Sustainably Amplifying the Natural Carbon Cycle

White Paper - Sustainably Amplifying the Natural Carbon Cycle

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Introduction

The ocean's biological carbon pump plays a significant role in the global carbon cycle. The biological pump is a natural process through which carbon is transported from the fast carbon cycle, involving the atmosphere, biosphere, and upper ocean, to the slow carbon cycle, involving the deep ocean and geosphere. The biological pump's primary mechanism is the biological transformation of CO2 and nutrients into organic carbon in the upper ocean via photosynthesis, which then sinks through the water column, and ultimately decomposes or is buried at depth. Running Tide is developing a nature-based carbon dioxide removal (CDR) system that sustainably amplifies the biological pump's transfer of carbon from the fast to the slow carbon cycle.

This white paper provides an overview of the Earth's carbon cycle, the ocean's natural processes for capturing and storing carbon, and how Running Tide's system is designed to sustainably enhance these processes. Running Tide's CDR system combines distributed open ocean aquaculture, the sinking of biomass, and ocean alkalinity enhancement to make a significant contribution to the fight against the global climate crisis, while delivering co-benefits for biodiversity, sustainable development, inclusive economic growth, and food security.

The Earth's Carbon Cycle

The global carbon cycle operates through a variety of response and feedback mechanisms between the Earth’s primary carbon reservoirs, namely the marine and terrestrial biospheres, the atmosphere, the ocean, and sediments/rocks. The carbon cycle can be broken down into two distinct, but overlapping, components: the fast carbon cycle and the slow carbon cycle.

Fast Carbon Cycle

Fast carbon encompasses the movement of carbon via photosynthesis and respiration, as well as the continuous exchange of CO2 amongst the biosphere, atmosphere, and surface ocean. The fast carbon cycle is dynamic and volatile, and it can be best understood as the flow of carbon through living ecosystems.

Slow Carbon Cycle

Slow carbon consists of the movement of carbon via gravity, pressure, chemical weathering, and ocean currents. These processes move carbon from living ecosystems into geological and deep ocean reservoirs such as sediments, mineral deposits (oil, gas, coal), and deep waters. Slow cycle reservoirs evolve very slowly over thousands to millions of years.

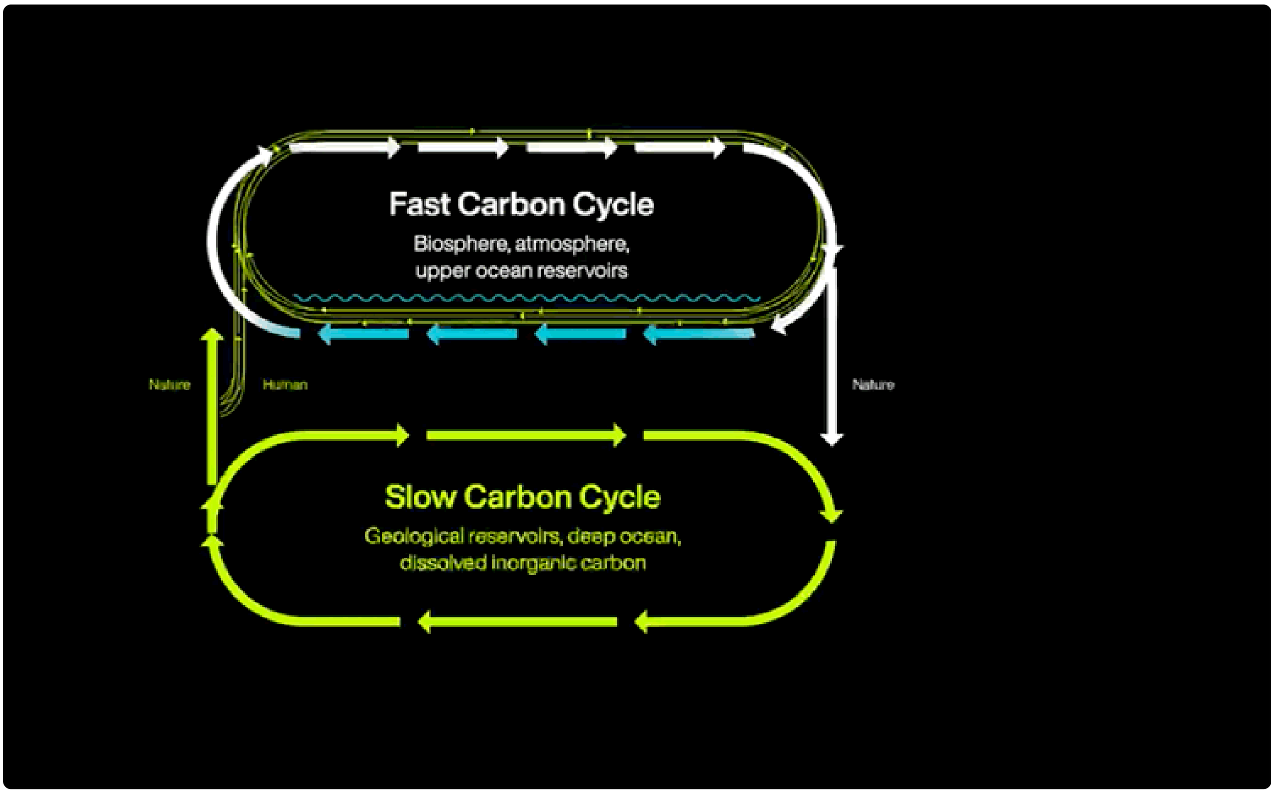

Figure 1 - The global carbon cycle consists of a fast and slow cycle. Fossil fuel emissions are a slow→fast mass transfer. Removals are a fast→slow mass transfer.

One pathway carbon takes from the fast to the slow cycle is through organic matter buried in marine sediments and rocks. Phytoplankton and other marine organisms in the surface ocean fix carbon, die, sink to the ocean floor, and are buried. The biomass is slowly converted into mineral resources such as fossil fuels: oil and natural gas. Coal is formed when a similar process occurs in freshwater environments on land. Globally, this process moves a net ~2 gigatons of carbon into the slow cycle annually.

Without human interference, carbon moves from the slow to the fast cycle over millions of years through volcanic activity, driven by the subduction and melting of limestones and oil and gas-bearing rocks, and over intermediate timescales through ocean upwelling. By extracting and burning carbon-rich resources, humans are effectively moving ~9 gigatons of carbon from the slow to the fast cycle every year.

Prior to human intervention, 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 climates, ocean chemistry, and ecosystems over human timescales.

Since the Industrial Revolution, widespread extraction of 2.4 trillion tons of slow carbon fossil fuels, deforestation, changes in land-use, marine habitat loss, and ocean acidification have accelerated the movement of carbon from the slow to the fast carbon cycle, while also decreasing the storage capacity of fast carbon sinks. These shifts have fundamentally destabilized the Earth's systems, causing dangerous and widespread disruption in natural ecosystems and suffering for billions of people around the world. Without significant and immediate action, this devastation is projected to increase dramatically over the coming decades.

Restoration projects such as reforestation, afforestation, and coastal blue carbon activities aim to rebuild natural fast carbon sinks, which are critically important to reestablishing system equilibrium, promoting a stable climate, and reducing disruption to natural ecosystems and human communities.

However, because most restoration projects are focused on increasing the capacity of fast cycle carbon sinks, restoration projects alone cannot rebalance the global carbon cycle at a scale that effectively combats climate change. For this, we must engage in carbon removal by transferring carbon from fast cycle sinks (i.e., biosphere, atmosphere, and upper ocean) to slow carbon sinks (i.e., deep ocean and marine sediments).

Carbon Removal is the intentional transfer of fast carbon to the slow carbon cycle.

By this definition, carbon removal is additive, durable, and quantifiable through a combination modeling, empirical testing, and direct measurements of mass transfer and/or reservoir size. When combined with activities that rebuild fast cycle carbon sinks, carbon removal can both enhance the productivity of the fast carbon cycle, while also moving carbon from the fast to the slow carbon cycle.

Restorative carbon removal both restores the capacity of fast carbon sinks while intentionally transferring carbon from the fast to slow carbon cycle.

As documented by the Intergovernmental Panel on Climate Change (IPCC), all reasonable scenarios that limit global warming to 1.5°C — the globally accepted limit beyond which the planet is likely to face dire and unpredictable effects — require the immediate reduction of CO_2 emissions across all economic sectors combined with large-scale carbon removal. The longer we wait to reduce emissions, the faster we must scale carbon removal. As seen in Figure 2, to reach net-zero targets consistent with 1.5°C warming scenarios, more than 10 gigatons of CO2 must be removed every year. To accomplish this, humanity must use its resources to tackle one of the largest mass transfer efforts ever attempted.

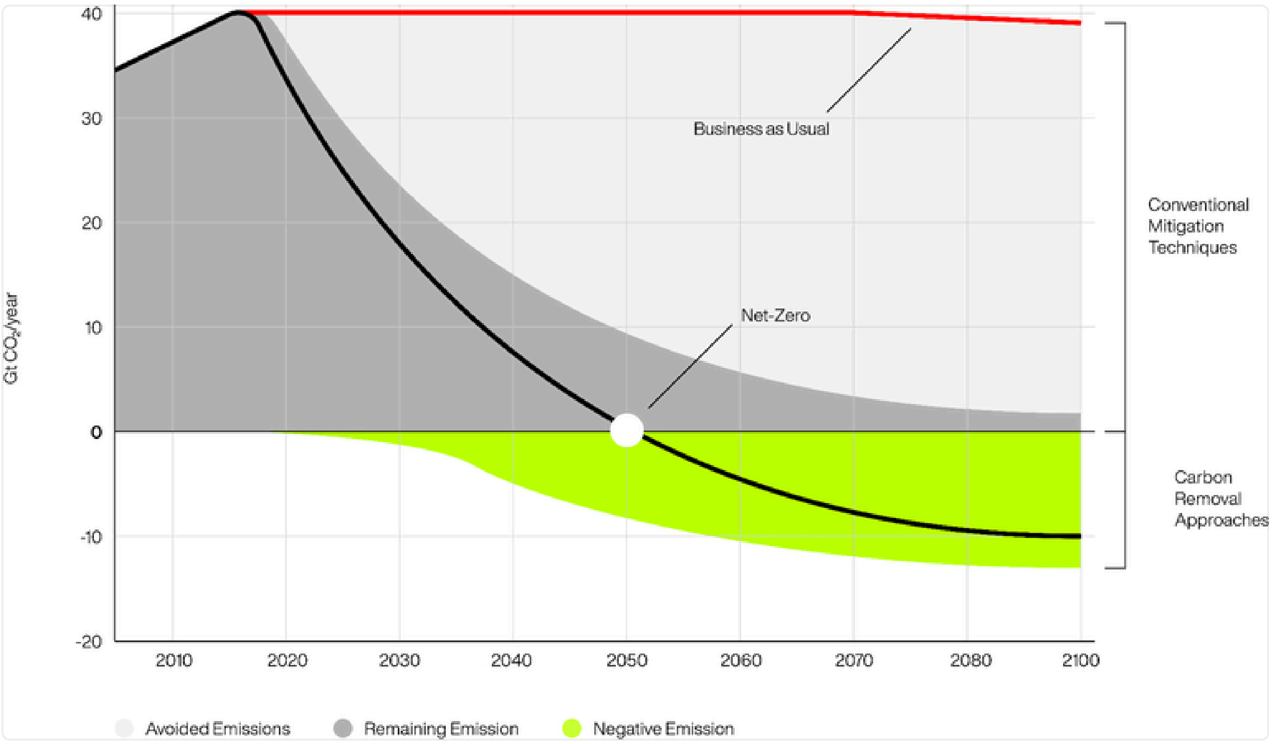

Figure 2 - All pathways to stay below 1.5 degrees of warming require carbon removal/negative emissions technologies (Source: Modified from the IPCC Special Report on Global Warming 1.5C)

The Ocean's Carbon Cycle

The Biological Carbon Pump

The surface ocean and the atmosphere are closely coupled systems within the fast carbon cycle, and CO2 levels in both rise and fall in parallel. As slow carbon emissions from human activities increase the concentration of carbon in fast cycle reservoirs, more and more CO_2 flows between the atmosphere to the surface ocean each year in a constant cycle of absorption and respiration.

By some estimates, the ocean has absorbed 30-40% of the CO_2 emitted since the beginning of the industrial era, mostly through photosynthetic activity. Approximately 85-90% of the carbon fixed through photosynthesis in the euphotic zone (the uppermost layer of the ocean) will be remineralized and recycled, remaining in the fast carbon cycle. However, a small percentage of plankton sinks into the deep ocean after it dies, transporting the carbon acquired at the surface along with it. Grazing on phytoplankton by higher trophic members of the ecosystem, such as zooplankton and fin fish, package this carbon into fecal pellets which sink rapidly, thereby removing biologically fixed carbon to the deep sea. Once in the deep ocean, this biomass is either remineralized as dissolved inorganic carbon, dissolved as organic carbon, consumed by benthic macrofauna, or buried in marine sediments.

The deep ocean is the largest slow carbon reservoir on the planet that, by current estimates, stores 39,000 gigatons of dissolved carbon. Seawater is stratified by density gradients, which are formed by salinity and temperature, and which suppress vertical mixing of the water and contribute to the slow turnover of ocean bottom water with the surface ocean and the fast carbon cycle.

As noted in the introduction, this process of photosynthetic marine organisms fixing and 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. Worldwide, the biological pump naturally transfers a gross magnitude of ~ ten gigatons of CO_2 from the fast carbon cycle to the deep ocean each year where it is projected to remain, on average, for longer than 1,000 years.

The exact durability of carbon stored is dependent on the depth, location, and chemistry where the biomass sinks.

Ocean Acidification

Greater total volumes of CO_2 within the fast carbon cycle manifests as higher concentrations of CO_2 in the atmosphere and the surface ocean. The Greenhouse Effect and its associated global warming are a result of this fundamental shift in atmospheric chemistry through the increased concentration of greenhouse gasses, and ocean acidification is the result of increased concentrations of CO2 reducing pH of the surface ocean.

This warming and acidification of the oceans is having a disastrous impact on the marine biosphere and on human communities that depend on the ocean for their economies, food, ways of life, and culture. All life on Earth depends on the ocean, and its continued decline will have dire consequences.

Photosynthetic organisms, largely phytoplankton, transform dissolved CO2, which is a form of inorganic carbon, into organic carbon in the same way that trees and other land-based plants transform atmospheric CO2 into terrestrial biomass. This process helps mitigate CO2-induced ocean acidification by decreasing CO2 concentration 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 and the associated acidification effects may be impacted due to changes in temperature and carbon chemistry.

Given its scale, the ocean is a critical part of the global carbon cycle that must be enlisted, through sustainable and positive interventions, in the fight to rebalance the carbon cycle and reverse climate change.

Carbon Removal System Design - Amplifying the Biological Carbon Pump

Carbon Removal Pathways

All existing carbon removal systems work to increase the rate at which one of two existing earth systems that naturally transfer carbon from the fast to slow carbon cycle occur: 1) increasing the rate of transfer of fast carbon mass to a slow carbon reservoir (ie. biomass burial/sinking), and 2) increasing the chemical weathering of fast carbon and chemically transferring it into a stable slow carbon mineral reservoir. (ie. enhanced weathering, direct air capture, ocean alkalinity enhancement, etc).

Amplifying the Biological Carbon Pump

At Running Tide we have developed a flexible restorative carbon removal system to improve the capacity of fast carbon sinks to fix carbon, restore ocean health, and increase the rate at which earth systems rebalance the carbon cycle. This system amplifies the natural carbon removal pathways with three simple and abundant resources - terrestrial biomass, alkaline minerals, and marine biomass. Terrestrial biomass and alkaline minerals can be combined in multiple configurations to create a floating substrate (“carbon buoy”) which can be seeded with select strains of juvenile algae and then introduced to open ocean currents to fix fast carbon through photosynthetic growth and alkalinity enhancement at the surface of the ocean, then sink rapidly to the deep ocean, transporting the embodied fast carbon in the form of terrestrial and marine biomass to the deep ocean, a slow carbon reservoir.

With a combination of efficient mass transport, sunlight, nutrients, chemistry, and gravity we efficiently remove carbon from the fast carbon cycle and lock it up in slow carbon reservoirs for thousands to millions of years.

The oceans are a complex and constantly changing environment, and any ocean carbon removal system we develop must be as dynamic and flexible as the system it's operating in. This means that our system must be able to operate in a variety of different ocean conditions and must be able to respond to changes in these conditions over time.

There are no fixed recipes, we work with the ingredients from nature to optimize the system. As such, buoy composition may differ from deployment to deployment and may utilize only a subset of the carbon removal pathways, such as deployments of terrestrial biomass that is coated with carbonate materials, but not seeded with macroalgae. The composition will be based on local ocean and operational considerations to optimize for maximum carbon removed from a specific deployment.

Any carbon removal system intervening in the natural environment must seek to achieve the highest earth system benefit while minimizing any adverse localized impacts. To bring this principle to life, we have established a set of key design principles that focus on efficiency, sustainability, and practicality.

Carbon Removal by Terrestrial Biomass Growth and Sinking

Running Tide produces carbon buoys using abundant sources of biomass feedstocks including forestry and/or agricultural byproducts, such as sawmill cutoffs, wildfire management burn piles, forestry residues, agricultural residues, etc.. For initial deployments, this biomass, if not utilized in Running Tide's CDR system, would either decay or be burned, increasing the volatility of the fast carbon cycle. Beyond initial deployments, biomass from sustainably managed forests will be considered as a potential terrestrial feedstock so long as the sustainable sourcing of biomass can both promote forest health as well as increase net carbon storage capacity of the biosphere as a fast carbon sink. This process enhances the transport of terrestrial biomass into the deep ocean, effectively transferring the carbon contained within that biomass from the fast carbon cycle to the slow carbon cycle.

Further, enhancing the natural transport of organic terrestrial carbon within the carbon buoy into the ocean also restores natural nutrient flows, which have been disrupted by human activity, and may supply a targeted nutrient payload required to support the growth of the juvenile algae and help to prevent the macroalgae growth from displacing microalgae (phytoplankton) communities.

Carbon Removal by Marine Biomass Growth and Sinking

Running Tide seeds carbon buoys with select species of algae. Macroalgae such as kelp and sea lettuce grow rapidly, converting nutrients to biomass in the surface ocean and fixing dissolved CO_2 as organic carbon. Certain types of macroalgae are up to three times more efficient than phytoplankton at fixing carbon, due to macroalgae's higher carbon-to-nutrient (nitrogen, phosphorus) ratios. These ratios cause macroalgae to sequester more carbon for the same nutritional input. As macroalgae are comparatively large and negatively buoyant, when attached to a carbon buoy they sink through the water column more rapidly than phytoplankton, enhancing the biological carbon pump by increasing the efficiency of nutrients to carbon transported into slow cycle reservoirs in the deep ocean.

Carbon Removal by Alkaline Mineral Dissolution

Running Tide sources alkaline minerals such as lime kiln dust, limestone ($CaCO_3$), olivine, or basalt from sustainable suppliers in the manufacture of carbon buoys. As the buoys drift on ocean currents in the open ocean, the alkaline minerals slowly dissolve into the surface of the ocean. Alkaline mineral dissolution in the surface of the ocean serves to increase the pH of surface waters by binding with hydrogen protons and ultimately converting aqueous fast carbon into bicarbonate - a form of slow carbon.

System Design Principles

Running Tide combines the expertise of leading third-party ocean and climate scientists - both through our independent science advisory board and through our research partners - with in-house engineers and an applied science team to create a clear set of design principles for our CDR system that aims to **maximize global system benefits, while minimizing localized impacts.**

This includes deployment of the system into select ocean currents that are nutritionally dense and that will ultimately transport the biomass to suitable sinking locations following a period of growth (as little as 2 weeks). Suitable sinking locations are deep, stable, and characterized by relatively high rates of sedimentation, which will increase the proportion of biomass that is buried and preserved for millennia. These environments exist throughout the world’s ocean basins; initial Running Tide pilot and research deployments are targeting the North Atlantic, with the North Pacific and Antarctic circumpolar regions of interest for further study.

To understand the efficacy and impact of this system, transparent quantification processes, proper carbon and emissions accounting principles, and technologies that provide in-situ monitoring and measurement of the location, timing, and progress of the carbon removal system in the open ocean are critical. The challenges inherent in measuring and monitoring phenomena occurring over the vast expanse of the open ocean require a focused and disciplined approach to quantification that is based upon computational modeling, direct in-situ observation, and laboratory ground-truthing.

This includes both software and hardware engineered to operate in the ocean, including highly capable machine vision and optical sensing capabilities that allow us to measure biological growth in the ocean at world-class resolution. The data collection these cutting-edge technologies enable will allow our team to better understand how our verification hardware moves through and interacts with the ocean in real world conditions. Building our verification hardware in-house also allows us to customize, adjust, and de-materialize efficiently so that we may maximize information gained from the ocean while mitigating ecological impacts.

Additional system design principles that optimize the performance of Running Tide’s carbon removal systems and ensure our interventions are effective, practical, and sustainable include:

Primary Principles

- **Fast to Slow -** The system must be designed to transfer a net amount of carbon mass from the fast carbon cycle to the slow, fully accounting for the supply chain.
- **Net Positive** - The ecological and chemical perturbation caused by the system must lead to a net positive outcome for the system it's intervening in
- **Kill Godzilla -** The system has the potential to scale to the scale of the problem.
- **Cost -** The system is designed to be the lowest cost possible
- **Quantifiable** - The system can be measured and modeled with known levels of uncertainty
- **Auditable -** All processes and quantifications of impact must be auditable by a recognized 3rd party auditor

- **Flexible -** The system is designed to be adaptive to changing ocean and market conditions.

Supporting Principles

- **Progressive Scale -** The system scales as certainty of the net positive benefit of the system increases
- **Simple -** Complexity is only added to reduce risk and increase efficiency
- **Native + Natural -** Biological interactions are non-exogenous to the location of the system combined with the lowest amount of non-natural products possible
- **Size, Density, Location, and Distribution -** The system can control size, density, location, and distribution of the system at the surface of the ocean
- **Duration + Binary -** The system can be tuned for the amount of time it interacts with a natural system and can be turned off to reduce the risk of long lasting negative effects
- **Anthropogenic Inputs -** The system is designed with the least amount of anthropogenic inputs possible
- **Infrastructure -** The system is designed to leverage existing infrastructure and new infrastructure should be multimodal if possible.
- **Socio Economic -** The system is designed to have a net positive impact on communities hardest hit by climate change.

Conclusion

The energy provided by fossil fuels has immensely benefited humanity. However, the coinciding transfer of slow carbon to fast carbon has created an imbalance in Earth's carbon cycle that we have no choice but to restore. Decarbonization alone will not be enough. The increased volatility of fast carbon is already causing widespread damage to natural systems including increased warming, ocean acidification, habitat loss, and loss of biodiversity. This loss of natural capital is already starting to reverse humanity's gains by causing widespread human suffering, ecosystem collapse, and economic loss.

The 2022 IPCC report makes it clear: we have a small window of time to begin rebalancing Earth’s carbon cycle. This window gets smaller every year. It is essential that we respond not in 2050, not in 2030, but today, by leveraging technology, capital, and resources to turn the tide on climate change. To do that we need a broad set of safe and scalable carbon removal solutions.

Running Tide has developed a restorative carbon removal solution to sustainably amplify the rate at which the ocean’s biological carbon pump transports carbon from the fast to the slow carbon cycle. The company’s methodology minimizes human inputs by using the Earth’s most efficient process of fixing carbon (photosynthesis), transferring mass (ocean currents and gravity), and alkalinizing the surface ocean (alkaline mineral dissolution).

The distributed nature of Running Tide’s solution minimizes potential negative impacts, and open-ocean operations reduce conflicts with existing land use and coastal activities. The Running Tide system also delivers important co-benefits by promoting biodiversity, by supporting the sustainability of the forestry and fishery industries, and by revitalizing coastal communities that are disproportionately impacted by climate change. There are few natural limiting factors to this system's ability to remove billions of tons of carbon each year so long as it proves to be sustainable and has a net-positive impact on the ocean.

Climate change is Godzilla. No walls will keep him out. If humanity is to give him more than a paper cut, we must enlist nature in the fight.