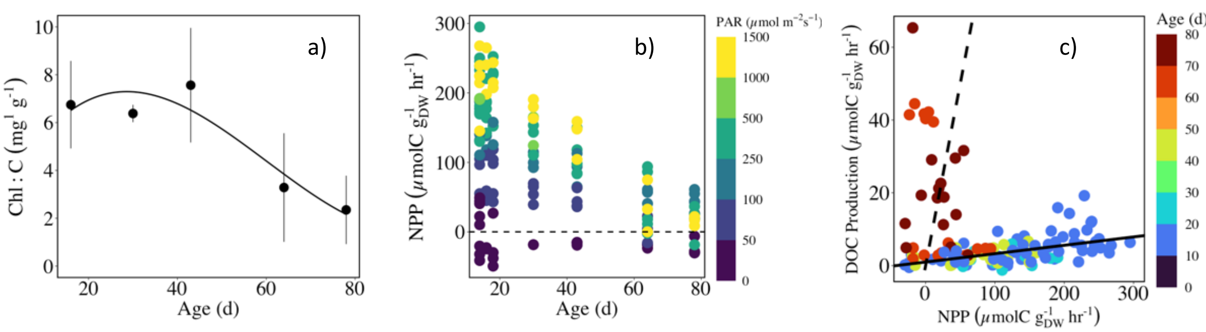

Figure 3: (a) Age related decline in kelp blade physiological condition and (b) NPP. (c) Relationship between DOC production and NPP across all age groups. The solid black line shows the significant linear relationship (Model II Linear Regression, $R^2 = 0.31$, $p < 0.001$). The dashed black line shows the 1:1 line highlighting that DOC production from older kelp can exceed new biomass production from NPP.

Kelp DOC Production Rates (M3.3) - 75% Completed

To parameterize DOC release rates, we performed laboratory incubations of whole giant kelp blades under varying environmental and physiological conditions. *M. pyrifera* biomass turns over several times a year during which whole fronds and blades senesce and are replaced by new frond cohorts. To control for the effect of progressive senescence on kelp DOC production, we tagged frond cohorts in the field and periodically sampled them every 2-3 weeks. We subsampled 6 blades from an age cohort at each sampling interval and transported them to our near-shore incubation chambers. Incubations were performed under 6 light levels ranging from 0-1500 µmol photons m^{-2} s^{-1} for 2-3 hours. Net primary production was measured as the change in dissolved inorganic carbon between the initial and final timepoint. DOC samples were collected alongside NPP measurements (measured by TCO_2 consumption), and both were normalized to the incubation volume and dry mass of the *M. pyrifera* blades. Blade physiological condition was measured as the Chlorophyll to Carbon ratio (Chl:C), a proxy which is correlated to kelp growth rate and age (Bell et al., 2018; Bell and Siegel, 2022). Blades were sampled across five different age cohorts between 16-78 days.

We observed a decline in Chl:C after 43 days and found that the maximum photosynthetic potential for giant kelp declined linearly with age (Figure 3ab). We found that hourly DOC release rates were positively correlated with hourly NPP rates when kelp was <50 days old (Figure 3c). After 50 days DOC became uncoupled from NPP, and hourly DOC release was often greater than or equal to hourly NPP. During senescence, the large DOC production rates continued in the dark when photosynthesis stopped. As a result, DOC production exceeds NPP when *M. pyrifera* blades senesce which suggests that kelp biomass was being solubilized into DOC. To parameterize solubilization, we normalized the DOC release rates for blades older than 50 days to the biomass carbon of each kelp blade, resulting in a solubilization rate (d^{-1}). The solubilization rate ranged from <0.01-0.08 d^{-1} and was exponentially correlated with tissue Chl:C (Figure 4a). As kelp Chl:C decreases with age, it is likely that large amounts of previously fixed carbon (i.e. biomass) are solubilized into the dissolved pool during progressive senescence. Based on our observations, we used an average solubilization rate of 0.022 d^{-1} to estimate the potential production of DOC from senescing kelp. We assumed that kelp senescence began at 50 days and ended at 100 days, which is the average lifespan of a giant kelp blade (Bell and Siegel, 2022; Rodriguez et al., 2013). The total amount of fixed biomass that could be lost to the dissolved phase through solubilization can be estimated as

$$\%Biomass\ Remaining = 100(1 - 0.022)^t$$

where 0.022 d^{-1} is the daily solubilization rate and t is time in days. This solubilization would result in 67.2% of kelp biomass carbon lost to DOC after 100 days (Figure 3b). We assume the remaining biomass would be lost as particulate organic carbon. We note that the use of an average solubilization rate (0.022 d^{-1}) may overestimate the solubilization at the onset of kelp senescence when tissue Chl:C is still high (Figure 4a), however it also underestimates the solubilization rates for older kelp where rates reach up to 0.08 d^{-1}. Current work is focused on building an age-dependent solubilization rate based on multiple age cohorts of giant kelp, which would more accurately constrain the role of solubilization in kelp DOC production.

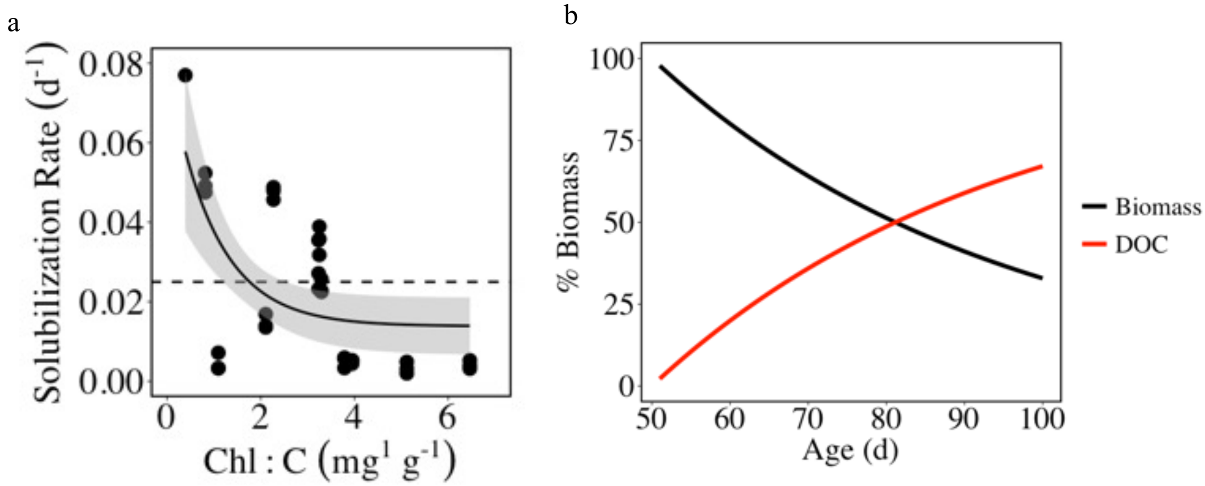

Figure 4: (a) Solubilization rates for kelp blades older than 50 days as a function of kelp physiological condition. Low Chl:C indicate more degraded kelp and higher Chl:C indicate less degraded kelp. Solid black line is the exponential best-fit line with ± 1SE (shaded region). The dashed black line is the average solubilization rate (0.022 d^{-1}) for kelp older than 50 days. (b) Model results for the biomass solubilization based on average rates from (a). The cumulative proportion of biomass carbon lost over 50 days of senescence is shown in the black line and the proportion that would be recovered as DOC is shown in the red line. At day 100 nearly 70% of kelp biomass would enter the DOC pool assuming a constant solubilization rate.

Kelp DOC Composition (M3.4) - 75% Completed

DOC produced by seaweeds is a complex mixture of compounds including carbohydrates, small metabolites, and volatile organic compounds. Carbohydrates make up the bulk of the DOC released by marine autotrophs, including seaweeds (Abdullah and Fredriksen, 2004; Buck-Wiese et al., 2023; Myklestad, 2000; Myklestad et al., 1997; Wada et al., 2007). We characterized the sugar composition of giant kelp-derived carbohydrates using high-performance anion exchange chromatography. We found that there was a significant shift in the contribution of individual sugar monomers between mature and senescent kelp (PERMANOVA, $p<0.05$). In blades younger than 50 days, we found that fucose was the main component of *M. pyrifera* derived DOC, whereas mannuronic acid became the largest component after 50 days (Figure 5). As mannuronic acid is associated with alginate, a structural polysaccharide in kelps, its release is consistent with the observed solubilization described in section 1. This shift in carbohydrate composition may also change the bioavailability of the DOC released by giant kelp. Fucose-rich polysaccharides such as fucoidan are structurally recalcitrant and may turnover much slower than alginate which is typically remineralized quickly (Sichert et al., 2020; Zhang et al., 2024).

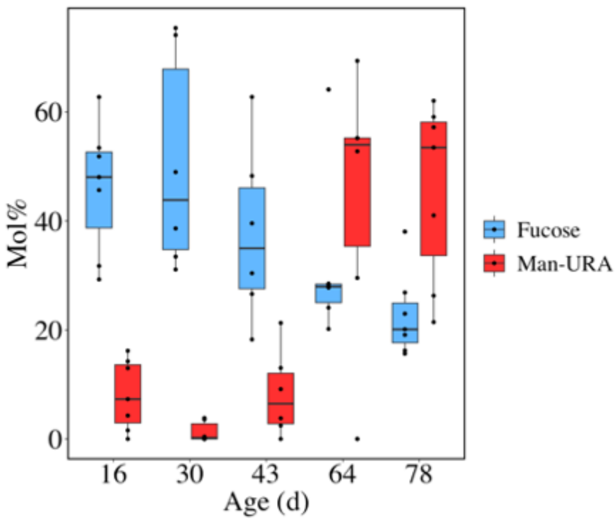

Figure 5: Molar percentages (Mol%) of Fucose and Mannuronic-acid (Man-URA) to the total carbohydrate pool accumulated in laboratory incubations of giant kelp blades. The molar percentage of the two sugars are reported at 5 age timepoints for a single tagged cohort of kelp. The boxplots at each age are offset at each age to allow comparison.

Task 4 – Modeling the environmental impacts of seaweed cultivation and sequestration

Deliverable – None

Leads: Daniel Dauhajre, Danielle Bianchi, Ahn Pham & Jim McWilliams (UCLA), Kaley Sten, Kana Yamamoto & David Siegel, (UCSB)

We are actively continuing the ROMS-BEC-MAG model development and validation efforts targeting a virtual seaweed mCDR experiment in the Southern California Bight (Task 4.5-4.6). On April 19, we held an all-hands workshop at UCSB focusing on finalizing our initial set of model equations and parameters for the coupled ROMS-BEC-MAG model by integrating our empirical results. This will be documented in a model description paper to be submitted this summer.

We also have made great progress on assessing the durability of seaweed mCDR (M4.6 - Assessing Sequestration Time Scales for Seaweed CDR). This work builds on the paper by Nowicki et al. 2024, which developed a linearized model for organic carbon storage by the natural biological pump and the very significant role of finite time of air-sea CO_2 exchange (increases estimates of carbon storage by ~35% globally). Yamamoto et al. (submitted) extended this work developing a linearized modeling system for assessing generalized metrics for mCDR durability with an interacting atmosphere and applied it to ocean alkalinity enhancement (OAE). Here, we have applied this approach for assessments of durability metrics for seaweed CDR.

M4.6 - Assessing Sequestration Time Scales for Seaweed CDR - 50% Completion

The goal of this work is to understand the timescales of carbon sequestered by the purposeful sinking of seaweed by answering two questions. 1) How do these timescales vary by location and conveyance to depth? 2) What roles do the burial and remineralization of partially buried seaweed biomass have on durability? This work is underway and preliminary results were presented at this year's Ocean Science Meeting in New Orleans (Sten et al. 2024 OSM Poster Presentation).

The goal of any CDR action is to reduce atmosphere CO_2 levels. Following Coleman et al. (2022), we define the cumulative additionality (α) as the ratio between the perturbation in the atmosphere and the perturbation in the ocean resulting from a CDR action, or

$$\text{Cumulative Additionality} = \alpha = \frac{\Delta C_{atmosphere}}{\Delta C_{CDR}}$$

where $\Delta C_{atmosphere}$ is the change in atmospheric CO_2 concentration and ΔC_{CDR} is the change in ocean carbon relative to its starting perturbation (Yamamoto et al. submitted). In regions where there is instantaneous exchange between atmosphere and the ocean before a parcel of water is subducted into the interior ocean, α will be equal to one. However, any mCDR action will affect the surface ocean and not the atmosphere. Thus, initial α values will be zero. Over the next several years to decades, there an ingassing stage near the location of the mCDR action increasing values of α (Figure 6a). The duration of the ingassing stage is a function of the time scales of air-sea CO_2 exchange and residence times of waters at the surface and hence, location. After this initial ingassing phase, the mCDR perturbation to the global atmosphere-ocean system will create an imbalance that is compensated by a global outgassing from the ocean, reducing α values. Figure 6a shows examples of direct air capture (DAC) and instantaneous conveyance of seaweed carbon to the seafloor for several locations where seaweed CDR is considered. Values of α for DAC CDR start at one (there is no ingassing phase) and decrease over time, while cumulative additionality determinations for seaweed CDR start at zero increase towards one and then decrease following the DAC curve. After >100 years, the seaweed α values decrease further as the conveyed seaweed carbon is now transported back to the sea surface where it interacts with the atmosphere lowering α further (Figure 6a).

Direct air capture is obviously the most effective means of removing CO_2 from the atmosphere and hence, is a useful standard to compare all CDR approaches to. Here, we define the relative efficiency, ε, as the ratio of the cumulative additionality for a mCDR approach to that for DAC, or

$$\text{Relative Efficiency} = \varepsilon = \frac{\alpha_{mCDR}}{\alpha_{DAC}}$$

Figure 6b illustrates differences in the time course of seaweed CDR relative efficiency with instantaneous conveyance to the seafloor for selected locations. The initial ingassing phase is quite short (~5 y) for the Gulf of Maine site while it is much longer (>20 y) for equatorial Pacific sites. The initial ingassing phase is followed by the global outgassing phase that mirrors DAC CDR for up to about 100 years after the mCDR action. Values of relative efficiency are quite high (nearly 1) during this phase indicating that seaweed CDR can be highly efficient if the farmed carbon biomass conveyed rapidly to the seafloor. After 100 years, the conveyed biomass is transported back to the sea surface where it can interact with the atmosphere, reducing values of ε (Figure 6b). This illustrates that seaweed CDR is not a permanent solution unless the conveyed biomass is incorporated into seafloor sediments.

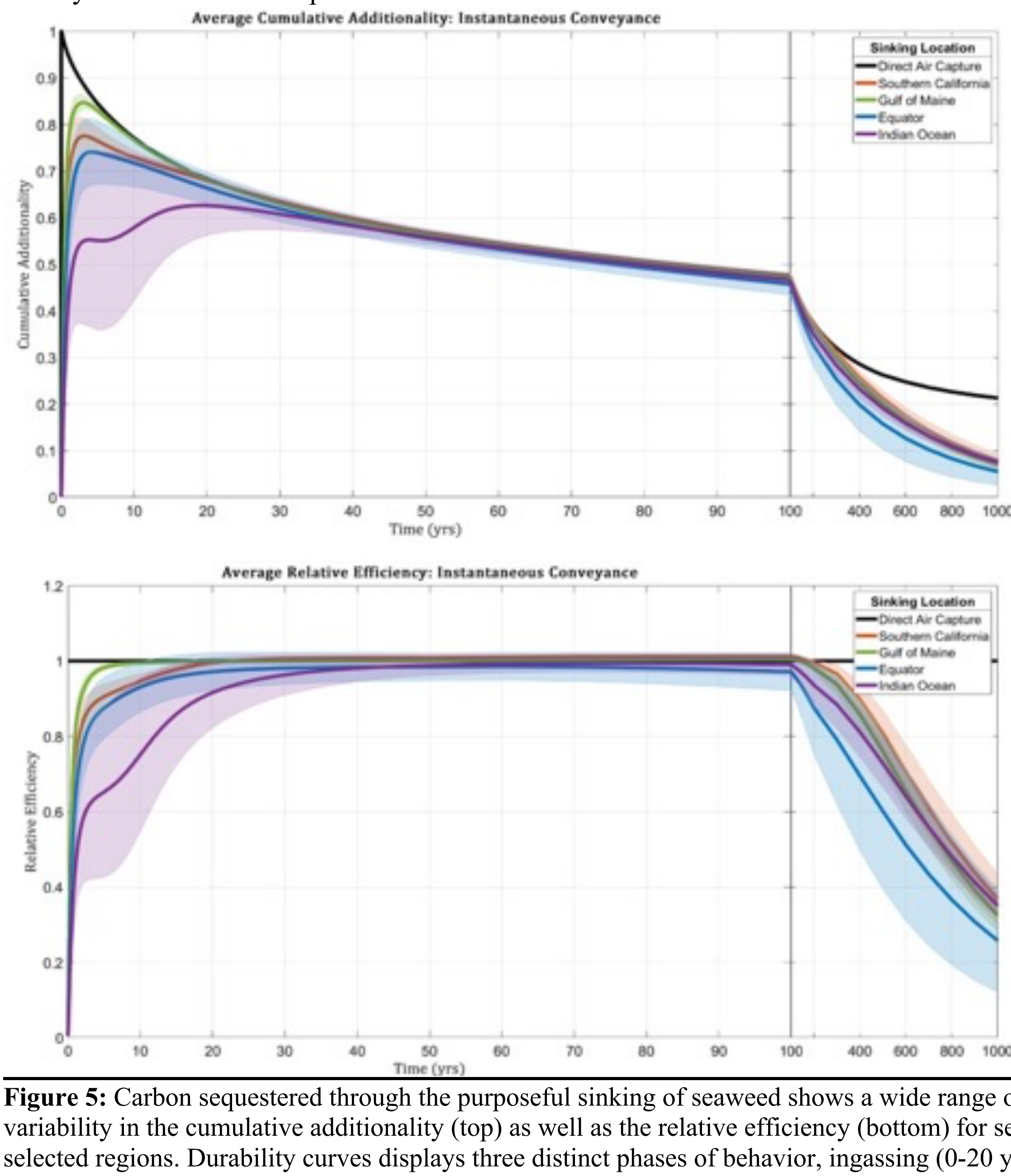

Figure 5: Carbon sequestered through the purposeful sinking of seaweed shows a wide range of spatial variability in the cumulative additionality (top) as well as the relative efficiency (bottom) for several selected regions. Durability curves displays three distinct phases of behavior, ingassing (0-20 years), outgassing insync with DAC (20-100 years), and outgassing of originally sequestered carbon through mixing (100-1,000 years). Due to the inefficiency of ingassing timescales, no location ever reaches a

cumulative additionality of one, and due to outgassing of originally sequestered material seaweed mCDR cannot be considered a permanent solution. Envelopes illustrate the standard deviation among sites within each region selected.

Next steps include evaluating the impacts of finite time conveyance of biomass to the seafloor using our empirical assessments of biomass sinking speeds and decomposition rates. Preliminary work has shown that the durability metrics are highly sensitive to slow sinking speeds (< 100 m/d), but are not as sensitive to faster sinking speeds (> 1000 m/d). This implies that there is a critical threshold for maximizing the total quantity of carbon conveyed to depth. We are also in the process of assessing the roles of burial on durability, the importance of the CO_2 air-sea flux disequilibria assumption and the collocation of suitable seaweed farms and sequestration sites following Arzeno-Soltero et al. (2023). We expect to submit a manuscript on the durability of seaweed CDR by the end of the summer.

Task 6 – Technology to Market

M6.6 - Publication of Method Protocols - completion = 67%

The goal of this milestone is to publish our methods protocols for both the modeling and empirical work. To date, we have published on the preprint server EarthArXiv four white papers detailing rationale and procedures for several aspects of the SeaweedCDR project. These white papers have Digital Object Identifiers (DOIs) and hence are searchable in Google Scholar and other tools (see listings below). We consider these publications as appendices for scientific publications that will follow once we have completed our research objectives. The four white papers published to date are listed below. Note that we have decided to publish our planned white paper on modeling the impacts of seaweed cultivation and sequestration biomass as a peer reviewed publication and expect to have that submitted this summer.

M6.7 - Scientific Outreach - completion = 20%

As mentioned above, we have developed and validated a linearized modeling framework for assessing the durability for any mCDR approach that includes finite time gas transfer. A description of this model is in Yamamoto et al. (submitted). A list of peer reviewed papers is given below and is listed on our website.

The SeaweedCDR project made five presentations at the 2024 Ocean Sciences Meeting in New Orleans, LA during this past quarter. Authors and abstract titles are listed below.

A few upcoming events of note. First, PI Siegel will be participating in a webinar on seaweed CDR organized by the California Ocean Science Trust on May 23. More information and registration for the webinar is at https://us02web.zoom.us/webinar/register/WN_EpNPU-f7S1GZG2LlMdaKNQ?mc_cid=dbee2df97f&mc_eid=b66b2bd788#/registration. Further, we will be visited next month by Warren Cornwell, a reporter at *Science* magazine, who is writing a news article on seaweed CDR. He wants to learn about the SeaweedCDR project and get some pictures for the article. His visit is being coordinated with the sampling of Ocean Rainforest farm led by Kristen Davis and her team.

References:

Abdullah, M.I., Fredriksen, S., 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.

Arzeno-Soltero, I. B., Saenz, B. T., Frieder, C. A., Long, M. C., DeAngelo, J., Davis, S. J., & Davis, K. A. (2023). Large global variations in the carbon dioxide removal potential of seaweed farming due to biophysical constraints. *Communications Earth & Environment*, *4*(1). https://doi.org/10.1038/s43247-023-00833-2 Bell, T.W., Reed, D.C., Nelson, N.B., Siegel, D.A., 2018. Regional patterns of physiological condition determine giant kelp net primary production dynamics. Limnol. Oceanogr. 63, 472–483.

Bell, T.W., Siegel, D.A., 2022. Nutrient availability and senescence spatially structure the dynamics of a foundation species. Proc. Natl. Acad. Sci. 119, e2105135118.

Buck-Wiese, H., Andskog, M.A., Nguyen, N.P., Bligh, M., Asmala, E., Vidal-Melgosa, S., Liebeke, M., Gustafsson, C., Hehemann, J.-H., 2023. Fucoid brown algae inject fucoidan carbon into the ocean. Proc. Natl. Acad. Sci. 120, e2210561119.

Coleman, S., Dewhurst, T., Fredriksson, D., St. Gelais, A., Cole, K., MacNicoll, M., Laufer, E., & Brady, D. (2022). Quantifying baseline costs and cataloging potential optimization strategies for kelp aquaculture Carbon Dioxide removal. https://doi.org/10.31223/x5vs84

English, C.J. and Carlson, C.A., 2023. Protocols for the quantification and characterization of dissolved organic carbon from seaweed and its sequestration potential. White paper available at https://doi.org/10.31223/X5167F.

Krause, S. J. E., Dauhajre, D. P., Bell, T., Miller, R., Valentine, D., and Siegel, D. 2023a: Comparing Kelp Conveyance Strategies for Marine Carbon Dioxide Removal with Farmed Macroalgae, https://doi.org/10.31223/X5M66B.

Krause, S. J. E., Matsumura, S., English, C. J., Carlson, C. A., Miller, R., Valentine, D., and Siegel, D. 2023b: Methods for assessing Giant Kelp (Macrocystis pyrifera) biomass sinking rates and decomposition for carbon dioxide removal applications, https://doi.org/10.31223/X5FH6W.

Myklestad, S.M., 2000. Dissolved Organic Carbon from Phytoplankton. In: Wangersky, P.J. (Ed.), Marine Chemistry, The Handbook of Environmental Chemistry. Springer-Verlag, Berlin/Heidelberg, pp. 111–148.

Myklestad, S.M., Skånøy, E., Hestmann, S., 1997. A sensitive and rapid method for analysis of dissolved mono- and polysaccharides in seawater. Mar. Chem. 56, 279–286.

Nowicki, M., T. DeVries, and D.A. Siegel, 2024. The influence of air-sea CO_2 disequilibrium on carbon sequestration by the ocean's biological pump. *Global Biogeochemical Cycles*, *38*, e2023GB007880. https://doi. org/10.1029/2023GB007880.

Rodriguez, G.E., Rassweiler, A., Reed, D.C., Holbrook, S.J., 2013. The importance of progressive senescence in the biomass dynamics of giant kelp (Macrocystis pyrifera). Ecology 94, 1848–1858.

Sichert, A., Corzett, C.H., Schechter, M.S., Unfried, F., Markert, S., Becher, D., Fernandez-Guerra, A., Liebeke, M., Schweder, T., Polz, M.F., Hehemann, J.-H., 2020. Verrucomicrobia use hundreds of enzymes to digest the algal polysaccharide fucoidan. Nat. Microbiol. 5, 1026–1039.

Wada, S., Aoki, M.N., Tsuchiya, Y., Sato, T., Shinagawa, H., Hama, T., 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.

Yamamoto, K., T. DeVries and D.A. Siegel, (submitted), Metrics for quantifying the efficiency of atmospheric CO_2 reduction by marine carbon dioxide removal (mCDR). *Environmental Research Letters*.

Zhang, Y.-S., Zhang, Y.-Q., Zhao, X.-M., Liu, X.-L., Qin, Q.-L., Liu, N.-H., Xu, F., Chen, X.-L., Zhang, Y.-Z., Li, P.-Y., 2024. Metagenomic insights into the dynamic degradation of brown algal polysaccharides by kelp-associated microbiota. Appl. Environ. Microbiol. 90, e02025-23.

SeaweedCDR Publications to Date:

Project Peer Reviewed Journal Articles to Date:

Yamamoto, K., T. DeVries and D.A. Siegel, submitted, Metrics for quantifying the efficiency of atmospheric CO_2 reduction by marine carbon dioxide removal (mCDR). *Environmental Research Letters*.

Nowicki, M., T. DeVries, and D.A. Siegel, 2024. The influence of air-sea CO_2 disequilibrium on carbon sequestration by the ocean's biological pump. *Global Biogeochemical Cycles*, *38*, e2023GB007880. https://doi. org/10.1029/2023GB007880.

Published Project White Papers:

Krause, S., Matsumura, S., English, C., Carlson, C., Miller, R., Valentine, D., Siegel, D., 2023. Methods for assessing Giant Kelp (*Macrocystis pyrifera*) biomass sinking rates and decomposition for carbon dioxide removal applications, Eartharxiv, https://doi.org/10.31223/X5FH6W.

English, C.J. and Carlson, C.A., 2023. Protocols for the quantification and characterization of dissolved organic carbon from seaweed and its sequestration potential. White paper available at https://doi.org/10.31223/X5167F.

Krause, S.J.E., Dauhajre, D.P., Bell, T., Miller, R., Valentine, D. and Siegel, D., 2023. Comparing kelp conveyance strategies for marine carbon dioxide removal with farmed macroalgae. White paper available at https://doi.org/10.31223/X5M66B.

Dauhajre, D.P., Bell, T. and Siegel, D., 2023. Considerations for Regional Simulations of Seaweed Carbon Dioxide Removal. White paper available at https://doi.org/10.31223/X52Q1N.

Project Presentations:

Dauhajre, D., D. Bianchi, A. Pham, J.C. McWilliams, C. Frieder, T.W. Bell, S. Krause, C. English, N. Eegholm, K.A. Davis, C.A. Carlson, D.L. Valentine, R.J. Miller and D. Siegel, 2024, Towards a regional, coupled modeling system to robustly quantify the viability and environmental impacts of seaweed mCDR. Presentation to be made at the 2024 Ocean Sciences Meeting in New Orleans, LA, February 2024.

English C., and C.A. Carlson, 2024, Controls on the production and composition of macroalgal DOC and its potential contribution to coastal ocean carbon budgets. Presentation to be made at the 2024 Ocean Sciences Meeting in New Orleans, LA, February 2024.

Krause, S., S. Matsumura, D. Dauhajre, R.J. Miller, D.L. Valentine and D. Siegel, 2024, Comparing conveyance strategies and determining the fate of Giant Kelp (*Macrocystis pyrifera*) biomass for marine carbon dioxide removal. Presentation to be made at the 2024 Ocean Sciences Meeting in New Orleans, LA, February 2024.

Sten, M., Yamamoto, K., T. DeVries and D.A. Siegel, 2024, Large-scale seaweed cultivation and its purposeful sequestration: influence of vertical conveyance methods on durability.

Presentation to be made at the 2024 Ocean Sciences Meeting in New Orleans, LA, February 2024.

Yamamoto, K., T. DeVries and D.A. Siegel, 2024, The importance of using an interactive ocean-atmosphere model in estimating the durability of marine-based CO_2 removal methods. Presentation to be made at the 2024 Ocean Sciences Meeting in New Orleans, LA, February 2024.

Siegel, D.A., 2023, Quantifying the efficacy & environmental impacts of large scale macroalgal cultivation & purposeful carbon sequestration. Invited oral presentation made at the Seagriculture USA 2023 in Portland ME on September 7, 2023.