Comparing Kelp Conveyance Strategies for Marine Carbon Dioxide Removal with Farmed Macroalgae

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

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June 23, 2023

This is a non-peer reviewed preprint submitted to EarthArXiv

Abstract

Sequestration of carbon dioxide via sinking of farmed seaweed into the ocean is a promising strategy to the ever-growing need to achieve negative emissions of carbon dioxide. A key component to the durability of the strategy is the method to which seaweed biomass is conveyed to the seafloor. The purpose of this white paper is to introduce four different conveyance techniques, plans for how each technique will be implemented at smaller scales, and describe how each conveyance method will be modeled. The development of each conveyance technique is guided by the balance between overcoming the positively buoyant kelp biomass, overall feasibility given resources and technology, and the ability to monitor, validate and record the environmental impact of sinking Giant Kelp biomass. We plan to use a combination of laboratory and field-based experiments at a smaller scale, to acquire information about sinking rates, dissolved organic carbon release rates, and kelp decomposition rates for each conveyance method. Lastly, the white paper will describe how the data acquired from the laboratory and field-based experiments will inform a series of models, that when combined together, will simulate the durability and the environmental impact of each conveyance method if adopted to scale.

1. Introduction

Large-scale farmed seaweed carbon dioxide removal (CDR) has been proposed to be a promising strategy to remove carbon dioxide from the atmosphere by utilizing the photosynthetic capabilities of seaweeds and kelp and conveying their biomass to the deep sea and/or marine sediments (National Academies of Sciences, 2021). A challenge posed to conduct this form of

CDR is the conveyance of large quantities of, in this case, *Macrocystis pyriferia* or Giant Kelp to the seafloor rapidly to minimizes losses of fixed organic carbon in the upper ocean. The purpose of this document is to introduce example current conveyance methodologies, plans for testing each method and to outline each method's durability and simplicity for monitoring, reporting, and verification (MRV) if applied to scale.

2. Conveyance Methods

Giant kelp is the world's largest algal species, and is uniquely adapted to achieve high rates of photosynthetic carbon capture and high growth of biomass due to its size and extensive sunlit surface canopy (North, 1994). The floating canopy, moreover, facilitates easy and sustainable biomass harvest of giant kelp through surface cutting, analagous to mowing an oceanic lawn. Nevertheless, the buoyant tissues that make the surface canopy possible are also a potential obstacle to rapid and efficient conveyance of giant kelp biomass to depth. There are a variety of sinking methods available to overcome this issue for the purposes of carbon sequestration. On average the kelp component biomass (stipe, pneumatocyst, and blades) tends to be slightly positively buoyant, but there is considerable variability (Figure 1). A major component of the durability of large-scale farmed seaweed CDR will be the conveyance method that overcomes this variable buoyancy to deliver kelp biomass to the deep ocean and/or seafloor for long-term sequestration.

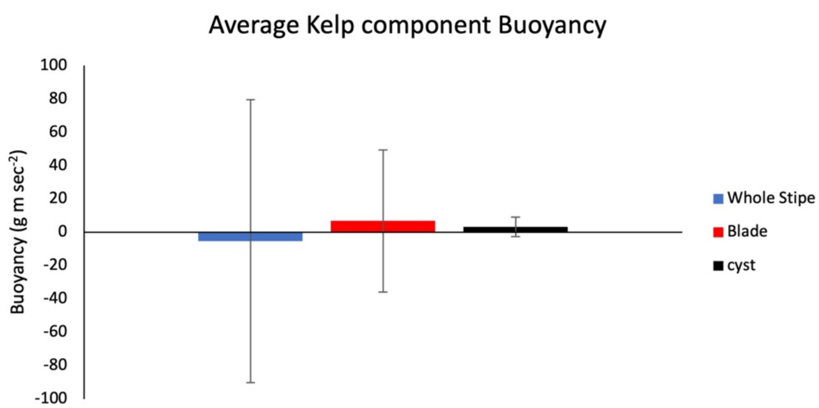

Figure 1. Average buoyancy of each component (stipe, blade, and cyst) of *Macrocystis pyrifera* in seawater. If negatively buoyant, this means the kelp biomass is likely to sink. Average biomass densities are calculated from measured densities of 14 healthy Giant Kelp fronds ranging from 0.8 m to 12 m in length. Error bars represent the standard deviation of the buoyance of each Giant Kelp component (whole stipe, blade, and cyst). Giant kelp fronds were collected from Mohawk Beach, California and processed in the laboratory within 1 to 2 days of collection.

For this project, we will evaluate four field- and laboratory-based methods for conveying harvested giant kelp biomass to the deep ocean (Table 1):

1. Natural sinking - where the harvested macroalgal biomass is released into the ocean as whole frond or plants and sinks due to natural processes,
2. Mastication – where biomass is shredded and released to sink according to its buoyancy, possibly via pumping to depth,

3. Short-depth pumping – where harvested biomass is pumped to a shallow depth (50 - 100 m) where rapid increase of hydrostatic pressure leads to negative buoyancy, and
4. Baling - where harvested kelp is packaged and sunk to depth.

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

Sinking Method	Sinking Rate	DOC Release Rate	Decomposition Rate
Natural Sinking	Lab	Lab	Lab
Mastication	Lab	Lab	Lab
Short Depth Pumping	Lab/Field	Lab	Lab/Field
Bailing	Field	Lab	Field

The optimal sinking method will maximize sinking speed (and eventually minimize processing cost and handling time) thereby minimizing decomposition rate and release of dissolved organic carbon (DOC) in the upper water column. Importantly, careful consideration must be placed on the feasibility and potential quality and uncertainty of MRV for each method. 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 on average positively buoyant biomass and the pneumatocyst present on each blade (Fig. 1). If an offshore kelp farm used this sinking method, either (1) naturally detached kelp would be allowed to sink on its own after separation from the farm, or (2) kelp biomass would be harvested from the farm and released at the surface nearby. Transport to depth will not occur until the kelp tissue has partially decomposed and pneumatocysts have become ruptured, rendering the biomass negatively buoyant (Hobday, 2000). The potential advantage of this conveyance method is its similarities to the fates of giant kelp biomass from natural kelp forests. This similarity to natural processes may help minimize impact to deep-sea ecosystems and be valued by the public and government regulators. Another obvious advantage to letting farmed giant kelp fronds sink naturally is that it would require minimal or no effort after harvesting, reducing the cost of the operations.

The disadvantages of the natural sinking method are due to the time between release and conveyance to depths conferring CDR value. During this time DOM release, biomass degradation, and remineralization will reduce the CDR value of the farmed biomass, and this reduction will vary greatly due to physical and biological drivers including water temperature, currents, and microbial community composition.

Floating duration of giant kelp is affected by its condition at release and its interaction with water currents. Free-floating giant kelp can aggregate into rafts averaging between 2-3 meters in diameter (Hobday, 2000). The larger surface area of positively buoyant tissue in kelp rafts can allow the giant kelp to float on the surface longer. Although the giant kelp can still remain photosynthetically active while detached (Hobday, 1998; Hobday, 2000), the kelp can then release more organic carbon due to decomposition which has a greater chance of remineralizing back to carbon dioxide at the sea surface, where exchange with the atmosphere is greater. Furthermore, the fate of the kelp rafts is variable in that rafts can be washed up on the beach, stay in the kelp forest entangled with attached kelp, or float to the open ocean and eventually sink to the deep ocean. Hobday (2000), conducted a study that aimed to determine the age of floating *Macrocystis* kelp rafts and reported that the maximum days kelp rafts stay afloat is between 65 and 109 days, depending on the season. As a result, there is uncertainty in the efficacy and MRV aspects of this method because of the difficulty tracking where the floating kelp will go and the variable duration at the surface.

Hobday (2000), suggested that floating giant kelp raft ages would be best constrained with ample funds and ship time such that rafts could then be monitored for months. This is, however, rather impractical thus 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 1). Laboratory experiments will also allow us to 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 duration and locations of sinking.

Mastication - Mechanized shredding of the kelp biomass may be a cost-effective method of sinking kelp biomass to depth at, near, or at distance from the site of harvest. Mastication could be achieved with currently available agricultural techniques such as chopping or tilling that is often used for biogas pretreatment (Roesijadi et al., 2010). The mastication would inevitably rupture kelp pneumatocysts and make the kelp biomass more negatively buoyant (confirmed by experiments by Krause at UCSB). While this may be a cost-effective sinking method, a possible disadvantage to cutting the kelp into smaller pieces is the kelp biomass will sink slower and possibly generate a kelp biomass plume in the water column. Slower sinking rates could result in more carbon from the kelp biomass to be converted back to carbon dioxide through aerobic respiration while sinking through the water column (Cael et al., 2021). 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 (Reed et al., 2015).

This conveyance method will likely need higher levels of effort and funding put towards MRV if this is to be conducted at scale, similar to the ***Natural Sinking*** method discussed above. For this project, we will measure the change in DOC release and decomposition rate of particulate biomass as kelp biomass is cut into progressively smaller pieces in the laboratory as well as examine the relationship between size and sinking speed. Sinking, decomposition, and DOC release rates derived from these experiments will be implemented in the seaweed CDR model to simulate 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 >50m should implode pneumatocysts and render the biomass negatively buoyant based upon pressure chamber experiments conducted in the laboratory on Giant Kelp pneumatocysts (Fig. 2). This method is currently used by [SOS Carbon](https://soscarbon.com/) (https://soscarbon.com/) to sink floating Sargassum collected near beaches in the Caribbean. Short-depth pumping, similar to the natural sinking and mastication strategies MRV for short depth pumping will likely need higher levels of effort and funding if this approach was adopted at scale. For this project we will complete on-going laboratory experiments using the pressure chamber at UCSB to understand the pressure 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 field experiments with bails (see below).

Figure 2. A) Photo of pressure chamber with an observation window and B) photo of ruptured pneumatocysts after the pressure chamber experiments. Note white arrows point to the lesions along the pneumatocysts caused by pressure.

Baling - Packaging 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. Strengths in this approach include that the bales of kelp can be weighted to ensure rapid conveyance of the kelp biomass to the seafloor much more efficiently than the other conveyance methods. Rapid delivery reduces the amount of time the kelp can release particulate material and DOC, and respire dissolved organic carbon (DIC) and DOC at shallow water depths and quickens the process of sequestration in the sediment. Additionally, investigators may attach kelp bales to platforms or moorings to facilitate measurements of loss of the kelp to the surrounding environment, adding to the robustness of the approach in the context of MRV (Figure 2). Various sensors (dissolved oxygen, pressure, etc.) may also be attached to the kelp bales when bales are deployed in water depths that are not accessible by divers, to monitor degradation and validate the strategy (Fig. 3).

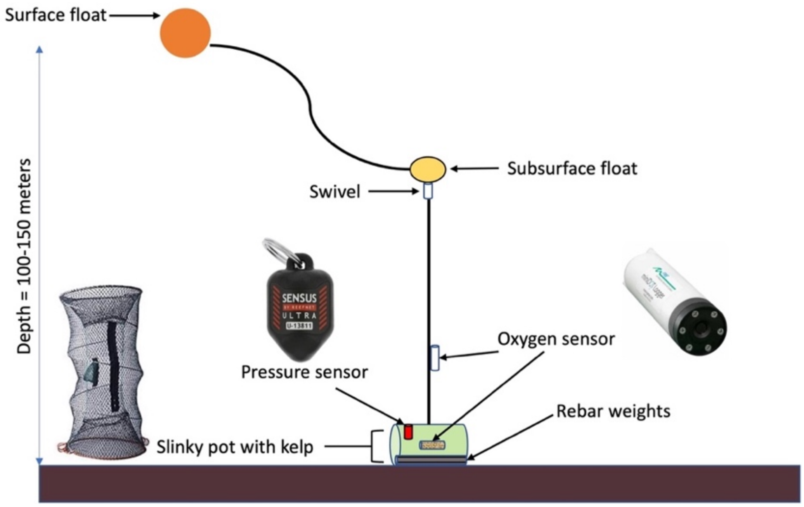

Figure 3. Schematic of a mooring system for deployment and recovery of kelp packages/bales. The kelp packages will be weighed down with rebar or natural stone and equipped with a pressure sensor and dissolved oxygen sensors.

Currently, Co-PI Miller and Krause are investigating the use of plastic milk crates, burlap sacks, and 'slinky pots'to simulate the baling of kelp biomass (Fig. 4). These pots will be filled with whole kelp fronds and compressed or weighted to sink. We may also investigate compression methods in the laboratory to establish if compression of other parts of the kelp plant led to excess DOC release. The accordion-like bags allow for variable 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.

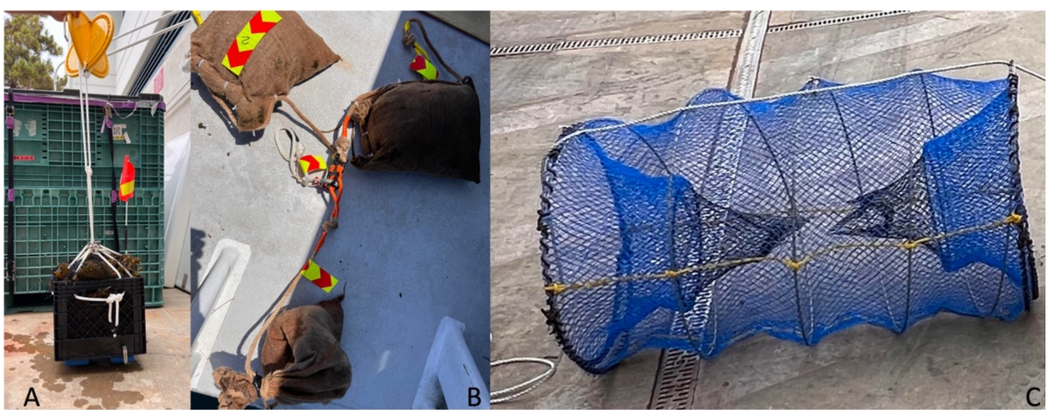

Figure 3. Photos of kelp packages being currently implemented for this project. A) Plastic milk crate kelp package equipped with vinyl coated weights, reflective tape and buoyant reflector comprised of plastic bucket lids. B) Burlap sacks filled with kelp affixed to a jute line mooring and weighted by a burlap sack filled with rocks. C) Slinky pot trap affixed to a mooring line similar to Figure 3.

3. Modeling Conveyance Methods to Scale

Due to the industrial scales required for globally relevant seaweed CDR, this project will ultimately rely on virtual seaweed CDR experiments to assess the durability and environmental impacts of each conveyance method. The biophysically coupled modeling system to be deployed for this purpose (ROMS-BEC-MAG, described in a companion white paper) will resolve the coupling between regional oceanic circulation (Regional Oceanic Modeling System; ROMS, (Shchepetkin and McWilliams, 2005), biogeochemical cycling (Biogeochemical and Elemental Cycling Model; BEC, (Deutsch et al., 2021), kelp growth (Macroalgal Growth Model; MAG, Frieder et al., 2022), and conveyance of kelp biomass.

The conveyance component of the model will simulate the sinking, decomposition, and DOC release of kelp biomass as additional Eulerian tracers (biomass and DOC) in ROMS-BEC that are released as a function of the kelp biomass and harvesting strategy simulated by MAG. Empirically derived sinking, decomposition, and DOC release rates (Table 1) will be prescribed to these tracers in order to simulate individual conveyance methods and compare viability. Importantly, the coupling of the conveyance module to ROMS-BEC-MAG will simulate the competition between sinking speed and advection by ambient currents of kelp biomass, as well as resolve the reactions between the descending kelp biomass and other biogeochemical tracers.

The simulated interplay between regional oceanic circulation and the conveyance of kelp biomass will allow assessment of optimal sequestration sites (assuming enough kelp growth) relative to each conveyance method. Once the Giant Kelp biomass does reach the seafloor by way of any of the above conveyance method(s), the Giant Kelp tissue will go through the process of decomposing, remineralization, burial and sequestration. These final stages to sequestration will be simulated primarily via BEC, where the kelp biomass tracers are declared stagnant based on their proximity to the seafloor and bottom current speed. At that point, the decomposition and remineralization rates (again, empirically derived) of this "locked" kelp biomass at the seafloor will feed back onto the deep-sea biogeochemistry. This conveyance-to-sequestration algorithm is in development. Overall, the virtual seaweed CDR experiments performed via ROMS-BEC-MAG with the above-described, in development conveyance module will allow us to understand the feasibility and environmental impacts of seaweed CDR from a multidimensional perspective.

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