

Carbon Removal is Mass Transfer from Fast to Slow

White Paper: Carbon Removal is Mass Transfer from Fast to Slow Carbon Cycles

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Part 1 - Carbon Removal and the Earth System

The human-caused climate emergency is commonly and narrowly understood to be a problem of atmospheric carbon dioxide, as this greenhouse gas contributes directly to warming and destabilizing the biosphere. However, in order to develop effective solutions to our carbon problem we must develop a systems-level understanding of atmospheric carbon within the context of the global carbon cycle.

1.1 Earth System Carbon Cycling

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.

The **fast carbon cycle** consists of carbon that flows in and out of reservoirs continuously or up to a decadal timescale, including the reservoir of atmospheric CO₂. It encompasses the movement of carbon via photosynthesis and respiration, as well as the continuous exchange of CO₂ amongst the biosphere, atmosphere, and ocean. The fast carbon cycle is dynamic and volatile, and it can be best understood as the flow of carbon through living ecosystems.

The **slow carbon cycle** consists of the movement of carbon via gravity, pressure, chemical weathering, and ocean overturning circulation. 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 over centuries to geologic timescales.

The fast and slow carbon cycles are **loosely coupled**. The global carbon cycle operates through a variety of response and feedback mechanisms which maintain a balance between these cycles, keeping the biosphere in the **Goldilocks zone** for ecosystems to thrive.

1.2 The Climate Emergency

The problem statement of the anthropogenic climate emergency is that carbon has been artificially moved from the slow carbon cycle to the fast, at a rate that overwhelms the natural feedback mechanisms which can regulate this balance.

We did this by burning, over the course of two centuries, carbon which the Earth accumulated over eons into slow cycle reservoirs. Barring a Venus-level cataclysm, the Earth system may eventually reverse this anthropogenic carbon imbalance, but this will occur millions of years too late to mitigate the destruction done to ecosystems and civilization.

When carbon is released into the fast cycle, it pools in a number of fast carbon reservoirs. It dissolves into the surface ocean and soil, gets fixed into photosynthetic biomass and, of course, mixes into the atmosphere.

Saturating these reservoirs is an insidious ecological problem. The biosphere is famously being destabilized by the greenhouse warming effect of atmospheric carbon dioxide. Similarly the ecologies of shallow seas are threatened by the acidifying carbon concentration in surface seawater, which especially harms shell-forming organisms such as corals and mollusks.

1.3 Carbon Removal

Carbon removal is the **mass transfer** of carbon back **from the fast to the slow cycle**. Carbon removal occurs naturally in the Earth system over geologic time. The goal of **carbon removal technologies** is to amplify and accelerate this transfer in order to mitigate the human-caused climate emergency. The task for carbon removal technologies of moving mass cannot be overstated: gigatons of carbon-containing mass have to be transferred to the slow cycle net of the emissions it takes to move them.

Carbon removal technologies achieve carbon removal through a deliberate anthropogenic intervention. To be relevant, these interventions must be **additional**

to the fast-to-slow cycle transfer that is naturally occurring already by way of the Earth system carbon cycle. In order to be commercialized, these interventions must be **quantifiable**. Carbon removal is **durable** by definition, as these interventions actuate a transfer to the slow carbon cycle.

Even if the only goal of carbon removal were to remove the anthropogenic perturbation to atmospheric carbon, this cannot be achieved in isolation from the rest of the fast cycle. Fast cycle reservoirs are **tightly coupled**; adding or removing carbon to one of them will induce a fast cycle rebalancing among the others. Only a portion of the carbon emitted by humans resides in the atmosphere today.

When CO₂ is artificially removed from the atmosphere, it will be replaced by CO₂ outgassing and other fluxes from other fast cycle carbon reservoirs such as the soils and surface ocean, as these reservoirs are tightly coupled in the fast cycle. This is an example of why it is important to define carbon removal as fast to slow removal, not narrowly as atmospheric removal. The only way to mitigate anthropogenic emissions is to remove the totality of those emissions – be they pooled in the atmosphere, soils, or oceans – from the fast to the slow carbon cycle.

1.4 Fast Cycle Carbon Fixation

Carbon **fixation** means the aggregation of carbon into the non-atmospheric fast cycle reservoirs.

From the perspective of carbon removal, fixation includes not just photosynthetic carbon fixation, but such things as the inorganic dissolution of carbon into the soils and surface oceans.

Fast cycle fixation is not carbon removal. Tree-planting, for example, may amplify fast cycle fixation but it does not remove carbon to the slow cycle. Forests are a fast cycle reservoir, and carbon credit programs which rely on fast cycle reservoirs such as forestry rightly have to be concerned with durability, as forest carbon can burn down or otherwise continue to move through the fast cycle. By the same token, burning wood for fuel is conceptually different from burning coal; only the latter reintroduces carbon from a slow cycle reservoir back into the fast cycle.

Fast cycle fixation does not achieve carbon removal but plays a critical role in enabling it. Because carbon removal is a **mass transfer** proposition, the role of fast cycle fixation is to change the density and phase of carbon such that it is easier to transfer the fast carbon mass back to slow. Collecting ambient atmospheric gaseous carbon is a thermodynamically onerous task and before carbon can be removed to the slow cycle it must be fixed in the fast cycle. For this reason, restoration and improvement of fast cycle reservoirs are critically important to re-establishing fast cycle system equilibrium, promoting a stable climate, and reducing disruption to natural ecosystems and human communities.

1.5 Ocean-Based Carbon Fixation and Removal

The ocean actuates several pathways of fast cycle carbon fixation and carbon removal.

One such pathway is inorganic: fast-cycle fixation occurs when the surface ocean dissolves atmospheric CO₂. The ocean is particularly well-suited to retain large amounts of carbon. Carbon dioxide performs specific reactions with water, combining to form carbonic acid and further dissociating into carbonate and bicarbonate. The result is a buffer pool of dissolved inorganic carbon, allowing a volume of seawater to dissolve many times more carbon than might be otherwise expected.

Carbon removal occurs in the inorganic pathway when the surface ocean mixes and sinks down into deeper water.

This mixing carries the inorganic carbon dissolved in surface water to the slow carbon cycle of the deep ocean

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Other pathways involve more complex biogeochemical leverage. The **biological pump** is the name given to one such phenomenon – phytoplankton photosynthetically fix dissolved inorganic carbon from the surface ocean, allowing it to in turn dissolve more CO₂ from the atmosphere. Grazing on phytoplankton by higher trophic members of the ecological web, such as zooplankton and fin fish,

packages this carbon into fecal pellets which sink rapidly thereby removing biologically fixed carbon to the deep sea.

Coastal macroalgae forests, like terrestrial forests, participate in fast cycle fixation but do not contribute to carbon removal except insofar as ocean currents transport some of the biomass they fix to the deep sea. Much has been made about fast carbon cycling in seaweed forests and its consequences for blue carbon crediting projects. This is another ambiguity that can be resolved by understanding carbon removal as the transfer from fast to slow cycles.

1.5.1 Additionality of Biologically Sunk Carbon

The biological carbon, such as phytoplankton, that sinks into the deep ocean was likely already destined to be removed to the slow cycle because it was already inorganically fixed in surface ocean waters, which mix and sink to deeper water. Biological pumping of organic carbon causes **additional** removal when the inorganic carbon content of surface water is replaced by additional fast cycle fixation of atmospheric carbon into dissolved carbon.

When dissolved inorganic carbon is removed from surface water via biological fixation, it creates capacity for additional dissolution of atmospheric carbon. Dissolution will continue until the surface water either becomes saturated with carbon, or else mixes into the deep ocean and out of atmospheric contact. Carbon removal technologies which leverage these biological pumping pathways remove the quantity of carbon represented in the novel dissolution of carbon they induce, not the quantity of biological carbon which they sink.

1.5.2 Durability of Carbon Removal Via Sinking

Dissolved inorganic carbon may arrive to deep ocean water via downward mixing of surface water, or else via biological pumping of organic carbon that is later remineralized. Either way, it will remain out of contact with fast carbon reservoirs, including the atmosphere, for hundreds to thousands of years given the slow-moving ocean overturning circulation and

suppressed ventilation of dissolved carbon at depth. If sunken carbon makes its way into ocean sediments, either through inorganic or biogeochemical pathways, it will remain out of the fast cycle for geological time scales. From the perspective of the anthropogenic climate emergency, either outcome can be considered durable removal to the slow cycle.

1.6 The Bicarbonate Reservoir

When carbon dioxide dissolves in the ocean, it undergoes a series of reactions with seawater resulting in a rebalancing of different chemical species of dissolved inorganic carbon: aqueous carbon dioxide, carbonate, and bicarbonate. The balance of these species is governed in a given region of water by thermodynamics (temperature, pressure, salinity), and pH. Because water at the ocean surface can freely exchange acidifying carbon with the atmosphere, the pH in this region is ultimately parameterized by **alkalinity**. Alkalinity is the imbalance in the total concentrations of cations and anions in seawater. Because these alkalinity-governing solutes are stable in seawater, the bicarbonate reservoir is stabilized for a given thermodynamic condition.

A key characteristic of the bicarbonate reservoir is its enormous quantity (~90%) compared to the amount of carbon dioxide (~1%) in the general seawater system. The bicarbonate reservoir is mechanistically tied to the fast carbon system through marginal exchange with the smaller CO₂ reservoir. But because the magnitude of the bicarbonate reservoir is so large compared to the aqueous CO₂ reservoir, the residence time of carbon within the bicarbonate reservoir is comparably longer than the residence time of carbon in the CO₂ reservoir.

Both the relatively long residence time and stability of the bicarbonate reservoir render it functionally consistent with a slow carbon reservoir rather than a fast one.

Part 2 - Running Tide Carbon Removal and System Architecture

Mass transfer is a challenging engineering problem. Gigatons of mass must be fixed in the fast cycle and then transferred to slow cycle reservoirs. Running Tide's thesis is that fully engineered systems will struggle to scale to the magnitude of the climate emergency because enormous mass transfer places enormous demand on energy, construction materials, and supply chain logistics. We therefore pursue interventions which amplify naturally-occurring mechanisms of carbon removal.

We frame our solutions from the perspective of **mass transfer ratio** – the ratio of mass that has to be manipulated by artificial systems to the **gross** mass of CO₂e removed from the fast to slow cycle. In order to quantify carbon removal and generate commercial carbon credits, gross CO₂e removal must be converted to **net** CO₂e removal by deducting all emissions across the lifecycle of the carbon removal technology.

2.1 Running Tide Carbon Removal

Running Tide has developed a global CDR system that integrates and amplifies three natural carbon pathways. Running Tide processes sustainably-sourced, carbon-rich forestry residues into **carbon buoys**: drifters on which to grow macroalgae. Carbon buoys are coated with calcium carbonate that stimulates a process known as enhanced alkalinity, a recognized CDR approach to sequestering CO₂. Macroalgae growing in the surface of the open ocean fixes carbon through photosynthetic growth, then sinks, transporting the embodied fast carbon from the atmosphere-ocean interface into the deep ocean, a slow carbon reservoir.

2.1.1 Terrestrial Biomass Sinking

Terrestrial forestry systems photosynthetically fix fast cycle carbon, storing it in primary biomass, soils, and their supported secondary biomass such as mycelium

networks. As forest systems mature, the ecosystem becomes more adept at recycling carbon, and the rate of novel carbon drawdown slows.

Oceans and rivers transport fixed carbon from these terrestrial systems and carry this biomass to the deep ocean, thereby creating a removal. This process can be amplified by deliberate harvest, release, and sinking. If biomass is removed from forests at a rate which does not harm its rate of growth, we can preserve the fast-cycle fixation function of the forest while amplifying the removal mechanism to the slow cycle. Forest carbon cycling is fast carbon cycling. In creating an intervention which siphons this cycling carbon into slow cycle reservoirs, we actuate the forests as a carbon removal pump.

Roughly speaking the gross mass transfer ratio of terrestrial biomass sinking is about unity: a ton of forestry residue is a ton of CO₂e.

2.1.2 Surface Ocean Alkalinity Enhancement

Dissolution of alkaline minerals, such as calcium carbonate, into the surface ocean alters the balance of the carbonate system in seawater and increases the surface water's capacity to dissolve carbon dioxide from the atmosphere.

Alkalinity enhancement increases the capacity of seawater to hold inorganic carbon. It achieves carbon removal by reallocating fast cycle carbon to the larger and more stable bicarbonate reservoir. It simultaneously amplifies the fast cycle transfer of atmospheric CO₂ into surface waters as the dissolved CO₂ that was reallocated to the bicarbonate reservoir is replaced by novel CO₂ exchange across the air-sea boundary.

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.

2.1.3 Surface Ocean Macroalgae Cultivation

Growing and sinking macroalgae at the surface of the ocean is not the same as coastal blue carbon seaweed afforestation. Because photosynthetic fixation occurs in the open ocean, and because the entire intact organism later sinks to the deep ocean, this pathway achieves carbon removal in a manner similar to the biological pump.

Photosynthetic carbon fixation by phytoplankton in the open ocean is known to be nutrient-limited. Macroalgae species generally have more favorable **Redfield ratios**, or ability to fix carbon per available nutrients, than phytoplankton. Macroalgae cultivation in the open ocean may therefore **amplify the fast cycle fixation** of the biological pump.

Carbon fixed by phytoplankton is eaten by higher tropic members of its food web. They metabolize and exhale much of that carbon back into the surface ocean, only sinking a portion of it by aggregating it into fast-sinking fecal pellets. By contrast, non-buoyant species of macroalgae will sink rapidly as an intact organism. Macroalgae cultivation in the open ocean may therefore **amplify the fast-to-slow transfer** of the biological pump.

Because of this dual amplification, open ocean macroalgae cultivation may present a powerful pathway for carbon removal technology. However, macroalgae is a coastal organism that has evolved to thrive in nutrient-rich and low-energy waters and cultivating macroalgae in the open ocean will be challenging. The good news is that macroalgae present as a diverse array of species with myriad lifecycles and they are highly plastic and adaptable organisms. Open ocean macroalgae cultivation should therefore be seen as a biotechnology frontier which deserves our attention and investment.

Macroalgae grows from microscopic starting material to a macroscopic bulk organism; its mass transfer ratio is essentially infinite from the perspective of moving macroalgae seed to the open ocean. However, macroalgae, and especially non-buoyant macroalgae, must be grown on a floating substrate to remain in the photic zone. Coastal macroalgae aquaculture regularly achieves a biomass to substrate mass ratio in excess of 20:1. These yields may not be attainable in the open ocean, but Running Tide further defrays this mass transfer ratio by synthesizing carbon buoy substrates out of terrestrial biomass and ocean alkalinizing materials.

2.2 Running Tide System Design

Running Tide has designed a system around the purpose of amplifying ocean based carbon removal. Because carbon removal is the transfer of carbon from the fast to the slow cycle, we deploy our system far from coasts and focus on pathways which already remove carbon: ocean transport of terrestrial biomass, dissolution of CO₂ in surface waters, and photosynthetic fixation and sinking of marine biomass.

The core principle of Running Tide's architecture is the development of simple, modular, mass-producible components (carbon buoys) which can be placed in ocean currents, will remain buoyant for a tunable period of time, disperse in ocean currents, and then rapidly switch buoyancy and descend to the seafloor.

While drifting, the carbon buoys deliver an intervention to the chemistry of the surface ocean: they either alkalinize it through mineral dissolution or remove carbon from it by growing macroalgae. Upon sinking, they deliver both terrestrial and marine biomass to the ocean floor. Because these carbon buoys disperse over a vast geographic area, the spatial density of individual carbon buoys is dilute. This minimizes acute environmental exposures and allows the intervention to be delivered as a perturbation to ocean-scale carbon cycling dynamics.

Because carbon removal is a mass transfer problem, the commercial viability of carbon removal technologies will depend on the net, rather than the gross, mass transfer ratio. The architecture of numerous passively drifting carbon buoys provides Running Tide's system with a powerful mass transfer lever. Engineered systems reliant on anthropogenic energy inputs are only required to move the seeded carbon buoys offshore and place them in surface currents. The fixation of carbon from ambient seawater, and the relocation of biomass from regions of growth to regions of durable storage, is powered through sunlight, ocean currents, and gravity.

This system is being specifically developed to amplify carbon removal technologies to a climate-relevant Earth-scale operation. Bringing it into full existence will require

key breakthroughs in applied science as well as investments to rewire the logistics chains of the industrial economy.

Part 3 - References

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