Framework Protocol

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For Multi-Pathway Biological and Chemical Carbon Removal In The Ocean

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1. Introduction

Statement of Intent

This protocol, intended for use in the Voluntary Carbon Market, details a high-level framework for the quantification of the net carbon removed using a multi-pathway carbon removal system. Specifically, this protocol describes the combined chemical and biological interventions of three naturally occurring carbon removal pathways: terrestrial biomass growth and sinking, ocean biomass growth and sinking, and ocean alkalinity enhancement (OAE). The intention of this protocol is to provide maximum transparency into the system that combines these carbon removal pathways, the approach to accurately quantifying the carbon that is removed through these pathways, and the foundational science that informs the use of these pathways to transfer carbon from the fast to the slow cycle.

Critically, this protocol is not intended to detail the exact processes a carbon removal intervention in the ocean must follow, but rather provides a framework to ensure that the correct components of quantification are effectively considered and accounted for, and that the work is done responsibly and in line with the best available science.

Additional technical details required for evaluating outcomes — models used and applied, sampling protocols followed, correlation between in-situ measurements and modeled outcomes, specific discount rates, and more — are reported via separate intervention-specific documentation that adheres to the system-level processes described in this framework. It is expected that this protocol will continue to evolve as additional data are collected, research is conducted, and uncertainty is reduced.

The approach detailed in this protocol is based on natural pathways, both organic and inorganic, through which the ocean durably stores carbon. The explicit goal of the carbon removal system outlined in this protocol is to improve ocean health and reverse the degradation and collapse of ecosystems caused by the anthropogenic emission of slow carbon in the form of CO_2.

This protocol has been reviewed by Deloitte in accordance with ISO 14064-2:2019.

2. Context and Background

The Fast and Slow Carbon Cycles

The Earth system stores carbon in several primary carbon reservoirs, namely the marine and terrestrial biospheres, the atmosphere, the ocean, sediments, and rocks. The Earth system has two distinct, but coupled, carbon-cycling dynamics: the fast carbon cycle and the slow carbon cycle, a framing that has been put forward by NASA [Riebeek, 2011] amongst others.

Fast Carbon Cycle

The fast carbon cycle consists of carbon that flows into and out of reservoirs continuously or up to a decadal timescale, including the reservoir of atmospheric carbon in the form of CO_2. The fast carbon cycle encompasses the daily and seasonal cycling of carbon in the biosphere, atmosphere, and surface ocean primarily through photosynthesis and respiration. The fast carbon cycle is dynamic and volatile, and can be best understood as the flow of carbon through living ecosystems and the atmosphere.

Slow Carbon Cycle

The slow carbon cycle consists of the movement of carbon through longer-duration pathways and reservoirs via natural processes including chemical weathering, sedimentary burial, and ocean overturning circulation. These processes move carbon from living ecosystems into geological and deep ocean reservoirs, such as sediments, hydrocarbon deposits (oil, gas, coal), and deep waters. Carbon moves through slow cycle reservoirs over centuries to geologic timescales [Prentice et al., 2021].

The fast and slow carbon cycles are loosely coupled, and the global carbon cycle operates through a variety of response and feedback mechanisms which maintain a balance between these cycles, keeping the Earth’s atmosphere and ocean in a “Goldilocks zone” (i.e., the narrow range of conditions in which ecosystems and communities can thrive). Prior to the Industrial Revolution, carbon cycling between the atmosphere, ocean, biosphere, and geologic reservoirs, in both the fast and slow carbon cycles, was generally balanced in a manner that promoted stable climate, ocean chemistry, and ecosystems over human timescales.

The Necessity of Fast-to-Slow Framing

Because of the interconnectedness of these fast and slow carbon cycles, a singular focus on atmospheric carbon in existing carbon removal accounting practices is not consistent with the best available science and presents an incomplete framing of complex Earth system dynamics.

When anthropogenic activity transfers slow carbon to the fast carbon cycle through fossil emissions as CO_2, that increase in fast carbon is distributed throughout the fast carbon cycle, including in the atmosphere, the ocean, soils, and aboveground terrestrial biomass. That gross transfer of slow carbon to the fast carbon cycle represents a **carbon liability**. This carbon liability cannot be discounted based on the fate of where that fast carbon ends up – i.e., whether that fast carbon ends up in the soil, the surface ocean, or is naturally transferred back to the slow carbon cycle. To fully resolve that carbon liability – and to mitigate the harm caused by that liability, whether that be atmospheric warming, ocean acidification, or other – a carbon removal activity must occur. Functionally, this carbon removal activity is the inverse of the carbon liability; until an activity has occurred that reverses (i.e., removes) the damage, a liability remains on the emitters' (and the Earth system's) "balance sheet", and a total system imbalance will remain. The only way to mitigate anthropogenic emissions and rebalance the global carbon cycle is to remove the totality of those carbon liabilities — the more than 2.4 trillion metric tons of anthropogenic carbon that have been released from the slow carbon cycle since the onset of the Industrial Revolution [IPCC, 2022], and which include those pooled in the atmosphere, biosphere, or upper ocean — from the fast to the slow carbon cycle.

The activity of carbon removal can be defined as the intentional movement of carbon from the fast carbon cycle to the slow carbon cycle, where the total fast carbon removed exceeds the total slow carbon emitted within a given project boundary.

A fast-to-slow framing is inherently conservative in early-year calculations of net carbon removed due to the current atmosphere-centric design of emissions accounting standards and models used to quantify emissions. This conservatism considers both fossil carbon (slow-to-fast) and fast cycle fluctuations in evaluating the net carbon impact of a project, and as such allows for the implementation of an accounting approach that promotes the rebalancing of the full carbon cycle in line with the best available science as carbon accounting standards mature.

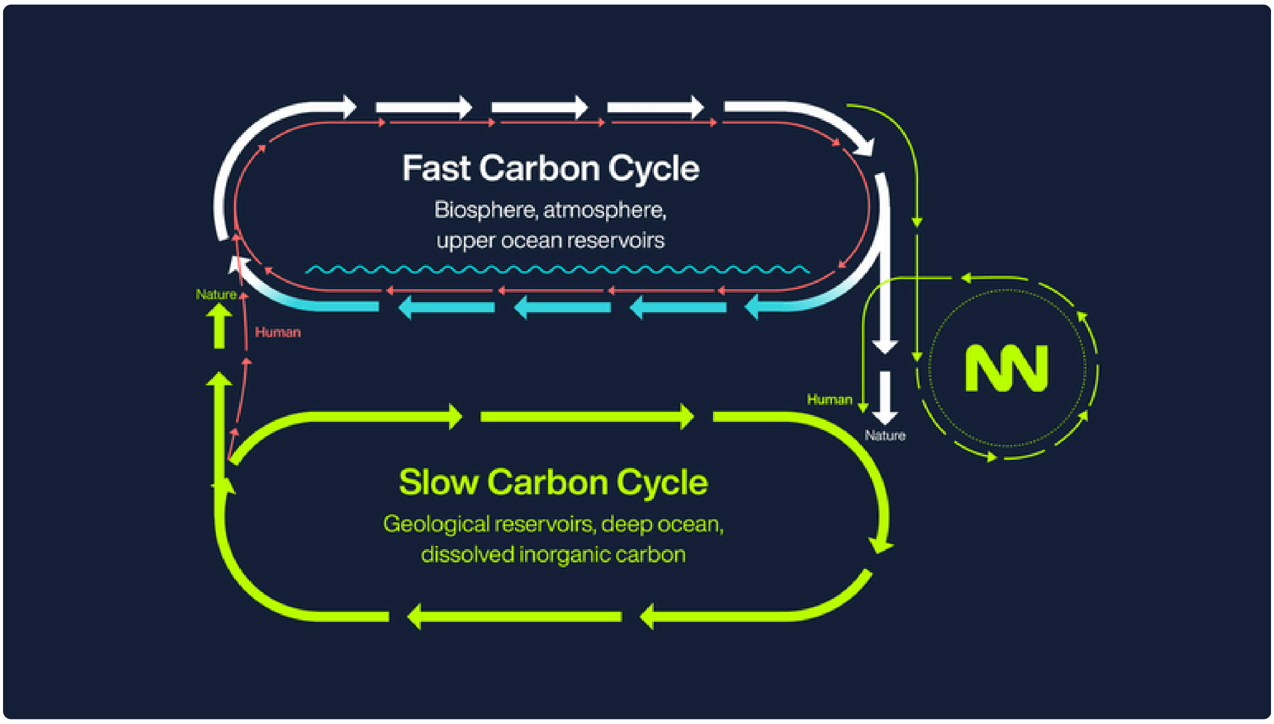


Figure 1: The fast and slow carbon cycles.

The Ocean as a Durable Carbon Sink

The surface ocean and the atmosphere are closely coupled systems within the fast carbon cycle, and CO_2 levels in both rise and fall essentially in parallel. As anthropogenic emissions increase the concentration of carbon in fast cycle reservoirs, more and more CO_2 flows from the atmosphere to the surface ocean each year [NOAA GFDL Earth System Model] through direct absorption, which is then recycled through respiration and photosynthesis. The ocean is estimated to have absorbed at least 25-30% of the total CO_2 emitted since the beginning of the industrial era [Friedlingstein et al., 2022] ,with some estimates as high as 40% [Carroll et al., 2022].

Seawater is stratified by density gradients, which are formed by variations in salinity and temperature, and suppress vertical mixing of the water, contributing to the slow turnover of ocean bottom water with the atmosphere [Sprintall, 2009]. Therefore, once carbon is transported to the deep ocean, it remains trapped there for hundreds to thousands of years – becoming part of the slow carbon cycle.

Organic Carbon Pathways

Biological carbon fixation occurs mainly in the ocean surface layer, where marine organisms, primarily phytoplankton, photosynthetically fix dissolved inorganic carbon, allowing the surface ocean to absorb more CO_2 from the atmosphere [Heinze et al., 2015]. Approximately 85-90% of the carbon fixed through photosynthesis in the euphotic zone (the uppermost layer of the ocean) will be remineralized and recycled [Fox et al., 2020], remaining in the fast carbon cycle at the surface ocean or re-releasing into the atmosphere. However, a small percentage of plankton sink into the deep ocean after they die, transporting the carbon acquired at the surface along with them. Grazing on phytoplankton by higher trophic members of the ecosystem, such as zooplankton and fin fish, packages this carbon into fecal pellets which sink rapidly, thereby removing biologically fixed carbon to the deep sea. The process of photosynthetic marine organisms moving carbon from the fast carbon cycle in the surface ocean to the slow carbon cycle in the deep ocean is known as the “biological pump” [De La Rocha et al., 2014].

Once biomass sinks into the deep ocean, it is subject to several sequestration fates: labile organic carbon is likely to be metabolized by microbes and benthic macrofauna (e.g. amphipods) and remineralized into deep ocean waters [Gao et al., 2021], while biomass that is naturally resistant to degradation in marine environments (such as wood) is likely to be buried in ocean sediments, where much of it will be stored for geological timescales [Burdige, 2007]. Depending on location, ultimate depth of settlement, and chemical fate of the biomass, this process results in carbon storage for a minimum of centuries, to upwards of geologic timescales (i.e., hundreds of thousands to millions of years). The ocean is a massive reservoir that, by current estimates, stores approximately 39,000 gigatons of dissolved carbon [Rackley, 2010] — roughly 50 times more than the amount contained in the atmosphere [Kayler et al., 2017].

Worldwide, the biological pump transfers approximately ten gigatons of carbon from the atmosphere to the deep ocean each year [Sarmiento, 2002], where it is projected to remain, on average, for longer than 1,000 years [Orr, 1992].

Terrestrial forest systems photosynthetically fix carbon in the fast cycle, storing it in aboveground biomass (wood), belowground biomass (root structures and soils), and their supported secondary biomass, such as mycelium networks. Oceans and rivers naturally transport fixed carbon from these terrestrial systems (e.g. fallen trees transported to the ocean through river systems) and carry this biomass to the deep ocean [Kandasamy et al., 2016], thereby transferring carbon from the fast to the slow cycle.

Growing and sinking macroalgae at the surface of the ocean differs from coastal blue carbon seaweed afforestation, as the biomass growth — and thus the photosynthetic fixation — occurs in the open ocean. Thus, when intact macroalgae sinks, it is transferred to the slow carbon cycle in the deep ocean. This contrasts with organic carbon that sinks in coastal waters on the shallow continental shelf, where warm temperatures, wave action, intense bioturbation, and more rapid currents support remineralization of most of that organic carbon to CO_2, which is released back to the fast carbon cycle. Because macroalgae species generally have more favorable Redfield ratios (the ability to fix carbon per available nutrients) than phytoplankton [Martiny, 2013], macroalgae cultivation and sinking in the open ocean may increase the amount of carbon transported to the deep ocean by the biological pump.

The exact durability of carbon stored is dependent on the depth, location, and chemistry where biomass sinks [LaRowe et al., 2020]. Ideal sinking locations are deep, stable, and characterized by relatively high rates of sedimentation, which increases the proportion of biomass that is buried and preserved for millennia.

Inorganic Carbon Pathways

Greater total volumes of CO_2 within the fast carbon cycle manifest as higher concentrations of CO_2 in the atmosphere and higher concentrations of dissolved inorganic carbon in the surface ocean. Ocean acidification is the result of CO_2 dissolving in the ocean and reducing the pH of surface waters. This acidification of seawater makes it harder for many types of marine organisms, like oysters, corals, and scallops, to form their protective calcium carbonate shells and skeletons [Doney et al. 2009], which has the potential to cause catastrophic ecosystem impacts over the coming decades.

Photosynthetic organisms — primarily phytoplankton — transform dissolved CO_2, a form of inorganic carbon, into organic carbon in the same way that trees transform atmospheric CO_2 into terrestrial biomass. This process helps mitigate CO_2-induced ocean acidification by decreasing CO_2 concentrations in the surface layer of the ocean. However, ocean acidification, warming, and pollution affect photosynthesizing organisms in the ocean in complex ways, potentially diminishing the ocean's capacity to fix inorganic carbon through photosynthesis. Without positive interventions, the capacity of the ocean to sequester and store atmospheric CO_2 may be impaired by warming and acidification [Chikamoto 2021].

As atmospheric CO_2 dissolves in the surface ocean, carbonic acid is formed and subsequently dissociates into protons and bicarbonate ions, the balance of which is governed in a given region of water by temperature, pressure, salinity, and pH. The result is a “buffer pool” of dissolved inorganic carbon, which allows a volume of seawater to dissolve many times more carbon than might be otherwise expected [Sarmiento et al., 2006]. When and where surface waters mix and sink into deeper water, inorganic carbon that has been taken from the atmosphere and dissolved in surface water is carried to the slow carbon cycle of the deep ocean.

Dissolution of alkaline minerals into the surface ocean — i.e., “alkalinity enhancement” — alters the balance of the carbonate system in seawater, increasing surface seawater’s capacity to convert dissolved CO_2 to dissolved bicarbonate ions, and thus take up more CO_2 from the atmosphere. **Alkalinity enhancement achieves carbon removal by reallocating fast cycle carbon (aqueous CO_2) to the larger and more stable bicarbonate reservoir.**

Because the magnitude of the bicarbonate reservoir is so large compared to the aqueous CO_2 reservoir [Zeebe and Wolf-Gladrow, 2001], the residence time of carbon within the bicarbonate reservoir is comparably longer than the residence time of carbon in the CO_2 reservoir, rendering the bicarbonate reservoir functionally consistent with a slow carbon reservoir rather than a fast one. Simultaneously, this process amplifies the fast cycle transfer of atmospheric CO_2 into surface waters, as the dissolved CO_2 that was reallocated to the bicarbonate reservoir is replaced by novel atmospheric CO_2 exchanged across the air-sea boundary [Campbell et al., 2022].

Notably, this differs from an atmospheric-centric framing of carbon removal for alkalinity enhancement, which is primarily concerned with the fast cycle transfer of atmospheric CO_2 that “replaces” the associated reduction in the partial pressure of CO_2 resulting from a CO_2 transfer to the bicarbonate reservoir.

The gross mass transfer ratio of ocean alkalinity enhancement will vary seasonally and regionally between 0.26-0.95 with the physico-chemical conditions of surface seawater and the molecular weight of the alkaline source mineral [He et al., 2023].

3. Intervention Design

System Overview

With this scientific foundation, interventions to amplify the fast-to-slow carbon pathways in the Earth's natural carbon cycle can be conducted safely, in line with the application of the precautionary principle considered against a baseline of rapidly deteriorating ocean and planetary health.

This protocol describes a system in which responsibly sourced, carbon-rich terrestrial biomass (forestry residues) and carbonate materials (CaCO3 and/or CaO) are processed and combined to make "carbon buoys." These buoys act as a substrate that may be seeded with marine macroalgae, such as *Saccharina latissima* or *Ulva*, and are deployed in the surface ocean to be distributed by ocean currents. As the buoys float and disperse, macroalgae grow, biologically fixing carbon over a period of weeks to months, while the carbonate minerals dissolve, sequestering CO_2 and combatting ocean acidification via ocean alkalinity enhancement. After a calibrated period of time during which the buoy has absorbed sufficient seawater, it flips from positive to negative buoyancy, thus sinking and carrying the embodied organic carbon to the deep ocean for durable storage.

In this context, 'durable storage' is synonymous with the movement of carbon from the fast carbon cycle to the slow cycle with negligible reversal risk. Exact durability will vary based on deployment location (targeting sinking sites at a minimum of 1,000 meters in depth), local ocean conditions, and the fate of sunk biomass — but, critically, the sunk carbon will remain out of contact with fast carbon reservoirs because of the slow-moving ocean overturning circulation [Rousselet et al., 2021] and suppressed remineralization of organic carbon at depth [Siegel et al., 2021].

Currently, the benchmark established by Siegel et al. [2021] is used for assessing durability from a specific deployment, wherein the retention of CO_2 injected and dissolved into the ocean interior is sensitive to its location, given general overturning circulation. It's important to note that the approach described in this protocol does not rely on the injection of gaseous carbon at depth, but on the sinking of intact biomass. Durability is thus likely to be longer than the centennial timeframes predicted by Siegel et al., given that the biomass will first need to be remineralized from its solid form prior to being subject to overturning circulation in an aqueous form. Furthermore, biomass that is buried in marine sediments and avoids remineralization will be removed from the fast cycle for even longer (hundred of thousands to millions of years).

Buoy composition may vary from deployment to deployment and may not necessarily utilize all of the carbon removal pathways outlined in this protocol. For instance, it might consist of the deployment of terrestrial biomass coated with alkaline materials, but not seeded with macroalgae. The composition will depend on the local ocean and operational factors, such as the availability and carbon content of the biomass, to increase the efficiency of carbon removal. This process's organic components are intended to amplify the ocean's biological pump.

System Design

A carbon removal system, especially one that intervenes in the natural environment, should seek to achieve the highest climatic benefit while minimizing any adverse localized impacts. The system should be designed to have a net positive impact, inclusive of benefits to the climate, ecosystem, and affected communities; it should be designed to be deployed safely, with appropriate safeguard mechanisms and controls in place; and, while starting small, it should be designed for scalability, such that it has the potential to scale to the size of the problem.

From that foundation, a set of key system design principles can be established. The principles outlined below are non-comprehensive and may vary based on project type, but can serve to guide the development of a carbon removal system from initial research to eventual operational deployments.

Net Positive Impact

- **Net positive environmental and ecological impact:** The carbon removal system must be designed to have a measurable net positive environmental and ecological impact, meaning that the benefits of the intervention must outweigh any potential negative impacts as evaluated by a third party audited environmental impact assessment (EIA). Where possible, any potential negative impacts must be proactively identified and mitigated prior to deployment.
- **Positive socioeconomic impact:** The system must be designed to have a measurable positive impact on communities that are most vulnerable to climate change, and subject to input and feedback from local stakeholders directly connected to planned research and operational sites.
- **Non-exogenous materials:** The system will utilize materials that are non-exogenous to the ocean (in this case, regionally native species of macroalgae, minerals that are distributed throughout the world's oceans such as $CaCO_3$, and terrestrial biomass that already enters the oceans in vast quantities through rivers and other natural pathways). To the extent possible, all algae species within the system should be native to the location where they are deployed, limiting invasive species risk.
- **Natural products:** The system should minimize the use of non-natural products, particularly plastics, including in any data collection or monitoring hardware

deployed.

- **Location selection:** The system deployment locations are targeted to affect the highest benefit for ocean health, coastal communities, and system efficiency, and factors including but not limited to: carbon removal duration, system performance, the health of the ecosystem, coastal community perspectives (including Indigenous Peoples and Tribal Nations) near operational sites, and possible conflicts with other ocean-based operations. Where available, locations should be considered within the context of Sustainable Ocean Plans.

Safety

- **Staged progression towards scale:** The system must be designed such that as certainty around intervention outcomes and benefits increases, deployments can be incrementally scaled in both volume and complexity in a responsible and sustainable manner.
- **A binary switch:** The system must be designed with the capacity to be turned off or removed if necessary to minimize the risk of any long-lasting negative effects.
- **Intervention duration control:** The system must be designed with the ability to control for the amount of time it interacts with the natural environment.
- **Intervention size, density, and distribution control:** The system is designed such that these factors can be controlled and iterated upon to optimize system performance.

Scalability

- **Cost effective:** The system is designed to be deployed at the lowest cost possible.
- **Simple:** The system should be as simple as possible, and complexity should only be added to reduce risk and increase efficiency.
- **Quantifiable:** The system must be measurable and modelable so that impacts and performance can be accurately assessed with known levels of uncertainty.
- **Auditable:** All processes and quantifications of impact must be auditable by a qualified independent third party so that outcomes can be effectively evaluated in a transparent manner, building trust in the underlying system and results.

- **Utilizing existing infrastructure:** The system should be designed to leverage existing infrastructure (such as underutilized ports or shipping assets), and new infrastructure should be multimodal if possible.
- **Minimal slow carbon inputs:** The system must be designed with the least amount of slow carbon energy inputs possible.

In seeking to adhere to these principles, the system described in this protocol has been designed to be adaptable to dynamic ocean conditions, can leverage multiple natural pathways for carbon removal, is comprised of readily available natural materials, and is simple in its structure to enable flexibility, mass-producibility, and minimal use of anthropogenic inputs. The small unit size of the carbon buoys enables efficient manufacturing that can integrate a range of substances and components, which are dispersed by natural processes over a widely distributed geographic area, not unlike how the wind carries seeds over long distances. This low-density distribution of buoys limits the potential for negative localized impact while maximizing potential scale. This system also utilizes existing natural energetic pathways, including ocean currents, photosynthesis, and gravity, and has the potential to be deployed at scale without significant land-use tradeoffs, energy consumption, or operational technologies that may require costly maintenance and upkeep in the open ocean.

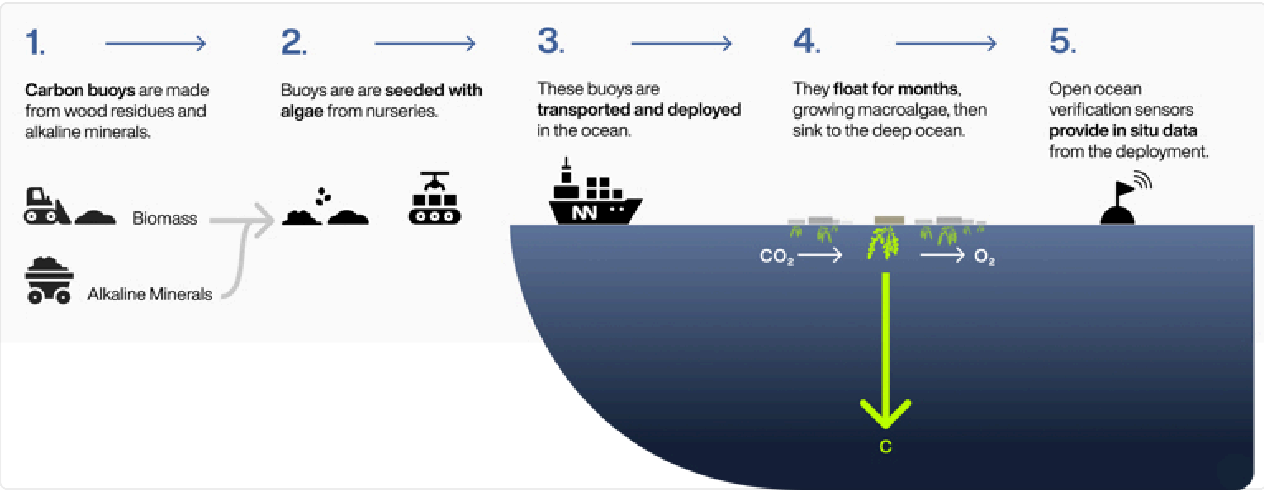


Figure 2: Illustrative multi-pathway carbon removal system flow.

The multi-pathway design and system flexibility means that the optimal intervention for each deployment may differ, with initial deployments acting as a baseline data set for evaluating changes. As an example, different terrestrial biomass sources (wood species and other biomass residues) or sources of alkalinity may be procured locally, saving transportation emissions, or ensuring a better fit to a specific geography or season.

Terminology

For the purposes of this protocol, the following definitions can be used:

- **Carbon accounting** is the system for measuring the net flow of carbon from one carbon system (fast or slow) to the other, both inside and outside project boundaries. Carbon accounting encompasses fast-to-slow (removal) **quantification**, i.e. the measurement of intervention outputs, and emissions accounting.
- **Emissions accounting** relates specifically to what greenhouse gasses are emitted while conducting a project or as a result of the project activity - i.e., how the carbon liability from operating a business and conducting interventions is measured. Processes must adhere to globally recognized standards such as the Greenhouse Gas Protocol.
- Carbon removal is achieved by implementing a deliberate **intervention** — in this case, conducting activities that replicate and amplify the natural processes by which the ocean captures carbon.
- **Carbon buoys** are the mechanisms by which this intervention is packaged and delivered. These carbon buoys represent a calibrated combination of materials designed for the specific purpose of creating an intervention once deployed.
- **Verification** is the process by which the impact of an intervention can be demonstrated to have created a net movement of carbon from the fast carbon cycle to the slow carbon cycle, following the relevant criteria and considerations dictated by this protocol. Qualified, independent third parties — global quality and assurance leaders, and particularly those with a proven track record of providing independent verification of carbon projects — are engaged as audit partners for external review of specific carbon accounting processes and results.

Conventional definitions used for carbon removal and carbon accounting are typically presented within an atmospheric – rather than a systems-level – framing. Similarly, emissions accounting standards like the GHG Protocol and most standard emissions factors encompass both fossil and land-use emissions (i.e. both “slow-to-fast” and “fast-to-fast” emissions). While a fast-to-slow framing is necessary for addressing total system imbalance, an effective fast-to-slow carbon removal system must ensure atmospheric warming is effectively considered and accounted for within project boundaries.

System Boundaries

Effective carbon removal accounting requires well-defined system boundaries and a complete understanding of emissions resulting from project operations and material sourcing. All carbon sources, sinks, and reservoirs (SSRs) within the system and project boundaries have been identified according to the ISO 14064-2 framework for identifying and selecting greenhouse gas SSRs for regular monitoring or estimating GHG emissions or removals.

Emissions associated with each deployment are directly correlated to where project boundaries are drawn in relation to company operations, and as such must be clearly defined and stated to avoid misrepresenting system efficacy and total climatic impact. Project emissions are the portion of total company emissions directly related to intervention operations and deployment, as shown in the illustrative graphic below:

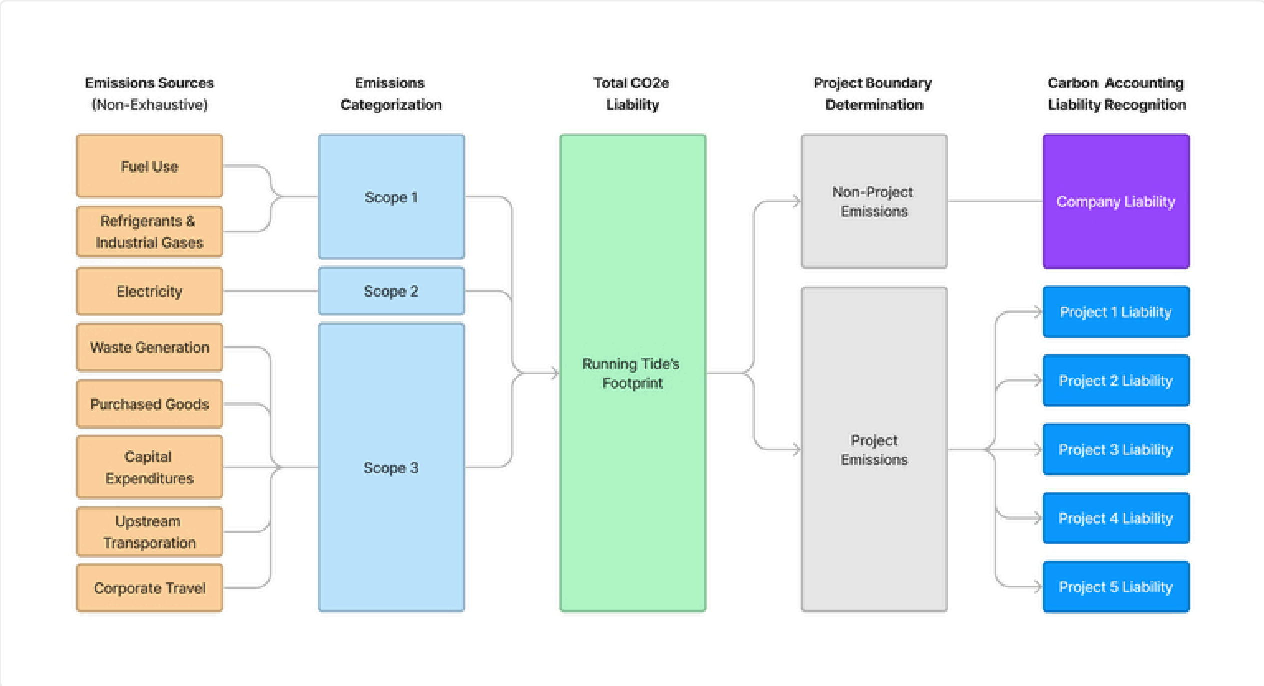


Figure 3: Illustrative carbon accounting for company versus project-level emissions over the course of five hypothetical carbon removal projects. Notably, based on the GHG Protocol's Draft Land Sector and Removals Guidance, there are no Scope 2 removals, since removals do not occur in the generation of electricity, steam, heating or cooling, and any removals occurring in the value chain of the energy generation process are accounted for in Scope 3.

As the size and scope of the project expands, it will begin to encompass additional company emissions and broader sourcing considerations. Emissions sources currently identified within the project boundary, in line with ISO SSR requirements, include the following:

Material Sourcing

- Upstream transportation and distribution of materials to production sites.
- Production and processing of materials that are a direct result of project sourcing.
- Considerations of direct or indirect land-use changes resulting from sourcing materials.

Production Site Operations

- Energy use for the production of carbon buoys.
- Emissions associated with capital equipment purchases and site construction.
- Contractor activities including maintenance and equipment setup.
- Energy use for loading and transportation of the deployment vessel.

Other Production Sites (Macroalgae Hatchery and Verification Hardware Development)

- Energy use for production operations.
- Construction, equipment purchases, and maintenance.
- Cradle-to-gate emissions of raw materials.
- Upstream transportation & distribution of materials and equipment.

In addition to the categories listed above, any other emissions sources that are directly related to project operations such as data center use should be evaluated for materiality and included in deployment reporting.

Both company and project emissions accounting are performed under the Greenhouse Gas Protocol

. In addition, any life cycle assessments (LCAs) utilized in emissions calculations must be verified by a third party, and where possible, supported by supplier records.

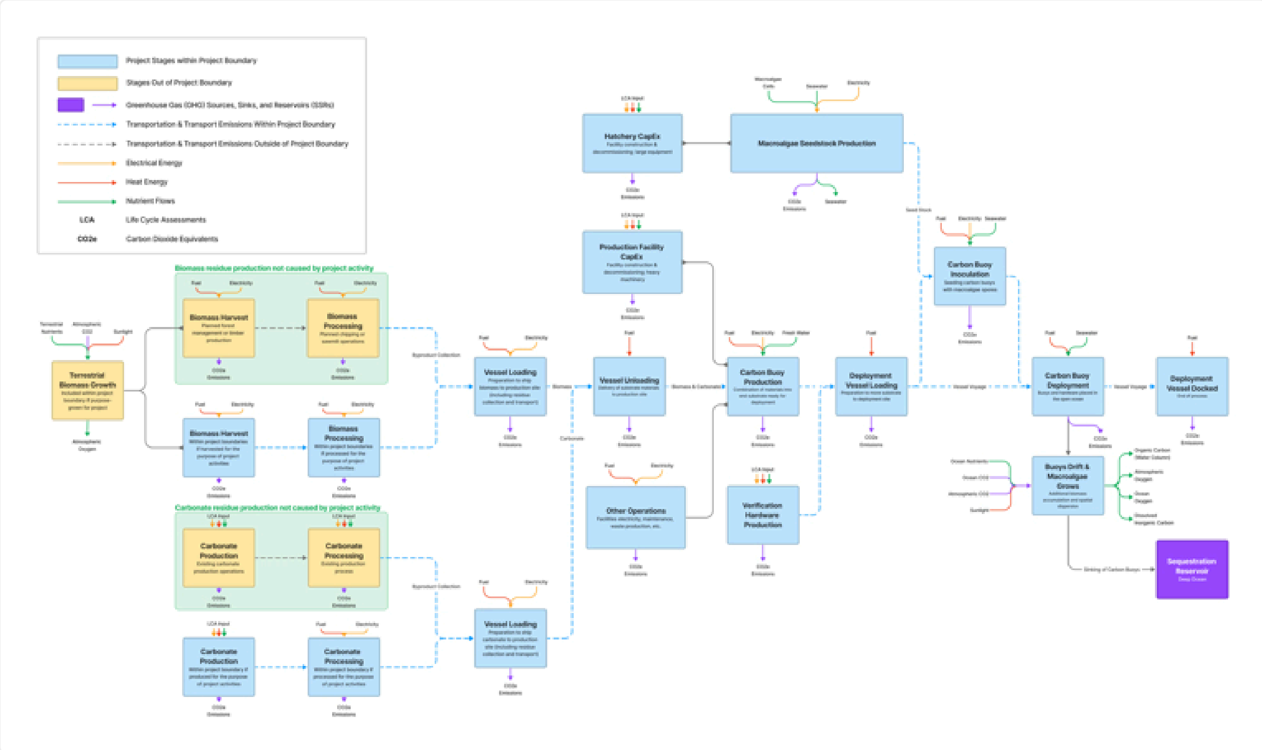


Figure 4. Intervention system process flow, including likely CO2e sources, sinks, and reservoirs within the project boundaries.

For all deployments, conservative standard emissions factors and discount rates will be utilized where project emission sources cannot be directly measured. In the event there is not a clear line between project and company emissions within the defined project boundary, emissions will be reasonably applied to the project level to ensure conservative accounting.

Project-related emissions associated with capital goods will be amortized over a maximum of 12 months from the in-service date. Construction in progress ongoing for longer than 12 months will commence amortization on a rolling basis until the asset is put into service, at which point the remaining emissions liability will be recognized in line with the standard amortization policy. All project emissions liabilities will be recognized in project carbon accounting to net the metric tons of CO2e removed during a project.

A short amortization period is a unique approach for project-level CapEx carbon accounting. This approach ensures that the carbon removal project recognizes emissions carbon liabilities on a time frame where the emissions do not have a material, compounding negative effect on the planet. As a result, this liability can be recognized and removed from the emitter’s balance sheet when balanced by the carbon removed during project operations.

Consideration of Critical Research Priorities

A benefit of each deployment is the opportunity to contribute to advancing the scientific community's collective understanding of the ocean. Several areas of research that will inform and reduce uncertainty around net carbon removed include:

Deep ocean benthic experiments

Deep-sea benthic research to quantify the ecological and geochemical impacts and rates of degradation of carbon buoys and macroalgae biomass in the deep sea, as well as to quantify potential associated changes in the structure and function of benthic communities, including macroinvertebrates, vertebrates, and microorganisms.

Prior and ongoing research:

- Replicated observational experiments of biomass degradation in coastal and shallow waters. Coastal experiments are similar in design and method to a program of deep-sea benthic experimentation, but afford a higher frequency and quantity of direct water and sediment sampling in addition to method testing. An initial benthic pilot was conducted in Casco Bay, Maine in 2022.
- Running Tide has planned and is preparing to deploy a shallow water fixed site experiment in Q2 2023 on the Icelandic shelf to observe carbon buoys during their degradation life cycle on the seafloor and their impact on species abundance and diversity, as well as to monitor for changes in sediment carbon concentrations. Due to the ease of accessing the shallow water location when compared to the deep ocean, a more intensive monitoring plan will be used to sample water on a weekly/bi-weekly basis, and sediment and substrate on a monthly basis. In-situ image capture and microscopy of samples will be used to identify larger organisms and eDNA will be used to identify microorganisms. Experts at the Southwest Iceland Nature Research Center will perform visual identification, while NatureMetrics will be used for eDNA analysis. In addition,

continuous data loggers for temperature, pH, salinity, and dissolved oxygen will measure these environmental conditions.

Planned near-term research:

- Replicated deep-sea benthic experiments on the abyssal plain.
- Running Tide is currently finalizing a research partnership with Ocean Networks Canada (ONC), a non-profit ocean research organization affiliated with the University of Victoria. In this proposed program of experimentation, ONC will place treatments of carbon buoy materials at their established deep-sea observation stations in the Cascadia Basin off the west coast of Canada. ONC will then conduct one-year benthic monitoring of these treatments. The evolution of the carbon buoys will be observed with cameras and environmental sensors (salinity, temperature, and dissolved oxygen) throughout the duration of the experiment. Water samples and sediment cores will also be obtained throughout the experiment by remotely operated vehicles and/or submersibles to allow observation of carbon flux into the sediment, as well as eDNA characterization of changes to the microbial community composition in response to the presence of carbon buoys.
- Running Tide is also engaged in the planning of a sinking seaweed and carbon buoy experiment with researchers at the Alfred Wegener Institute Helmholtz Center for Polar and Marine Research (AWI). The proposed program of research will include observational experiments in the deep sea (4,000m) of the Fram Strait area of the Arctic Ocean. The goal of this work is to understand how different seaweed species (kelp, Sargassum, and Ulva) degrade at 4,000m depth and to replicate Running Tide's observation of carbon buoy degradation in the deep sea, in a different marine biome.

Ecological investigations

A program of research to study the exposure to ecological risk associated with proposed carbon removal methods. Sinking terrestrial biomass, and eventually macroalgae biomass, will introduce organic matter into pelagic ecosystems and enhance the flux of organic matter to benthic ecosystems (overlapping with the above research area).

Prior and ongoing research:

- Participation in a year-long Ocean Visions working group to support the production of a research framework to guide the investigation of the efficacy and impacts of sinking marine biomass into the deep sea for carbon sequestration.
- Funding of research at the Stubbins Lab at Northeastern University to study the bio-lability of dissolved and particulate organic carbon generated by macroalgae. The outcome of this research will inform questions posed by the Ocean Visions working group considering the degradation rate of macroalgae tissue in the benthos and algal-derived dissolved organic carbon in the water column.
- RADI Modeling: Running Tide has advised researchers at Utrecht University as they perform biogeochemical modeling of the impact of sinking organic carbon into the deep ocean. This research explores the consequences of enhanced organic carbon delivery to the seafloor on oxygen, dissolved carbon, and alkalinity cycling in the deep ocean.

Planned near-term research:

- Fixed site experiments focused on the growing and sinking of macroalgae biomass, studying the metabolic interactions between macroalgae and the pelagic ecology for eventual incorporation into open ocean deployment.
- Running Tide is engaged in conversation with a leading European oceanographic institute to perform in-situ observations of our open ocean deployments and assess their impact on the local carbon cycle and ecological dynamics.

Modeling and computational experiments

Research to develop capabilities to perform predictive physical and biogeochemical modeling of carbon removal system behavior.

Prior and ongoing research:

- Running Tide worked closely with the Ocean Dynamics research group within the Atmosphere and Ocean Dynamics Group at Cambridge University in their work to run a sugar kelp growth model for macroalgae growth at densely distributed locations across the North Atlantic. This modeling work bounded the carrying capacity of ocean afforestation with sugar kelp as a carbon removal tool.

- Running Tide has adapted the OceanParcels framework for lagrangian advection modeling to create a predictive model for the ocean transport of its system across various ocean basins. The analysis has integrated HYCOM global ocean circulation data with ECMWF reanalysis data for Stoke's drift. In addition, CMEMS ocean state forecasts were integrated for predictions of deployments. Running Tide continues to explore the application of numerical techniques such as the addition of stochastic noise and refining the contribution of different velocity components in improving the correlation between model predictions and in situ trajectory data.
- Running Tide has begun to adapt the ECCO-Darwin ocean biogeochemistry model to 1) demonstrate the impact and scalability of future carbon removal systems on the coupled Earth system and 2) optimize the efficiency of carbon removal interventions. This includes studying the impact of surface-ocean carbon uptake or alkalinity addition on the air-sea gas exchange of carbon dioxide within the fast carbon cycle, the vertical transport of dissolved inorganic and organic carbon from the sunlit upper-ocean to the seafloor, and the potential nutrient and trace metal competition between proposed macroalgae afforestation projects and the endemic phytoplankton ecology. In addition, open-source biogeochemical datasets have been incorporated into the advection model platform to pair observational and operational model data to material trajectories including data from CMEMS and Aqua/MODIS.
- Running Tide has begun to build software tools to understand and analyze CMIP6 model output data and connect the CESM climate model with a macroalgae growth model for the purpose of understanding the carrying capacity of the ocean for marine carbon removal using macroalgae open-ocean cultivation and sinking.

Planned near-term research:

- Computational experiments within the framework of accepted biogeochemical models of the Earth system.
- Running Tide has engaged in a collaboration with scientists from the ECCO-Darwin project at NASA's Jet Propulsion Laboratory and Moss Landing Marine Laboratories (San José State University) with the goal of building robust ocean carbon removal modeling packages into this existing data-constrained ocean

biogeochemistry modeling tool, as well as designing a suite of easy-to-use analysis tools for end users.

Macroalgae genetics, cultivation, and quantification research

Research to advance foundational work on macroalgae genomics and life cycle in support of the eventual quantification and enhancement of macroalgae biomass cultivated offshore.

Prior and ongoing research:

- Foundational genetics work around the isolation, cultivation, and banking of various developmental stages of macroalgae species in collaboration with Los Alamos National Laboratory, leading to the expected first published long-read genomes for Ulva lactuca and Saccharina latissima.
- Breeding program for the enhancement of survivability and growth of Ulva lactuca in low-nutrient, high wave energy open ocean environments.
- Ecological risk mitigation exploration to understand the natural variation between populations of sugar kelp and Ulva lactuca when separated by geographic distance — i.e., how macroalgae populations differ between the U.S., Iceland, and other coastal countries, providing insight into how distinct macroalgae species move and mix naturally (both genetically and biologically). This research contributes to risk mitigation in that it enables the use of native material in a given deployment area to ensure invasive species or populations are not introduced.
- Abiotic stress testing to determine how Ulva lactuca grows in response to different biogeochemical and abiotic factors (nutrient levels, pH, temperature, light levels, and more), and additional stress testing to better understand how macroalgae survive out of the water (e.g., on ships during transport to deployment zones).
- Ongoing image-analysis of underwater macroalgae growth attached to substrates of interest to inform growth modeling around macroalgae biomass accumulation and carbon content.

Planned near-term research:

- Exploration into the relationship between macroalgae genotype and phenotype — i.e., developing a deeper understanding of what genes or genetic regions contribute to, or drive growth of, phenotypes of interest.
- Abiotic stress testing results that feed into pilot biological modeling that better predicts macroalgae growth in the open ocean based on input biogeochemical and abiotic factors across deployment trajectories.

This list is illustrative and not exhaustive and will be continuously refined based on the best available science and industry need. Additional information regarding ongoing high-priority research questions and recent research conducted can be found in Running Tide's Ocean Carbon Removal Research Roadmap.

Baseline Scenario and Additionality Considerations

Baseline Scenario Considerations

It can be assumed that the baseline scenario is the continued quantity of carbon, accounted for as CO_2e, remaining in the fast carbon cycle (ocean, atmosphere, biosphere), in the absence of the project activity. As with the project boundary, all SSRs within the baseline scenario have been identified according to the ISO 14064-2:2019 framework for identifying and selecting greenhouse gas SSRs for regular monitoring or estimating GHG emissions or removals.

For carbon buoy input materials sourced from residues, including forest residuals and alkaline waste byproducts, there is no change in baseline input material operations from project activities. In the event residue materials are not utilized, such as with biomass sourced via sustainable forest management or alkaline materials sourced from increased carbonate production, emissions associated with direct or indirect production, operations, and sourcing of input materials are included in the evaluation of the baseline state.

For marine biomass growth and sinking, given the lack of open ocean macroalgal growth in the absence of project activities, as well as the lack of additional inputs required for macroalgal growth and sinking, the baseline for this activity can be considered zero — though emissions associated with activities enabling this growth, including macroalgae seedstock production and carbon buoy inoculation, are included within project boundaries. In a future state of significant algal biomass growth, secondary effects on phytoplankton carbon uptake associated with competition for nutrients or light may be relevant, though are *de minimis* for initial deployments. While related to the ocean's baseline net primary productivity, this potential competition is currently accounted for as a discount factor in the carbon removal quantification approach detailed below.

As such, baseline sources and sinks identified in line with ISO SSR requirements include the following:

- Growth of terrestrial biomass.
- Growth and sinking of marine biomass.
- Bicarbonate storage and ocean mixing.
- Processing of terrestrial biomass (harvest and chipping operations).
- Production of carbonate materials.

Materials used in project activities must be tied to attestations from suppliers as proof of baseline conditions, particularly in regards to the alternative end-state of residue inputs. As an example, as it relates to terrestrial biomass residues, the baseline scenario assumes the contained carbon remains in the fast cycle either through combustion, natural decay, or some form of short-lived industrial processing (e.g., paper, cardboard, pulp), which must then be demonstrated via supplier attestations.

A comprehensive list of ISO-compliant SSRs for both the baseline scenario and activities conducted against the project baseline is detailed in the appendix of this protocol.

Additionality Considerations

In the absence of dedicated carbon finance, either via the voluntary carbon market or alternative carbon procurement programs, there is no current scenario in which project activities would take place, as the project requires significant resources and is unlikely to generate any other material sources of income. As it relates to common practice, an often-used metric when assessing additionality, the current level at which the project activity is conducted is near zero.

For fast-to-slow carbon removal projects, interventions must be additional to the fast-to-slow cycle transfer that naturally occurs within the Earth system carbon cycle — i.e., current state photosynthetic activity leading to durable removal via the biological pump, geologic time scale alkaline rock weathering, or similar natural processes.

For these reasons, deployments following this protocol can be considered additional.

Consideration of Potential Externalities

While generally outside of the direct scope of quantification and carbon accounting, the assessment of potential externalities — i.e., the indirect or unintended ecological, socioeconomic, biodiversity, and community effects, both positive and negative, of conducting carbon removal interventions in the ocean — is essential for demonstrating that the carbon removal system has created a net positive impact.

It is critical that the ancillary impacts of carbon cycle interventions on ocean chemistry, marine ecosystems, and human communities be carefully assessed — while also recognizing the devastating ecological and socioeconomic impacts caused by imbalance in the global carbon cycle. Where not directly measurable today, the approach to addressing these externalities must mature towards the ability to be effectively quantified, whether via existing measurement approaches or newer and emerging impact metrics (biodiversity reporting, quantitative and socioeconomic metrics, etc.).

Ensuring Net Positive Environmental and Ecological Impact

To ensure net positive impact, deployments are evaluated using a multi-stage approach that includes measuring baseline environmental conditions, modeling anticipated Earth system changes prior to conducting deployments, developing an initial environmental impact assessment unique to the system location and intervention, and maintaining long-term monitoring plans for all interventions.

Proactive environmental impact assessments (EIAs) and risk assessments must be conducted to evaluate and assess potential ecological (both benthic and pelagic), economic, and social impacts prior to planned deployments, along with post-deployment monitoring and evaluation

. EIAs should seek to identify and predict the impacts of deployments in terms of total carbon removed, ancillary impacts, and co-benefits— while also accounting for potential impacts of scale (both spatially and temporally) — and contextualize impacts in relation to a business-as-usual, no-action baseline for the ocean system. These EIAs must be conducted in accordance with local and national requirements, or proactive in the absence of such requirements. They must be validated by independent third parties and made available for public review.

As the project progresses, ‘boundary conditions’ and control rules around levels of a potential externality that cannot be exceeded must be collectively established so that a project can be paused if significant negative impacts are measured and observed. While responsible organizations conducting this work must have defined internal mechanisms in place for this circumstance, these boundary conditions need to be developed as an industry, in partnership with regulators and the scientific community, to assure effective oversight and regulatory clarity.

Laboratory testing of carbon buoy materials must also be conducted to screen for any potential pollutants and toxins that could be introduced into the marine environment.

Methods for the accurate assessment of ecological impacts will be informed by ongoing research and continuously refined based on the best available scientific understanding.

Scientific Collaboration and Transparency

Research plans must be shared and discussed with an independent Scientific Advisory Board or similar impartial expert body prior to planned deployments for additional oversight and to inform the design and implementation of open ocean interventions. Collaboration with the scientific and oceanographic community must continue to be proactively sought out to advance shared learning, including through the sharing of data and research results. Lastly, avenues for ongoing dialogue must be established with oceanographic, scientific, and academic leaders, including through new industry-academia research collaborations and coalitions where they do not exist.

This collaboration will accelerate the creation of standardized measurement approaches across the industry.

Effective Governance

Multi-stakeholder governance, including responsible research frameworks and the establishment of a code of conduct for ocean carbon removal practitioners, will be critical for ensuring responsible action in the ocean by all actors. As the ocean carbon removal industry matures, it will be critical that there is a level of self-governance and policing around actors who fail to adhere to these scientific and ethical standards.

While these standards continue to be developed at an industry level, organizations conducting interventions in the ocean must be clear about the principles that inform their ethical decision-making from initial research up to eventual deployments. These principles must be demonstrable in practice and aligned with standards for responsible conduct (as determined by diverse stakeholders across the industry), which can serve as a gating mechanism towards subsequent phases of research or operations. Smaller scale, low-risk research and deployment activities can be utilized to efficiently develop, test, refine, and operationalize effective governance structures that are designed for real-world application. This will ensure the creation of practical and actionable standards that mitigate risks and assure compliance without delaying critical research.

In the current absence of established governance structures at an industry level, the following areas of consideration can serve as a guide by which to demonstrate project maturity and ethical decision-making:

- **Science and research**: Is the project based on foundational science? Has the project identified key research questions and developed plans to address them?
- **Environmental and ecologica**l: Has the project effectively considered the potential environmental and ecological impacts of planned activities, both positive and negative?
- **Legal and regulatory**: Does the project have clear permission to operate and an understanding of the legal and regulatory frameworks that impact the proposed activities?
- **Technical**: Do those conducting the project activity possess the technical capacity to understand project impacts, and effectively monitor and measure results?

- **Social, community, and equity**: Have those conducting the project worked with all relevant local and community stakeholders to educate, engage, and garner feedback on plans and research?
- **External verification and oversight**: Have those conducting the project ensured that independent expert parties can effectively review and validate the project work, approach, and results?
- **Internal organizational structure**: Do those conducting the project have organizational checks and balances in place to ensure decisions are science-based and responsibly agreed upon?
- **Information sharing and transparency**: Has the project demonstrated the necessary level of transparency around processes, plans, and results such that reviewers and the public can effectively evaluate the proposed system?

Compliance in these areas may be demonstrated via a number of pathways, including but not limited to publicly available educational materials (i.e., white papers, research roadmaps, and project-specific experimental plans), defined oversight processes (i.e., consultation with an independent scientific advisory board, independent and documented reviews of work against defined standards such as ISO by accredited auditors), and records of project-specific documentation (i.e., permitting, stakeholder consultation records, and pre- and post-EIAs).

Failure to meet applicable standards in any individual category risks social license and trust, and may prevent the project from proceeding as planned.

Specific to regulatory oversight, clear permitting and permission to operate at the relevant local, state, federal, tribal, and international levels must be demonstrated prior to planned deployments, including alignment with any current or future national or subnational compliance carbon programs within proposed operational locations.

Socioeconomic Impact

Organizations conducting interventions in the ocean must engage coastal communities by seeking the perspectives and guidance of community leaders and in community forums, funding consultations with these communities where appropriate, and hiring local talent. Organizations must also establish ongoing feedback mechanisms, including grievance resolution processes, for all affected stakeholders.

Coastal communities often bear the heaviest burden of climate change. High-paying and living wage reliable jobs in these areas can advance livelihoods for waterfront communities and provide waterfront workers the opportunity to positively impact their own communities. These communities and industries possess inherent knowledge of, and experience working in, their local ocean; as such, they are ideal candidates for employment — especially given that their existing professions and livelihoods may be impacted by climatic shifts (fishing, aquaculture, and more) — and often require minimal retraining and skills development. The ocean is a cultural foundation of coastal communities around the world, and its decline has caused a crisis of identity that manifests itself in myriad ways. Restoring career opportunities for these communities has positive effects well beyond the financial implications.

Where possible, underutilized infrastructure should be repurposed and revitalized, further investing in communities and reviving community resources.

Over time, site-specific and measurable socioeconomic impact assessments must be designed and conducted to establish baseline socioeconomic conditions and include relevant economic, cultural, and social considerations. These assessments must be designed in partnership with affected communities and monitored over the life of the project.

4. Carbon Removal Accounting Framework

Quantification Approach

The approach to carbon removal quantification for this multi-pathway system is three-fold:

1. **Model the system** – specific to both carbon removal activities conducted and the broader Earth system.
2. **Quantify the intervention** – inclusive of a publicly available protocol for quantification, in-situ instrumentation, and record keeping.
3. **Audit the quantification** – based on carbon accounting and life cycle assessment best practices, and the ISO 14064-2 standard for quantifying and reporting greenhouse gas emissions. Along with an assessment of total carbon impact, comprehensive third-party auditing also includes an independent review of environmental impact assessments prior to deployments, relevant project documentation post-deployment, and ongoing socioeconomic impact reporting.

Transparent quantification processes, carbon and emissions accounting following industry best practices, and independent external auditing are critical to ensuring the quality and credibility of any carbon removal approach. The inherent challenges in measuring and monitoring phenomena occurring over the vast expanse and depth of the open ocean require a focused and disciplined approach to quantification that is based on computational modeling, direct in-situ observation, and laboratory ground-truthing.

This approach is informed by best practices from the field of climate research. All Earth-scale systems require a layered approach to generate uncertainty-bounded estimates of the impacts of a perturbation over a large geographic area. For diffuse systems, direct measurements are not inherently better than modeling, as there reaches a point of diminishing returns between the cost of direct measurement and the additional insight it provides. In-situ direct measurement, remote sensing, and modeling are complementary, rather than competing, approaches to building a rigorous quantification system.

This quantification approach is built on and informed by the ‘best available science’, an established practice in natural resource management that ensures an activity evolves to match the best currently available understanding of Earth systems.

Governing Principles for Quantification

- **Quantification will be model-driven** and validated by direct measurement and rigorous laboratory and field-based testing. The design, assimilation, tuning, and validation of the modeling framework will incorporate a variety of unique observational data from experiments designed to answer critical questions, as well as the latest scientific knowledge.
- **Quantification is uncertainty-bounded**. This means that quantification computations must include not only the expected value of carbon removed but also the accumulated uncertainty which bounds this expectation, accounting for the uncertainty of the measured inputs for each specific variable and the modeling framework itself (i.e., model stability). The goal of this effort is to quantify the total carbon removed through an intervention and demonstrate that the uncertainty associated with that quantity is bounded within a given error. Effectively characterizing this uncertainty ensures that conservative discounting is appropriately applied, increasing confidence in the quantified outcome.
- For the final estimation of removed carbon, **programmed conservatism is applied**, ensuring high certainty (95% or above) that at least the estimated amount of carbon was removed. In practice, this means that the estimate of carbon removed will be bound by the uncertainty (either lower or upper) in each input variable that yields the most conservative (i.e., lowest) quantity of total carbon removed. In cases of conflicting information with respect to model assumptions, such as standard emission factors, the more conservative assumption will be utilized.

The combination of these principles for conservative, model-driven quantification with bounded uncertainty provides a high degree of confidence in the total net carbon that has been removed from the system through a given intervention.

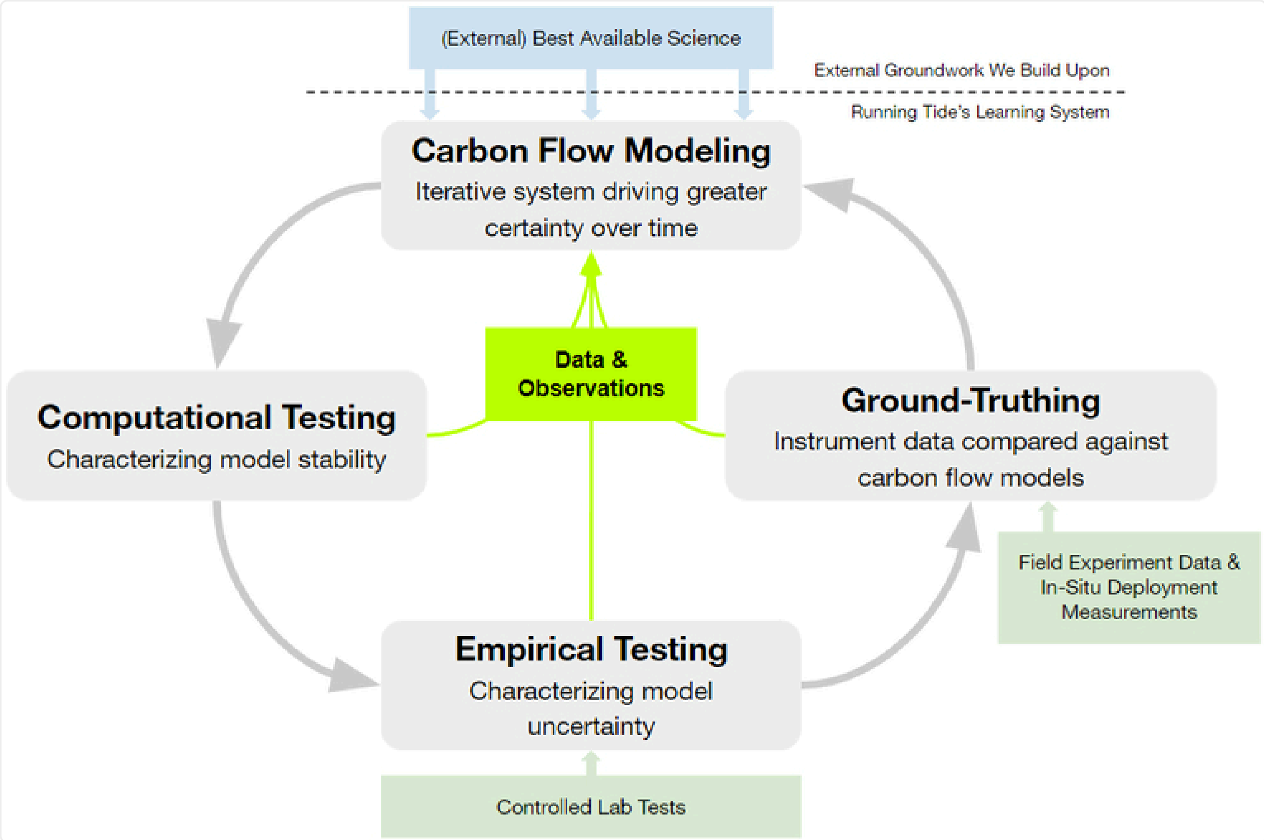


Figure 5: Quantification modeling system. An iterative system based on the best available science that integrates computational testing, empirical testing, and in-situ open-ocean data collection.

Modeling is at the core of this quantification approach. The ability to effectively model the system is achieved through:

- **Computational testing**: applied to characterize model stability as distinct from variation in the input data. This analysis is incorporated into overall uncertainty.
- **Empirical testing**: testing of models against large data sets generated in both laboratory and monitored open ocean settings, and characterizing model uncertainty against these observed data. Empirical testing is composed of two primary approaches:
    - *Regulated*: controlled variation of input parameters against a measured response. Where possible, regulated empirical testing will be a crucial component of model design. The key advantage of regulated testing is an ability to vary controlling parameters over the range expected in the offshore environment. In contrast to an uncontrolled observational environment, where controlling parameters are oftentimes correlated, properly designed regulated experiments can isolate causal relationships between the controlling responding parameters in the models.

    - *Observational*: monitored but uncontrolled variation of input parameters against a measured response. The observational testing will help validate and refine models built on experiments in regulated environments. For the model components that cannot be developed in regulated experiments, the observational testing is crucial.
- **Direct measurement**: in-situ data collected from an instrumented subset of the open-ocean project establishes the correlation between modeled and observed behaviors and informs the quantification of environmental impact. This correlation analysis supports extrapolation from subset to project total; the stronger the correlation, the lower the overall uncertainty of the extrapolation.

Models must be based on acceptable industry standards, developed in accordance with peer-reviewed academic best practices, and ground-truthed with empirical data. If and where models are developed or adapted to be fit for purpose in quantification, it is critical that detailed descriptions of models used and how they support replicable quantification are documented and provided alongside project outcomes to enable external validation and review, and build trust in the underlying results.

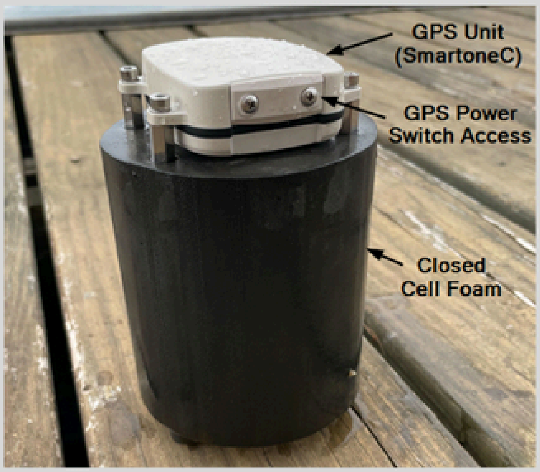
Open Ocean Observation Platforms

Measurement instrumentation for in-situ data collection

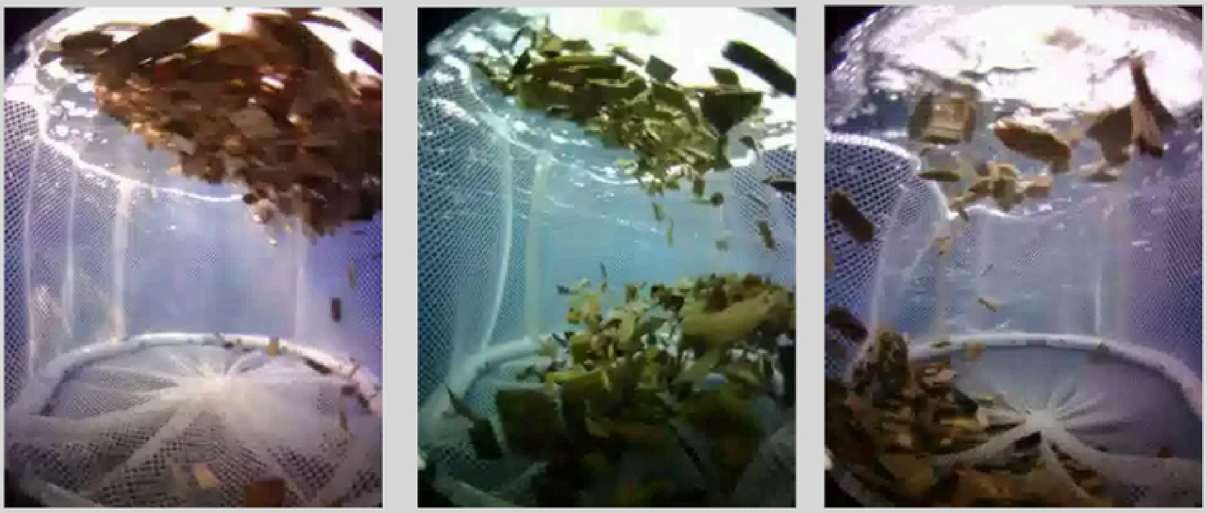
The offshore engineering required to collect in-situ data from the open ocean environment has been subject to ongoing iteration to improve on the ability to correlate real world data with modeled behaviors, and 'close the modeling loop' to refine model outputs and increase certainty in quantification results. The approach to verification hardware development has focused on dematerializing (i.e. making components smaller and more efficient), scaling to production, and developing an ecological impact design philosophy to maximize information gained with the minimum possible footprint.

Verification hardware sensor deployments conducted in the North Atlantic in late 2022 and early 2023 included custom designed camera buoys, as well as GPS-enabled trajectory buoys and environmental sensors (wave energy, chlorophyll-a, and temperature) — both pictured below. Extending open ocean sampling capabilities to include parameters of the carbonate chemistry of seawater is an active area of exploration.

Open ocean observation platform with integrated sensor suites, macroalgae growth image capture, OAE dissolution rates, sinking location, wave and wind action, and more.



Trajectory sensors with GPS and floatation system.



12/5/22 12/12/22 12/22/22

In-situ imagery of biomass over multi-week time series from verification hardware deployment in the North Atlantic, December 2022. Real time observation provides visibility into float time and performance of distinct carbon buoy compositions in varied weather and wave conditions, and enables comparison against models.

Offshore prototype tests have been conducted for multiple generations of verification hardware sensors over the past several years:

2021 - Proof of concept and working system for offshore data collection

North Atlantic 1 - March 2021

- Tested off-the-shelf GPS and remote imaging systems for the purpose of observing open ocean macroalgae seed recruitment. The basic functionality of these systems was validated.

Labrador Sea 1 - July 2021

- Custom-designed imaging prototypes were tested and certain failure modes were revealed. This deployment also allowed for the exploration of drifting dynamics in a location with less dispersive ocean gyre properties.
- First offshore photos from camera systems built in-house were captured, ~1,100 miles northeast from the Maine point of departure into the Labrador Sea.

North Atlantic 2 - December 2021

- Significant improvements to the camera system design, including move to internal solar panel, antenna bulkhead through lid to eliminate the need for an external harness, custom charger board (i.e. lower floor power), and more.
- Successfully tested the electronics and software systems for the second generation of custom imaging systems.

2022 - Reliable platform for offshore data collection fit to carbon removal system design

Open Ocean Observation Platform Development - Q1/Q2 2022

- Evolution from camera system testing to full-stack open ocean observation platforms outfitted with GPS-enabled trajectory instruments and environmental sensors alongside imaging instruments.
- Observation platforms outfitted with fluorometers (used to measure chlorophyll, a proxy for nutrient levels) developed in-house. Off-the-shelf fluorometers cost up to $2,000 each; Running Tide fluorometers, in development since early 2021, cost less than $300.

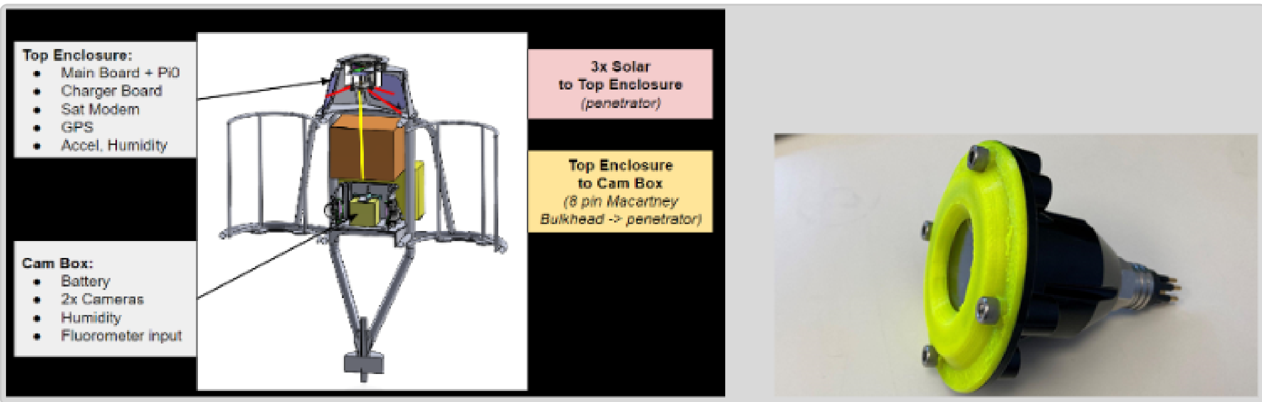


Figure 6: Instrumentation for open-ocean data collection.

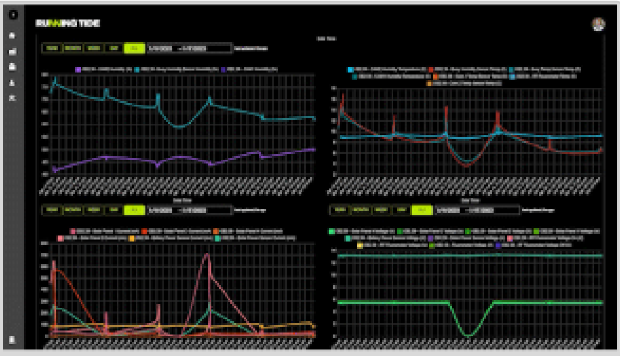
Gulf of Maine - June 2022

- Stress testing of observation platforms to prepare for open ocean deployments — drop testing, drag testing, and stability testing. First operational observation platforms with full capabilities deployed into the Gulf of Maine.



Iceland Sensor Deployment 1 - December 2022

- Successful deployment of fully operational verification hardware systems into the North Atlantic, providing real time biogeochemical data and in-situ imagery over multiple months.
- Sensor deployment location and trajectories were used to test and tune the trajectory model and improve deployment quantification processes from site selection and prediction to carbon credit quantification.
- Carbon buoy floatation data collected from open ocean observation platforms was compared to laboratory results.

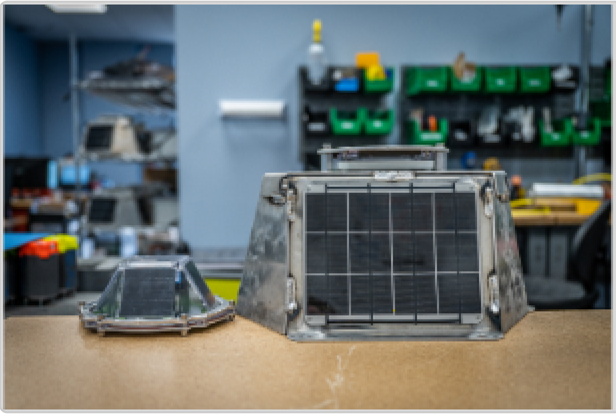
2023/2024 - Increased efficiency, dematerialized design, improved measurement capabilities

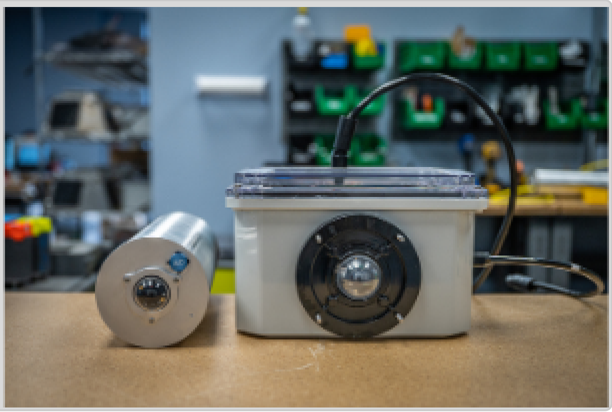
Iceland Sensor Deployments 2 and 3 - Q1 2023

- Two additional verification hardware deployments were conducted in January and March/April of 2023, collecting additional data on performance in varying wind/wave conditions and testing different deployment methods and trajectories (i.e. lowering camera buoys with a long line vs. trajectory buoys dropped off the side of the boat, released over a larger geographic area rather than in once place, etc.).
- More than 1,700 photos and 10,000 trajectory points were shipped back from the first two verification hardware deployments.

Ongoing Hardware Innovation

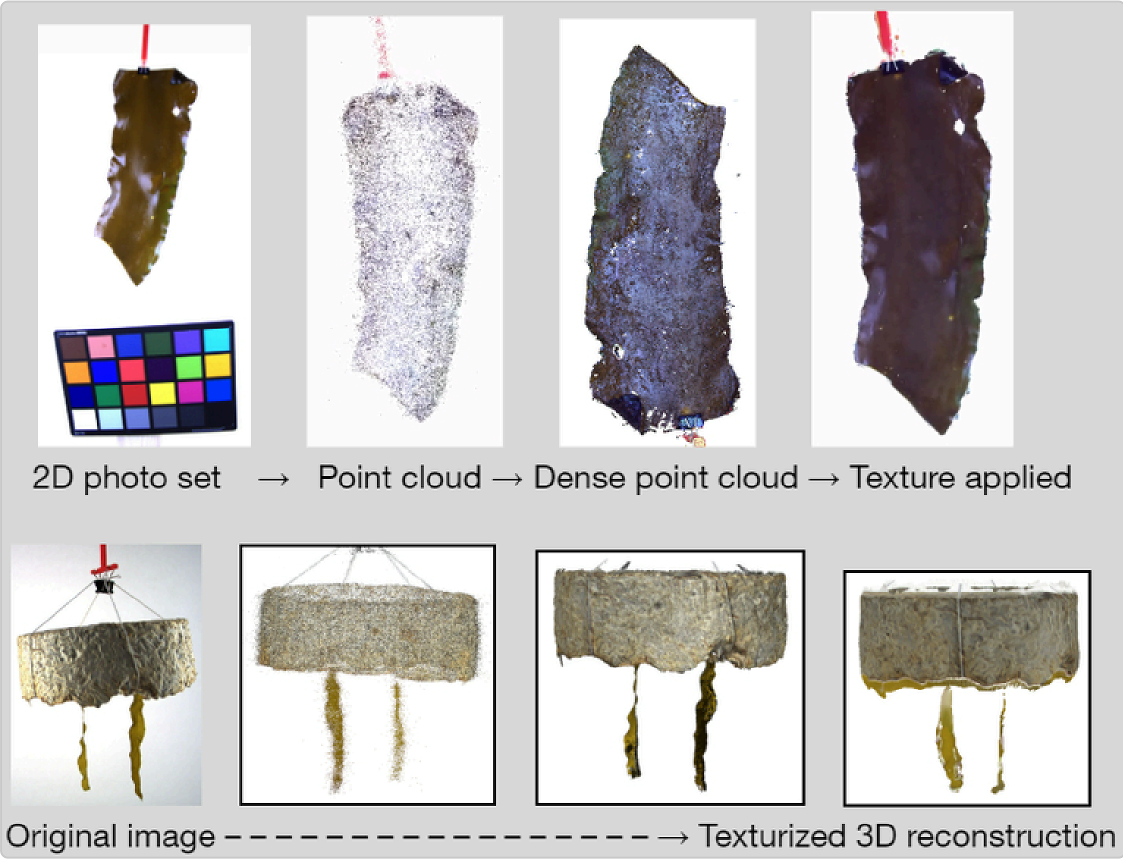
- Additional dematerialization of core hardware components (top enclosure and camera box evolution shown below).
- Preparing for rollout of next generation of open ocean observation platforms.
- Exploration of substrate “wearables” (i.e., verification components attached directly to a subset of carbon buoys) and capacity for onboard data processing.





Machine Vision Image Analysis for Macroalgae Growth Quantification

- Ongoing, multi-year project to generate texturized, three-dimensional models from a set of two-dimensional macroalgae images to verify macroalgae biomass accumulation and carbon content — more detail below


2D photo set → Point cloud → Dense point cloud → Texture applied
Original image – – – – – – – – – – – – – – – – – → Texturized 3D reconstruction

Calculation of Net Carbon Removed

At its simplest level, the net CO_2 removed from this multi-pathway system can be calculated as:

$$CO_2eRemoved = CO_2eTerrestrial + CO_2eOAE + CO_2eMacroalgae - CO_2eEmissions$$

Where:

$CO_2eTerrestrial$ = CO_2 Removal by Sinking of Terrestrial Biomass

CO_2eOAE = CO_2 Removal by Alkaline Mineral Dissolution

$CO_2eMacroalgae$ = CO_2 Removal by Macroalgae

$CO_2eEmissions$ = End-to-End System Emissions

Initial deployments will focus on the sinking of terrestrial woody biomass. This pathway is fully operationalized and accounted for today via:

- Direct measurement of the carbon content of representative terrestrial biomass samples contained in the carbon buoys, validated by laboratory testing of biomass characteristics.
- The adoption of existing ocean models for predictive modeling of expected carbon buoy transport behavior in the open ocean, also based on assessments of the physical behavior of carbon buoys in lab-replicated ocean environments and empirical data from GPS sensors released alongside deployment.
- Direct observation of biomass sinking from a subset of carbon buoys via in-situ image analysis from observational camera systems released alongside carbon buoy deployment.
- Quantification of emissions associated with biomass material inputs, production, transport, and deployment.

Initial deployments will also utilize a mixture of calcium carbonate and lime kiln dust for dissolution in the surface ocean. This pathway is operationalized for initial deployments and will be used to buffer any acidity generation that occurs during terrestrial biomass floatation, but will not be used to generate credits through the ocean alkalinity enhancement pathway until the quantification and monitoring methodology is refined in the open ocean environment.

- The primary objective in quantifying alkalinity enhancement is to determine what quantity of alkalinizing material has been successfully dissolved into the mixed layer in a given region of the ocean. The amount of CO_2 sequestered by the alkalinity addition will be discounted by the amount of CO_2 released by any reprecipitation of carbonate minerals that occurs in the surface waters, which will be estimated from laboratory experiments and measurements of key parameters in the field (salinity, temperature, pH). To-date, testing of ocean alkalinity enhancement has primarily been conducted in laboratory settings to characterize how quickly alkaline materials dissolve in water. In the laboratory setting, dissolution reactors continuously log temperature, pH, and salinity of water and pCO_2 of air at the surface, alkalinity is measured with an auto titrator, and water samples are sent to independent labs for elemental analysis. Experiments have also been conducted to characterize the effect of organic acid leaching from wood and the mitigation of this by alkaline mineral dissolution, namely lime kiln dust. Supplementing research by external collaborators, additional experiments are planned to further quantify rates of acid leaching from terrestrial biomass and neutralization of this acidity by dissolution of alkaline minerals, and to elucidate the degradation of dissolved organic carbon released by the macroalgae and terrestrial biomass.
- Weather permitting, surface water conditions will be monitored and sequentially sampled during deployments to help establish a solid empirical baseline for key parameters related to CO_2 removal, including pH, salinity, total alkalinity, and other chemical constituents as needed. Both the interactions observed from laboratory experiments and surface water sampling during deployments will be incorporated into predictive modeling of the perturbation against baseline seawater carbonate chemistry to evaluate net CO_2 sequestration.
- Over time and with scale, direct observation of the carbon chemistry perturbation and how it evolves in time may be possible, and in-situ imaging of alkaline mineral dissolution via instruments such as those shown above may be used to validate results in the open ocean.
- Geochemical dynamics embedded within global circulation models will be used to quantify the amount of additional CO_2 transferred from the fast to the slow carbon cycle. Although these models are adapted and developed on an ad hoc

basis today, best practices for modeling should be developed at an industry level.

- Ongoing research related to OAE quantification includes studying the impact of surface-ocean carbon uptake or alkalinity addition on the air-sea gas exchange of CO_2. While this air-sea flux is an important and well studied area of carbon cycle research, it is primarily a fast cycle transfer of atmospheric CO_2 into surface waters as the dissolved CO_2 that was reallocated to the bicarbonate reservoir is replaced by novel CO_2 exchange across the air-sea boundary. The slow cycle transfer that is the primary activity of carbon removal occurs via the reallocation of fast cycle carbon to the larger and more stable bicarbonate reservoir. While the time horizon to complete the exchange of CO_2 between the atmosphere and ocean may vary, it will eventually equilibrate, completing the fast cycle transfer. The air-sea exchange time horizon for CO_2 relative to the time it takes for surface waters to be subducted to the deep ocean [Sabine et al., 2004] may be relevant to establishing total carbon removed via natural ocean mixing – i.e. if full equilibration has not yet occurred at the time of mixing to the deep ocean, there may be an impact on the fast-to-slow transfer of carbon from that natural pathway associated with project activities. Determining and refining how this is considered in OAE quantification remains an active area of discussion amongst practitioners and the research community as the OAE field matures.

Carbon removal by macroalgae will not be operational for initial deployments and will be introduced in subsequent deployments based on the successful recruitment and growth of macroalgae in the open ocean and continued advancements in modeling algal growth versus observed growth.

- Most macroalgae species are coastal organisms adapted to thrive in environments with high nutrient concentrations and low wave energy relative to the open ocean. Research on open ocean cultivation of macroalgae has focused on species that will sink intact through the water column, particularly Ulva lactuca and Saccharina latissima. Foundational work has been performed on macroalgal genomics and life cycle, including extraction of high molecular weight DNA from Saccharina latissima and various Ulva species. Isolation, cultivation, and banking of various developmental stages of these species have been performed, and this basic research, conducted in collaboration with Los Alamos National Laboratory, should lead to the first published long-read genomes for Ulva lactuca and Saccharina latissima. Surveys of natural variation at initial deployment locations in West Iceland have also been performed to collect genotype and phenotype data for a variety of macroalgae species in that region.

- Alongside this foundational research, a series of coastal macroalgae growth experiments have been performed to establish technical capacity for macroalgae growth and image-based phenotyping alongside environmental time series data collection at the experimental growth site. Initial experiments included measurements of temperature, pH, salinity, light intensity at depth, photosynthetic active radiation (PAR) at depth, and chlorophyll-a content of the ambient water. Later experiments were expanded to include fluorescent dissolved organic matter (fDOM), ammonium, dissolved oxygen, nitrate, turbidity, and subsurface ocean currents. Ongoing coastal experiments afford the opportunity to explore methods of seeding carbon buoys with macroalgae, and observe and measure macroalgae growth rates in an ocean setting. The technology developed in this setting will be applied to the open ocean to support the quantification of macroalgae growth offshore.
- Open ocean tests of integrated prototypes have also been conducted, placing macroalgae seed on instrumented buoys in the open ocean to observe open ocean macroalgae seed recruitment and test verification hardware. Critically, the recruitment and growth of macroalgae was successfully imaged in the open ocean.
- The results of controlled laboratory experiments are being used to develop biological growth models for macroalgae carbon accumulation — based on inputs related to genetics, macroalgae development stage, and environmental parameters — to predict growth (and thus carbon sequestered) along an ocean deployment trajectory. Laboratory experiments replicate open ocean light, temperature, and nutrient conditions to enable robust models and predictions. Models developed are in part based on existing macroalgae growth models [Broch and Slagstad, 2012]; however, these pre-established models are not specific to macroalgae grown in the open ocean, and as such require significant modification, and must be built and refined against open ocean conditions via quantification outputs from both controlled and test deployments.
- Models are trained with imaging data, where predictive quantification of biomass growth is compared with observed growth in the open ocean validated by in-situ imaging, and discrepancies are used to refine model outputs. Machine vision enables the generation of texturized, three-dimensional models from a set of two-dimensional buoy and macroalgae images, providing additional data on macroalgae biomass accumulation and carbon content.

Following initial deployments, it is expected that the ratio of macroalgae to woody biomass will be gradually increased, with the long-term (decadal) goal of achieving a 5:1 ratio of macroalgae mass to carbon buoy mass on a carbon basis. Yields of 50:1 have been observed in fixed research locations with low wave energy, high-nutrient conditions.

With that context, CO_2eTerrestrial, CO_2eOAE, CO_2eMacroalgae, and CO_2eEmissions can be broken down into their component parts.

CO_2 Removal by Sinking of Terrestrial Biomass

CO_2 Removal by Sinking of Terrestrial Biomass can be quantified as:

$$CO_2eTerrestrial = Terr_{added} - Terr_{loss} - Shed - Shal - Terr_{stor} - LUC_{indirect}$$

Where:

$Terr_{added}$ = Mass of carbon contained in terrestrial biomass that is deployed to be sunk.

- Calculated based on the total mass of carbon buoys loaded onto a specific deployment vessel, the portion of buoys composed of terrestrial biomass, the moisture content of biomass at the time of loading, and the carbon content of ‘bone dry’ biomass.
- Quantified via a combination of direct measurement of mass of material used in buoys and a standard conversion factor for carbon content of material based on species used. Terrestrial biomass is sampled and submitted to a partner lab for analysis of moisture content, carbon content, and ash content.

$Terr_{loss}$ = Mass of carbon contained in terrestrial biomass that is lost between time of loading and time of deployment.

- A small amount of loss may be observed during transport due to high winds and waves.
- For initial deployments off of barges, loss is estimated by comparing time lapse camera image analysis to total volume calculated from barge dimensions and loaded height measurement.
- In the event of camera issues or unexpected weather events, additional conservative discount factors may be applied.

$Shed$ = Portion of carbon in terrestrial biomass separated from carbon buoys prior to or during the sinking process that does not make it to the ocean floor.

- Laboratory experiments are conducted to measure remineralization rates, sinking rates, and the amount of organic compounds leached, dissolved, or otherwise separated during the flotation time of terrestrial biomass (including particulate organic carbon and dissolved organic carbon such as organic acids).
- Direct observation of biomass loss via in-situ image analysis from observational camera systems further informs and refines float times.
- Conservative estimates of terrestrial biomass separation during floating periods outside of eligible sinking locations are applied.

$Shal$ = Portion of terrestrial biomass carbon that ends up beached or sunk in areas too shallow to be removed from the coupled upper ocean-atmospheric system in the fast carbon cycle, or at risk of upwelling.

- Spatial evolution of the carbon buoy population is evaluated across quantification approaches:
  - Carbon buoy sinking speed is evaluated in laboratory and coastal settings.
  - Lateral transport of carbon buoys during sinking can be modeled using publicly available ocean current models. These models resolve subsurface ocean currents at various depths, and are validated against in-situ data. Such models can be used to quantify the maximum horizontal distance that a carbon buoy may travel during its descent given a particular sinking rate.
  - Modeling and laboratory results can be further supported via direct measurement from GPS sensor buoys.
- For initial deployments, a Monte Carlo simulation is used. Models start with initial distribution of passive floating points (carbon buoys), simulate floating trajectories, and then simulate sinking to the terminal location on the seafloor. The time that carbon buoys sink is simulated using the float time distributions described above and trajectories defined by the interplay between wind, waves and currents. Thousands of simulations are run to determine the probability curve within the range of possible values. The results of these model runs produce a final probability plot of terminal carbon buoy distribution on the seafloor, which defines a single variable output with a given confidence level.
- Beyond initial deployments, additional in-situ observations of sinking rate — including the use of submersible AUVs to follow deployments throughout surface drifting and eventual sinking to the seafloor — are planned and

expected in the coming years. Benthic research programs with external oceanographic collaborators are currently being finalized.

- Actual depth in shallower locations may be of less importance than sedimentation and remineralization rates, as the percentage of organic carbon preservation varies with total sedimentation rate (i.e. the faster something is buried, the more likely its carbon will be preserved in its organic form). Similarly, benthic research programs will be needed to inform expected biomass burial and remineralization rates.

$Terr_{stor}$ = The portion of carbon in embodied terrestrial biomass that is likely to be removed from the fast carbon cycle in the absence of sinking.

- Related to the additionality of project activities. Effective drawdown from terrestrial biomass sinking occurs so long as the biomass would not have otherwise been moved into the slow cycle (certain types of biochar applications, biomass burial, bio-oil injection, etc.) and does not negatively impact the net carbon stock of the biomass source.
- With a fast-to-slow framing for terrestrial biomass, the primary consideration is the stability of the carbon reservoir in question. Carbon stored in aboveground biomass, whether in short-lived industrial processes, a managed forest, or subject to natural decay, is inherently volatile and subject to a high risk of reversal, meaning that the carbon contained within this biomass may move between fast cycle reservoirs in a matter of months, years, or decades. As such, the removal activity related to this biomass occurs when that potential volatility is eliminated. Aboveground biomass and surface soils are thus functionally fast systems that will largely remain in the fast cycle (in their baseline state, as atmospheric CO_2 or as dissolved CO_2 in the surface ocean) via soil/root respiration or decomposer respiration from dead wood/leaves. Conversely, the underlying "stable" soil carbon layer is functionally a slow cycle reservoir in that the carbon contained is unlikely to move into a different reservoir without human disruption or significant land use change.
- While this framing implies that all aboveground terrestrial biomass could potentially be additional from a purely carbon accounting perspective, practically speaking, the management of aboveground biomass and surface soils will impact both fast cycle carbon fluxes and the stability of the underlying stable soil layer, along with critical non-carbon secondary effects on biodiversity, ecosystem health including watershed benefits and oxygen production, and more. As such, biomass eligibility and sourcing considerations

are determined not just by fast and slow carbon cycling, but also by their potential impact (positive and negative) on the above secondary effects and fast cycle fluxes.

- For residue sources, this is straightforward; differentiating between materials that would be burned versus left to decay is de minimis, as GHG Protocol guidance for dead organic material states that the timing delay associated with baseline CO_2 emissions from degradation does not require amortization and can be claimed at the time of intervention. Supplier attestations on the alternative baseline state of sourced residue biomass are required to demonstrate additionality.
- For biomass sourced from non-residue origins, biomass obtained through sustainable forest management shall be utilized, and on a long-term basis, "purpose-grown feedstock" — i.e. terrestrial biomass that is grown on marginal or arid land for the explicit purpose of biomass-based carbon removal — will be considered, contingent on their impact on secondary effects.
- Biomass sourcing standards will need to continue to be developed and adopted at an industry level, especially as competition for available biomass is expected to increase.

$LUC_{indirect}$ = Emissions impact of any indirect land use change associated with changes in the production of the feedstock due to terrestrial biomass sinking.

- Related to the impact on the net carbon stock from land use change due to project activities, and encompassing the harvesting of terrestrial biomass leading directly to emissions elsewhere (i.e., leakage). Supplier attestations for all biomass sources will be required, and any additional emissions that directly result from increased demand for biomass will be monitored and included in the calculation of net carbon removed.
- For residues, all biomass sourced is FSC certified and sourced from FSC Forest Management Certified suppliers, or from an equivalent certification system in the event FSC is not in use in a given jurisdiction or with a given species. Low-grade biomass resources are currently in abundant supply, in part due to economic shifts in the demand for materials such as low-grade pulp wood, along with readily available materials such as sawmill cut offs and wildfire management burn piles.
- Land use change modeling will follow GHG Protocol best practices and industry standards specific to the biomass species used. Notably, existing land use change models are atmospheric-centric in their design, and as such early

deployments are likely to be inherently conservative in their accounting for potential fast cycle fluctuations.

CO_2 Removal by Alkaline Mineral Dissolution

CO_2 Removal by Alkaline Mineral Dissolution can be quantified as:

$$CO_2eOAE = Alk_{add} - Sec_{precip} - Carb - Acid_{add} - PMF + POC$$

Where:

Alk_{add}= Moles of alkalinity added to surface seawater through dissolution of alkaline minerals.

- Conversion of alkalinity into CO_2e can be calculated based on the measured addition of alkaline materials into the ocean and their modeled rate of dissolution prior to sinking, informed by laboratory testing in different conditions.

Sec_{precip}= Moles of secondary precipitation of calcium carbonate ($CaCO_3$) associated with high surface water alkalinity.

- Can be minimized by ensuring rapid dispersal of added alkalinity relative to the rate of alkalinity addition, and potentially assessed by measurements of Total Alkalinity (TA), pH, $[Ca^2+]$, and/or dissolved inorganic carbon (DIC) in the deployment region.

$Carb$= Moles of DIC added to seawater as carbonate equivalents (CO32-) by dissolution of calcium carbonate rather than as bicarbonate.

- Represents the uptake efficiency uncertainty associated with carbonate versus bicarbonate formation, as carbonate formation reduces the marginal storage capacity of DIC (via atmospheric CO_2) in seawater per unit of added alkalinity.
- Aqueous carbonate vs bicarbonate ion formation in a given area is based on environmental conditions (temperature, pressure, salinity) and pH, and must be accounted for to determine the total reallocation of fast cycle carbon (aqueous CO_2 pool) to the bicarbonate pool as a removal. Water sampling during deployments will be completed for a baseline understanding of these environmental conditions.

- Laboratory testing measuring alkalinity, pH, and DIC are conducted on water samples to calculate the distribution of aqueous carbonate species between aqueous CO_2, bicarbonate ions HCO3-, and carbonate ions (CO32-) at a given point in time.

$Acid_{add}$= Any addition of acidity to the ocean that reduces the alkalinity of surface seawater and the associated sequestration of atmospheric CO_2, expressed as the resulting change in moles of alkalinity.

- Terrestrial biomass contains organic compounds with functional groups that, when dissolved in water, may contribute acidity to the surface ocean environment. Leaching experiments in a laboratory setting will quantify the amount of acidity that is generated from organic carbon dissolution, which can be extrapolated to the scope of the project activity.
- This release of acidity would effectively counteract a molar-equivalent portion of alkalinity enhancement associated with alkaline mineral dissolution.

PMF= Physical Mixing Factor. The effect of ocean mixing processes on the efficiency of moving CO_2 from the fast to slow cycle – i.e., surface ocean subduction to deeper waters following alkalinity addition and prior to complete re-equilibration.

- A chemical perturbation to the surface ocean, such as alkalinity enhancement, that reallocates dissolved CO_2 to the stable bicarbonate reservoir increases the residence of the dissolved carbon, thereby constituting a transfer from the fast to slow cycle. This reallocation or increase in buffering capacity can lead to a chemically unstable gradient between the partial pressure of CO_2 (pCO_2) in the surface ocean and the atmosphere, drawing additional fast cycle CO_2 into the ocean for conversion to bicarbonate ion. If subduction of surface water due to physical mixing processes occurs prior to complete re-equilibration, the fast-to-slow transfer of carbon from that natural physical pathway may be reduced, and as such should be accounted for with a discount factor.
- The impact on total carbon removed from this factor is only in relation to the difference between the total amount of dissolved carbon mixed into the deep ocean for durable storage in the absence of project activity versus what is mixed into the deep ocean following the addition of alkalinity and the associated addition of DIC to the surface ocean.

- This remains an active area of research and discussion within the scientific community.

POC = Additional formation of dissolved inorganic carbon could lead to more Particulate Organic Carbon (POC) in the surface ocean, thereby providing additional CO_2 drawdown via increased photosynthetic activity (i.e., a “fertilization effect”).

- The positive increase in POC in the surface ocean would only lead to additional carbon removed based on the portion of additional POC that made its way to the deep ocean for durable storage via natural fast-to-slow pathways (i.e. biological pump or ocean mixing activity). When deployed in tandem with the macroalgae carbon removal pathway, this effect may be complementary to macroalgae growth and relevant for nutrient competition considerations (see the BAF variable below). This effect remains uncertain and is an area of further research and exploration.
- Quantification of increased primary production due to alkalinity-induced increase in DIC would require remote and/or in-situ measurement of localized chlorophyll-a. concentrations and/or phytoplankton populations.

CO_2 Removal by Macroalgae

CO_2 Removal by Macroalgae can be quantified as:

$$CO_2eMacroalgae = Macroalgae_{Accumulated} + Biomass_{Accumulated} - Shed - BAF - BFR - PMF - Shal$$

Where:

$Macroalgae_{Accumulated}$= Mass of carbon absorbed by deployed macroalgae attached to carbon buoys at the point of sinking.

- Ocean observation platforms capture photos of deployed carbon buoys to provide in-situ visual validation of macroalgae biomass accumulation and growth rates up to the point the buoys begin to sink. Image analysis (through machine vision) is used to extract growth characteristics (blade length, width, area) to correlate to biomass and carbon content. This imaging informs macroalgae loss or shedding that occurs during the growth process and float period.
- Models are trained using machine vision to map macroalgae mass using the camera systems deployed on the open ocean observation platforms. Preliminary data has shown high correlations in direct measurements of macroalgae biomass and carbon elemental analysis.
- Yields will depend on macroalgae species and genotype, environmental conditions such as macro and micronutrient availability, and episodic mortality events such as disease and storms.
- Future quantification will include refined analysis of imaging through water, which will help account for distortion from refraction and turbidity. Currently, image quality is more altered by physical constraints on the system (power, lighting, electronics, etc.).

$Biomass_{Accumulated}$= Mass of carbon absorbed by non-seeded macroalgae that accumulates on carbon buoys via natural recruitment at the point of sinking.

- Biomass accumulation in addition to the specific species of macroalgae seeded on the buoys. Carbon buoys and other materials placed in the ocean are subject to natural photosynthetic ‘biofouling’, i.e. the growth of microorganisms, algae, and other species on submerged surfaces. While this process tends to be undesired for maritime vessels or oceanographic sensors, much like seeded macroalgae recruitment, they represent natural recruitment and growth of carbon-fixing organisms that if sunk are additional to natural biological pump activity.

- Quantification of additional biomass accumulation is contingent on the ability to recognize macroalgae species and effectively image and model growth rates in the same fashion as macroalgae seeded on deployed carbon buoys described above.
- Similarly, this additional biomass is subject to further benthic and pelagic ecological investigations in relation to the species identified.

$Shed$= Portion of macroalgae carbon shed during the growth and sinking process.

- Open ocean observation platforms are collecting data on macroalgae biomass accumulation up to the point of sinking, and buoy design promotes an accelerated sinking rate compared to phytoplankton and particulate organic carbon, which will minimize potential shedding rates. Any shed material that has already started sinking is expected to behave similarly to the macroalgae material attached to the buoy.
- It is well established that many fish species have a natural affinity to aggregate near floating structures, and as such may view new macroalgae biomass as a potential food source as it moves through the water column. This impact is expected to be immaterial for initial deployments due to intervention design, but further research is being conducted into the potential impact of pelagic organisms on macroalgae consumption and the fraction of that consumed biomass that is transported to the seabed as fecal pellets (i.e., transported to slow carbon cycle) versus being remineralized to CO_2 in the surface water and released back to the fast carbon cycle.

BAF = Biogeochemical Additionality Factor, or the secondary effects on phytoplankton carbon uptake associated with competition with cultivated macroalgae for nutrients or light in the open ocean.

- The addition of macroalgae into the open ocean where nutrients are already limiting for photosynthesis has the potential to decrease phytoplankton net primary productivity indirectly through nutrient consumption by macroalgae. Since macroalgae have much higher C:N ratios than phytoplankton, they can form one unit of carbon biomass using a smaller nutrient load than phytoplankton. Although this makes macroalgae more efficient with respect to nutrient utilization, and prevents macroalgae from displacing phytoplankton on a 1:1 basis, macroalgae photosynthesis may still displace phytoplankton photosynthesis to some extent in waters where nutrients are limiting.

- For initial deployments, given that algal photosynthesis in the subpolar North Atlantic is primarily iron-limited [Moore et al. 2013], it is expected that phytoplankton-macroalgae competition will be driven by the micronutrient iron.
- Net primary productivity tradeoffs are expected to be immaterial for initial deployments. Additional research will be conducted to determine the expected nutrient tradeoff and the associated reduction in total carbon removed that must be accounted for in larger scale interventions. From a carbon perspective, only the expected carbon that would have been naturally removed via the biological pump should be discounted; however, the broader nutrient and ecosystem impacts must also be considered.

BFR= Biogeochemical Feedback Responses, or the range of potential environmental responses that develop in response to the introduction of macroalgae into the open ocean environment. As a specific example, it is possible that the growth of calcifying epibionts (i.e. an organism that lives on the surface of another living organism) may be observed as macroalgae grows, though their presence is not expected.

- This variable reflects a range of potential biogeochemical responses that may be observed when macroalgae grows in a new environment, and which may impact total carbon removed.
- Specific to calcifying organisms, it is unclear whether calcifying organisms will actually recruit onto the macroalgae over a short multi-month timeframe in the open ocean, given their preferred benthic environment on the coastal shelf. In the event calcifying organisms are observed, image analysis through machine vision will be used to identify the species and appropriately discount the modeled carbon content at the point of sinking.

PMF= Physical Mixing Factor. The effect of ocean mixing processes on the efficiency of moving CO_2 from the fast-to-slow cycles – i.e., surface ocean subduction to deeper waters before carbon removed from seawater by macroalgae growth is completely re-equilibrated.

- The removal of carbon from the fast to slow cycle in the macroalgae pathway occurs during organic carbon production (photosynthesis) and sinking. Like OAE, this leaves a deficiency of dissolved CO_2 compared to the baseline, particularly due to the high C:N ratio of some macroalgal species, some of which will instantaneously be replaced by a small amount of bicarbonate. If subduction of surface water due to physical mixing processes occurs prior to complete re-equilibration, this amount should be accounted for with a discount factor.
- It should be noted that the timescales of surface water subduction versus CO_2 re-equilibration, and the methods to quantify this, are an active area of research within the scientific community.

$Shal$ = Portion of macroalgae carbon that ends up beached or sunk in areas too shallow or at risk of upwelling.

- Similar to terrestrial biomass sinking, spatial evolution of the buoy population can be characterized through a combination of computational modeling, in-situ empirical observation, and laboratory testing, alongside a Monte Carlo analysis to determine the terminal carbon buoy distribution on the seafloor.
- Given the deployment areas and float times, this impact is expected to be immaterial for initial deployments.

End-to-End System Emissions

End-to-End System Emissions can be quantified as:

$$CO_2eEmissions = Energy_{CO_2e} + OpMat_{CO_2e} + CapMat_{CO_2e}$$

Where:

$Energy_{CO_2e}$= The emissions associated with energy use in the process of CO_2 sequestration.

- Based on an assessment of life cycle emissions of the specific electricity or energy sources consumed on-site and via transport across all three carbon removal pathways.

$OpMat_{CO_2e}$= The associated emissions (including transport) of any materials consumed during project operations, processing, and manufacturing.

$CapMat_{CO_2e}$= The associated emissions of equipment, facility construction, and other capital expenditures related to project operations.

While there are inherent complexities associated with the deployment and quantification of a multi-pathway carbon removal system, its interconnectedness offers numerous quantification advantages, such as logistical (transport, delivery) and verification efficiencies. For example, wave sensors enable cumulative damage analyses of carbon buoys, allowing for validation of remotely sensed wave data, but also of expected macroalgae accumulation and carbonate dissolution rates. Similarly, compressed photos from ocean observation platforms provide visual information about both macroalgae growth rates and terrestrial biomass float times.

It is expected that this quantification approach will continue to mature as the research conducted advances our collective understanding of the ocean's complex and interconnected systems.

Leakage

Leakage refers to emissions caused by the project activity but which are indirect or take place outside the project boundary. For this project, two potential sources of leakage have been identified: (a) harvesting of terrestrial biomass causing emissions elsewhere; and (b) lower amounts of biomass growth in the ocean due to nutrient resource constraints caused by the project’s macroalgae growth.

Both potential leakage considerations are mentioned for clarity, but are addressed and accounted for within the quantification framework above.

In the event other potential sources of leakage are identified, they will be considered and accounted for within future versions of this protocol.

Risk of Reversal

If sunken carbon makes its way into ocean sediments, either through inorganic or biogeochemical pathways, it will remain out of the fast carbon cycle for geological time scales [Rousselet et al., 2021], with the risk of reversal close to non-existent by design of the system deployed. This design includes selecting only sinking locations that allow for durable storage of accumulated biomass based on depth and local ocean conditions (stability, rates of sedimentation). Selection of sinking locations has a significant impact on mitigating potential reversal risks and is a key component of deployment design; as an example, the movement of deeper water to the surface driven by surface winds (i.e. upwelling) could potentially reduce the durability of storage by recirculating dissolved carbon in the deep ocean back to the surface faster than would occur with typical ocean circulation patterns. However, project activities are conducted far offshore and away from coastal zones where upwelling is prevalent. Non-coastal zones that are associated with upwelling, such as the Equatorial Pacific, would also not be considered ideal sinking locations for that reason.

Once sunk below the ocean’s thermocline, deep-sea ocean conditions and the ocean's natural circulation patterns mitigate virtually all natural reversal risk. Deployment areas must be monitored for potential economic use that could impact the stability of the deep-water area, such as deep-sea mining, trawling, or similar economic activities that could disturb the seabed — but these risks are minimal and can be mitigated through careful site selection and monitoring of deployments.

The exact durability of storage may vary based on site selection, local ocean conditions, and the end fate of sunk biomass, and further research will be conducted to advance a shared understanding of deep ocean circulation patterns.

5. Monitoring and Verification

Monitoring and Verification

Monitoring will be conducted throughout the project lifespan. In addition to internal verification to ensure accurate quantification, external parties will be engaged for an independent review of adherence to both the defined protocol and industry standards, as well as to validate quantification of net carbon removal. Impartial reviews must be conducted at each relevant stage of the project, and include external stakeholder consultation. This includes, but is not limited to:

- Scientific review of the intervention approach and research plans prior to deployments via an independent Scientific Advisory Board. For Running Tide, this independent Board is currently convened by Ocean Visions and is composed of relevant subject matter experts.
- Ongoing peer-review of protocols for quantifying net carbon removed via external parties and industry experts, along with open public feedback and consultation.
- Independent expert review of project-specific environmental impact assessments by a certified auditor.
- Independent audit of actual project operations compared against protocol and pre-deployment monitoring plans, including adherence to relevant industry standards, such as the GHG Protocol Inventory Best Practices and ISO 14064-2, by a certified auditor.
- Independently reviewed emissions accounting and relevant LCAs for all project emissions.
- Full end-to-end carbon quantification and leakage analysis prior to issuance of carbon removal credits. This includes an evaluation of models and assumptions grounded in empirical data and allows for confirmation of the accuracy of project results by an independent party.

Over time, along with the project-specific oversight detailed above, data and procedures across all deployments should be audited on an annual basis by an independent third party.

To the extent possible, records of necessary project documentation that are required for issuance will be made available for review. This includes but is not limited to:

- Pre- and post-environmental and social impact and risk assessments.
- Permitting records from all relevant local, regional, national, and intergovernmental/ international agencies.
- Records of community engagement, feedback, and grievance mechanisms.
- Supplier attestations for raw material sources, as well as records of material source locations and transportation details.
- Details on all observational instruments used and their role in quantification.
- Detailed descriptions of models used and how they support replicable quantification of project results, including quantitative benchmarking and uncertainty quantification.

Transparency into project processes and independent review are critical to building trust in the underlying carbon removal accounting system.

6. Conclusion

Conclusion

The goal of the system outlined in this protocol is to improve ocean health and reverse the degradation and collapse of ecosystems caused by the anthropogenic emission of CO_2 and the associated imbalance in the global carbon cycle.

The ocean is a global commons; it is made up of vast, intricate, and intertwined ecosystems, and is utilized and cared for by communities across the globe. No single entity has a claim to the ocean, and the decisions that impact it require buy-in and support from a diverse range of stakeholders, communities, and decision-makers.

But the health of the ocean is rapidly deteriorating as it continues to buffer humanity from the worst impacts of climate change. It has been subject to warming, acidification, and deoxygenation at a global scale, threatening coastal communities, food security, and biodiversity, and putting the natural processes that regulate our climate systems at extreme risk of collapse. Because of the urgency of the problem, it is essential that we — humanity — urgently adopt a bias towards action, in line with the application of the precautionary principle enacted against a baseline of rapidly deteriorating ocean health and a worsening climate crisis. This moral and ethical responsibility to act includes a rigorous and transparent determination of the efficacy of ocean-based carbon removal and all potentially scalable carbon removal solutions.

Running Tide looks forward to continuing to collaborate with academic, industry, and government leaders, ocean and climate researchers, and all other stakeholders to improve and iterate on this carbon removal system. We welcome, encourage, and value all feedback on this quantification approach.

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