

Introducing Microalgae Carbon Fixation and Sinking (MCFS): a new approach for controlled and scalable CDR

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Abstract:	Achieving global climate targets requires scalable and durable carbon dioxide removal (CDR) technologies to tackle both historical and hard-to-abate emissions. We introduce Microalgae Carbon Fixation and Sinking (MCFS), a marine CDR methodology designed to enhance carbon fixation and export to the deep ocean through a controlled process. At the core of the MCFS approach is a tailored substrate: a non-toxic organic and/or inorganic structure containing bound stable micronutrients that promotes local phytoplankton growth within it. It is designed for a dual-phase lifecycle: a fixation phase, allowing a sufficiently long duration of floating to maximize biomass accumulation (up to 30 days), followed by rapid sinking, which minimizes remineralization in the water column (hours-days to reach seabed). The MCFS methodology operates within a governance framework that includes site selection of physically and biochemically advantageous regions that ensure carbon sequestration durability of hundreds to thousands of years. To address potential ecological risks, a threshold-based approach is adopted, consisting of detailed activity design and pulsed deployments. Monitoring protocols are applied before, during, and after each activity. MCFS offers a controlled and scalable pathway to harness the ocean's sequestration capacity while maintaining the activities well within ecological safety and integrity measures.



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Introduction

Meeting global climate goals requires a rapid reduction in greenhouse gas emissions, coupled with the application of scalable and durable CDR solutions to address legacy and hard-to-abate emissions (IPCC 2023a, 2023b). While land-based methods are a critical part of the climate solution portfolio, their scalability is ultimately constrained by the finite availability of land and by energy-intensive procedures (Cross et al. 2023). The ocean is the Earth's largest active carbon reservoir, containing ~60 times more carbon dioxide (CO₂) than the atmosphere and ~18 times more than the terrestrial biosphere (Calvin et al. 2023; DeVries 2022; Roy-Barman and Jeandel 2016), making it a promising frontier for climate restoration. This reality and capacity necessitate a rigorous exploration of ocean-based approaches to CDR.

This perspective paper provides a strategic overview of Microalgae Carbon Fixation and Sinking (MCFS), a marine CO₂ removal (mCDR) methodology that offers a distinct, engineered, controlled and measurable solution, which utilizes the natural processes of CO₂ fixation by phytoplankton and its long-term sequestration on the seabed of the deep ocean. MCFS enhances the export of carbon via small substrates that float in the photic zone and contain a cocktail of nutrients in stable forms, promoting carbon fixation through photosynthetic carbon fixation within and around the substrate structure. Controlled, density change-driven rapid sinking then propels the substrate to the seabed for long-term sequestration (hundreds to thousands of years).

The ocean as a carbon sink: cycles and challenges

MCDR comprises a range of proposed approaches to enhance the ocean's uptake and long-term storage of atmospheric CO₂ (Cross et al. 2023; IPCC 2023b, 2023a). These methods are commonly grouped into biotic and abiotic pathways. Biotic mCDR relies on biological processes that increase photosynthetic carbon fixation and/or export, such as nutrient fertilization, artificial upwelling, and biomass cultivation and sinking. Abiotic mCDR targets physical or chemical processes, including mineral or electrochemical ocean alkalinity enhancement, direct ocean capture, artificial downwelling, and accelerated carbonate mineralization. Together, these approaches represent a diverse portfolio of mechanisms with differing permanence, scalability, and environmental risk profiles (NASEM 2019, 2022).

At the foundation of these methods is the ocean's primary mechanism of natural carbon cycling, or the carbon pump, which transports carbon from the surface to the deep ocean, removing it from the atmosphere for hundreds to thousands of years. In the ocean's natural carbon cycle, carbon is partitioned among particulate organic (POC), dissolved organic (DOC),

particulate inorganic (PIC), and dissolved inorganic carbon (DIC), with DIC comprising the dominant oceanic reservoir.

The biological pump is driven by marine photosynthesis, where phytoplankton in the euphotic zone convert DIC into POC. A fraction of this organic carbon sinks out of the euphotic layer as export production, transferring carbon from surface waters into the deep sea (Boyd et al. 2019). The solubility pump is a physicochemical process driven by the higher solubility of CO₂ in cold water, transporting carbon into the deep ocean via the large-scale thermohaline circulation (Roy-Barman and Jeandel 2016). The carbonate pump delivers inorganic carbon to the deep ocean in the skeletons of calcifying organisms that grow in the water column and construct their skeletons from polymorphs of calcium carbonate (calcite and aragonite; Holligan and Robertson 1996).

While the biological pump is a powerful natural process, it is inherently inefficient to combat the deleterious effects of excess emission of CO₂ attributed to human activities (Buesseler et al. 2020; Buesseler and Boyd 2009; Kienast and Torfstein 2022; Middelburg 2019). The vast majority of fixed POC is consumed by grazers or respired by bacteria and "remineralized" back into DIC within the mixed layer and throughout the water column, long before it reaches the deep sea. This inefficiency is profound, with only ~1% of the organic carbon fixed at the surface ultimately settling into deep ocean sediments for long-term sequestration (Dunne et al. 2007; Martin et al. 1987; Stukel et al. 2023). Its potential for augmentation has long been recognized, leading to a first generation of biotic mCDR approaches.

One of the well-studied proposed biotic approaches is ocean fertilization (Buesseler et al. 2023; 2026; Martin et al. 1990), which involves adding soluble nutrients directly to surface waters to stimulate primary productivity in the form of phytoplankton blooms (Buesseler et al. 2023; Cross et al. 2023; NASEM 2019, 2022; Yoon et al. 2018). The addition of nutrients lifts limitations to primary productivity and enhances photosynthetic carbon fixation. Ocean fertilization does not include a mechanism to ensure the export and sequestration of the fixed carbon, relying only on the natural biological pump. It is thus inherently inefficient due to the rapidity of heterotrophic (zooplankton and microbial) degradation relative to organic matter aggregation and sinking. Across thirteen ocean fertilization field trials conducted to date, carbon export efficiency has been highly variable; under typical biological pump conditions only ~1% of fixed carbon is estimated to reach deep ocean sediments (Dunne et al. 2007; GESAMP 2019), with substantial deep export demonstrated in only one experiment (Smetacek *et al.* 2012).

Moreover, ocean fertilization can potentially lead to undesired environmental risks, including alteration of local and far-field food webs, increases in water column oxygen

consumption, and involves challenges to measurability of carbon export (Bach et al. 2025; Buesseler et al. 2020; Jin and Gruber 2003; Keller et al. 2014; Oeschies et al. 2010; Wells et al. 2015; Williamson et al. 2012; Wingenter et al. 2004).

Active sinking of cultivated biomass (commonly known as biomass sinking) is another biotic mCDR approach that has been suggested and involves the rapid sinking of terrestrial biomass or macroalgae to the deep ocean (Chen et al. 2024; Krause-Jensen and Duarte 2016; Strand and Benford 2009). While this process can be controlled and quantified, several significant environmental risks have been identified (Oeschies et al. 2025a). For example, depositing high concentrations of biomass on the seabed can smother benthic ecosystems, deoxygenate them, and effectively disrupt benthic habitats and food webs. Other environmental risks include introducing foreign species into the ocean waters (associated with biomass sinking), and nutrient depletion (Chen et al. 2024; Chopin et al. 2024; Doney et al. 2025; Oeschies et al. 2025b; Ricart et al. 2022).

Introducing MCFS

MCFS is a biotic mCDR method specifically developed to establish a controlled, measurable, safe and efficient mechanism for capturing and storing carbon by addressing the scientific and environmental limitations associated with earlier biotic approaches, mitigating them by design. An engineered particle (hereafter called substrate) is a central technological innovation under the substrate-based MCFS approach. It is designed not only to achieve photosynthetic carbon fixation within the substrate but also to ensure efficient export of the captured carbon to the deep seabed (Figure 1). Two main key features address the specific limitations of previous biotic mCDR approaches: 1) the composition of the substrate and, 2) its sinking mechanism and properties. In terms of composition, the substrate is a non-toxic material, engineered into small (millimetric scale), stable particles. The current substrate formulation consists of a porous, physically entangled natural fiber matrix (currently cotton-based; future formulations may vary according to functionality) whose three-dimensional pore structure promotes phytoplankton colonization while remaining permeable to water and macronutrients, allowing exchange between the particle interior and the surrounding seawater. Stable forms of micronutrients, such as iron and manganese oxides or in stable, surface-bound complexes, constitute a very small portion of its total mass (maximum of 2%). They are bioavailable to local phytoplankton growing within the substrate, but are insoluble and therefore do not freely disperse into the surrounding seawater. Although localized or transient reductive dissolution of iron (Fe) and manganese (Mn) oxides could theoretically occur within suboxic micro-environments or benthic boundary layers, any

reduced species released (e.g., Fe^{2+} , Mn^{2+} , H_2S , CH_4) are rapidly re-oxidized upon contact with the surrounding oxic water column (Millero *et al.* 1987; Pakhomova *et al.* 2007; Reeburgh 2007). Furthermore, deep-sea marine sediments naturally harbor massive background reservoirs of solid-phase Fe and Mn minerals, averaging 6.5 wt% Fe and 0.67 wt% Mn in pelagic clays, and up to 18–20 wt% Fe in metalliferous seafloor deposits (Li & Schoonmaker, 2003; Burdige, 2006). Given the broad spatial distribution of deployed substrates, the total mass contribution of substrate-bound Fe and Mn oxide coatings is quantitatively negligible relative to these ambient sedimentary pools and natural diagenetic fluxes (Froelich *et al.* 1979; Pakhomova *et al.* 2007). The stability of bound Fe and Mn oxide phases is ensured by the oxygenated conditions of the deep water column in target HNLC regions, where dissolved oxygen concentrations far exceed the near-anoxic threshold required for dissimilatory iron and manganese reduction (Tagliabue *et al.* 2017). This produces a contained microenvironment, which the phytoplankton communities can colonize and proliferate.

The second design component relates to the substrate's controlled density. Flotation during the fixation phase is achieved through air entrapped within the porous fiber matrix at manufacture. Over ~20 days at the sea surface, ocean hydrodynamics (waves, currents, and surface turbulence) gradually drive seawater into the matrix, displacing entrapped air and progressively increasing bulk density; biomass accumulation within the substrate contributes a further density increase. Once the substrate's overall density exceeds that of surface seawater, the substrate sinks autonomously, independent of the accumulated biomass. The rapid sinking transports fixed carbon from the surface into the deep ocean, increasing export efficiency by minimizing the time organic matter spends in the upper water column, where biological remineralization would release CO_2 back into the atmosphere.

This strategic design, combined with a thorough operational planning framework, is the primary strategy to control the activity and prevent ecological disruptions (environmental risks discussed below) associated with biotic mCDR approaches. It maximizes export efficiency and operates by design under a conservative threshold-based approach to address environmental concerns.

The MCFS methodology: a framework for verifiable mCDR

To earn scientific and public trust and evaluate its climate benefits, any mCDR approach must be governed by a comprehensive framework that ensures its activities are environmentally sound, effective, and transparently quantifiable. The Puro.earth MCFS methodology (Puro.earth,

2025) provides such a framework, establishing rigorous rules for project design, carbon accounting and verification, and identification and mitigation of environmental and social risks.

Proper site selection and operational planning for the MCFS methodology requires adherence to both biogeochemical and physical oceanographic criteria to ensure additionality and durable carbon sequestration. MCFS operations are limited to high nutrient, low chlorophyll (HNLC) regions. These unique biogeochemical environments have high potential for carbon sequestration, which is naturally suppressed by limitations (micronutrients, light, etc.). Physically, the seafloor depth and deepwater currents must demonstrably ensure durable carbon sequestration for hundreds to thousands of years, and no less than 200 years, validated using global ocean ventilation models (DeVries and Primeau 2011; Holzer *et al.* 2020; Nowicki *et al.* 2024; Primeau 2005; Pasquier *et al.* 2025). Furthermore, site selection must optimize air-sea gas exchange efficiency by targeting areas where carbon-depleted surface waters remain in contact with the atmosphere long enough to absorb atmospheric CO₂ (Jones *et al.* 2014).

Operational planning imposes an additional layer of process control. MCFS activities are to be deployed during optimal environmental conditions, when net carbon removal by the project activity is expected to be highest. By determining time-dependent population sizes and the lag time between phytoplankton growth and zooplankton grazing, simulations will enable the optimization of both the duration of the fixation phase and the timing of triggered sinking (Truscott and Brindley 1994). Pre-deployment modeling to predict substrate trajectories and concentrations will ensure that the substrates sink towards designated sinking locations and are sufficiently distributed in space and time to mitigate environmental impacts (e.g., benthic smothering, localized oxygen depletion).

Following site selection, a comprehensive site and substrate characterization process is initiated to define the baseline conditions of the activity Area of Interest (AOI) and confirm substrate eligibility (Table 1). Oceanographic characterization, which utilizes historical field data and global model outputs is needed to establish regulatory compliance and environmental baselines. Concurrently, laboratory analyses are conducted on the pristine substrate to predict performance metrics and to validate adherence to the eligibility criteria regarding non-toxicity and composition.

Site characterization establishes pre-operational baselines by synthesizing high-resolution biogeochemical and physical reanalysis models (e.g., CMEMS PISCES at 1/4° and GLORYS at 1/12°) with multi-decadal in-situ cruise observations (e.g., GEOTRACES CTD/bottle archives), BGC-Argo float profiles, and satellite remote sensing data (e.g. MODIS, GlobColour).

This data synthesis validates HNLC criteria and characterizes seasonal dynamics. During deployment, operational uncertainty is mitigated through real-time, multi-platform field tracking. Monitoring and measurements adhere to standard oceanographic research methodology (Table 2; Knap *et al.* 1996; UNESCO 1988) and are divided into four distinct phases corresponding to the MCFS lifecycle:

Phase 1: *In-situ* baseline. Prior to substrate deployment, full water column profiles are taken at both deployment and control sites to measure background productivity and establish pre-deployment conditions (specified in Table 2).

Phase 2: Fixation (Floating). The monitoring framework employs a multi-tiered approach to assess the pelagic ecosystem state and carbon export during the application of the substrates. First, *in situ* profiles throughout the euphotic zone are acquired within the plume area to measure and sample the parameters (Table 2). Concurrently, floating substrates are collected from surface waters. These substrates are physically separated from free planktonic biomass and subjected to elemental analysis to empirically quantify organic carbon content. In parallel, to characterize export dynamics, autonomous multi-chamber platforms are deployed to intercept sinking substrates at discrete intervals, providing essential data on floating time variability and the cumulative sunk fraction.

Phase 3: Export (Sinking). To quantify sinking efficiency, sinking velocities can be measured *in situ* using acoustic and/or optical tracking during the sinking phase. Subsequent confirmation of carbon export is achieved through subsurface sampling with systems such as the Multiple Opening/Closing Net and Environmental Sensing System (MOCNESS), which validates that biomass-fixed substrates have successfully exited the surface waters. Finally, remineralization rates during the export phase are estimated by measuring surface remineralization rates and using them to derive the vertical remineralization profile through the water column, essential in evaluating the sinking efficiency of the fixed carbon (Table 2).

Phase 4: Post-operation (verification): After the end of the operation, full water column profiles are taken at both sinking and control sites to monitor ecosystem state, via comparison to pre-deployment baseline levels.

The final quantification of carbon removal credits is derived from a net carbon mass balance calculation that accounts for all fluxes. This accounting ensures net, durable carbon is permanently removed from the atmosphere and positive climate impact. The general quantification logic follows:

$$\text{Net CDR} = \text{Carbon stored} - \text{Baseline} - \text{Losses} - \text{Process emissions} - \text{Leakage}$$

- Carbon stored: The net total organic carbon that has accumulated on the substrates during the fixation phase, quantified via *in-situ* measurements and sampling. The carbon fraction lost to respiration as the substrate sinks is removed (surface remineralization rates, sinking velocity, and full water column oxygen and temperature profiles enable the calculation of the remineralization profile). Additionally, air-sea gas exchange modelling is used to account for the share of carbon that does not translate into net atmospheric removal (Zhou *et al.* 2025).
- Baseline: Where operations lead to a reduction in natural primary productivity below the prior approximations of seasonal minimum, this reduction is quantified and subtracted from the total carbon stored.
- Losses: The fraction of stored carbon expected to be released within 200 years as a result of deep-ocean ventilation.
- Process emissions: GHG emissions arising across the project lifecycle, including substrate cultivation and production, transport, and fuel consumption from vessel operations and deployment logistics.
- Leakage: Unmitigated, indirect emissions, arising outside the project boundary, primarily through potential market shifts and downstream ecological leakage pathways.

Modeling framework

The MCFS methodology relies on two complementary classes of numerical models, (Puro.earth 2025), that together support deployment planning, environmental risk assessment, and carbon accounting. Physical oceanographic and Lagrangian particle tracking models simulate substrate surface trajectories and dispersion during the fixation phase, informing deployment rate, spatial extent, and total substrate quantity required to meet carbon removal targets while remaining within ecological safety thresholds. Physical oceanographic models further characterize deep-water circulation pathways and water mass ventilation timescales to assess carbon storage durability (Nowicki *et al.* 2024; Pasquier *et al.* 2025). Biogeochemical models address phytoplankton growth forecasting as a function of nutrient availability and light, air-sea gas exchange efficiency (Zhou *et al.* 2025), surface macronutrient depletion, water column remineralization, and deep-water dissolved oxygen drawdown.

The modeling framework incorporates direct field-based observational inputs for parameterization and validation. This encompasses physical and hydrographic data, such as temperature, salinity, currents, and light penetration; kinematic measurements, including GPS

drifter tracking and acoustic or ROV-based sinking velocity assessments; and chemical and biological data, specifically baseline macronutrient concentrations and dissolved oxygen profiles, which are essential for driving growth rate and oxygen depletion models.

Environmental risk management in MCFS

The implementation of biotic mCDR approaches introduces several primary environmental considerations that must be managed to prevent unintended ecosystem disruption (NASEM 2022; Oschlies *et al.* 2025a). The main potential risks associated with enhancing biological carbon pumps include: 1) Nutrient redistribution (Bach *et al.* 2021; Oschlies *et al.* 2010; Ross *et al.* 2022); 2) Oxygen depletion (hypoxia caused by biomass remineralization; Keller *et al.* 2014; Oschlies *et al.* 2025b), and 3) Biodiversity alteration (such as Harmful Algal Blooms or benthic smothering (Boyd 2008; Boyd *et al.* 2022; Campbell *et al.* 2019).

Environmental risk management is designed within a structured framework that prioritizes proactive risk avoidance through site selection, substrate-specific core technological properties designed to eliminate risks at the source, and by enforcing a threshold-based operational planning approach that sets rigid boundaries for the operation and minimizes potential environmental impact. This approach dictates that initial deployments must be scaled appropriately to the current level of scientific understanding, ensuring that initial deployments are small enough to minimize and localize any unintended ecological consequences, and that ocean systems can return to their ambient conditions once operations cease. This precautionary scaling allows for ecosystem effects and changes to the baseline ocean health to be carefully monitored, permitting early identification of unexpected impacts with controlled and limited influence (Table 3).

The primary strategy for mitigating negative ecological impacts is found in the core design of the substrate. Distinct from open-ocean fertilization methods that rely on diffused nutrient release, the MCFS approach utilizes a containment mechanism wherein essential micronutrients are sequestered within the substrate's structural matrix as bound, insoluble oxides. This confinement mechanism prevents the unconfined dispersal of nutrients into the open ocean, thereby minimizing the risk of widespread, unregulated phytoplankton blooms. Furthermore, the deployment protocol allows for precise spatial control, facilitating the active management of discharge density at both the sea surface and the benthic interface. Finally, to limit oxygen consumption in the water column, the substrate is engineered for a high settling velocity (>20 m/h); this rapid sinking significantly reduces the residence time of organic matter in the upper ocean, thereby restricting remineralization during the export phase.

Moreover, risks are managed using a threshold-based approach. This framework defines quantitative environmental safety limits (e.g., maximum allowable oxygen depletion) derived from natural ecosystem variability and tolerance levels, which are set during the operational planning (e.g., deployment location, rate, and timing). Operations are planned to use predictive modelling to ensure these limits are not exceeded, and *in situ* monitoring is used to verify that thresholds remain within defined bounds.

Within this framework, specific risks are prioritized and managed. Thorough operational planning, informed by an extensive modelling framework based on historical physical, biological and chemical data, helps mitigate the risks of disrupting local and downstream food webs through nutrient depletion. The deployment of substrates is managed strategically along specific transects at controlled rates and within defined areas to minimize localized risks. This results in a limited density of the substrate on the ocean's surface and eventually on the seafloor. This strategy has two main goals: first, to limit nutrient uptake preventing surface macronutrient levels from dropping below intra-seasonal minimums; and second, to limit benthic ecological impact such as smothering and dissolved oxygen depletion. Furthermore, the pulsed deployment strategy ensures surface water has ample time to replenish macronutrients via advection and mixing between batches (Williams and Follows 2003).

The microbial breakdown of organic matter consumes oxygen, and can potentially create hypoxic zones in deep water or at the sediment interface (Diaz and Rosenberg 2008; Rabalais *et al.* 2002). In addition to the rapid sinking velocity described above, the methodology strictly enforces a requirement to protect sensitive deep-sea fauna. Specifically, operations must prevent the decrease in deep-water dissolved oxygen (DO) concentration from exceeding a 30% threshold and the creation of hypoxic conditions (less than 60 $\mu\text{mol/kg}$ DO) must be avoided. This is accomplished through an operational modelling and planning framework (Breiman 2001; Glasson 2008; Groffman *et al.* 2006; Vierod *et al.* 2014) that tests various deployment scenarios to determine the substrate density required to keep the remineralization of organic matter below the set threshold. Pulsed deployment strategy is integral to this local mitigation, mandating a necessary waiting period between deployments.

Risks to benthic organisms from smothering are also managed primarily through pre-operational dispersal modelling and planning, which estimates the spatial distribution of sunken material, ensuring that deposition density remains below the threshold required to create a consistent, suffocating sediment layer (i.e., 3 mm thickness; Fjukmoen *et al.* 2024).

Conclusion: a verifiable and responsible path for marine CDR

MCFS represents a significant evolution from first-generation biotic mCDR approaches, moving beyond simply stimulating biological activity or compiling biomass onto the seabed, to a paradigm of process control. By directly addressing the key historical challenges of high environmental risk, MCFS offers a pathway to harness the ocean's vast capacity for carbon storage without compromising its ecological integrity.

The strength of the MCFS pathway lies in the deliberate integration of two critical components: 1) an engineered substrate, designed for controlled biomass growth and rapid, efficient export, and 2) a robust and transparent governance framework that mandates accounting, multi-stage verification, and proactive risk assessment and mitigation. This combination ensures that carbon removal is not just effective but also controllable and quantifiable. The substrate's reliance on commodity natural fiber feedstocks and standard marine vessel operations means production and deployment volumes can increase without bespoke infrastructure, a prerequisite for contributing meaningfully to climate mitigation.

Looking ahead, the successful scaling of MCFS to act as a significant climate change mitigation technology will require continued interdisciplinary collaboration and technological refinement. Future research and operational development should focus on the following key areas:

- Technological and monitoring advancements: Enhancing autonomous *in situ* monitoring technologies, such as acoustic tracking, optical sensors, and subsurface sampling systems, will further reduce costs and uncertainties associated with deep-ocean monitoring.
- High-resolution modeling: The continuous improvement of global ocean ventilation, biogeochemical, and dispersal models will be essential to optimize site selection, predict secondary ecological interactions, and refine air-sea gas exchange and ventilation quantifications.
- Ecosystem resilience and long-term studies: Longitudinal studies assessing the long-term, cumulative impacts of sunken substrates on deep-sea benthic biodiversity and sediment chemistry are crucial for scientific validation.
- Regulatory alignment and market integration: As mCDR transitions from pilot testing to commercial deployment, integrating methodologies like MCFS into international compliance and voluntary carbon markets will be critical. Securing ongoing public and regulatory trust will depend on transparent and rigid adherence to standards.

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Author Contribution statement

N.B. and J.S. led the writing of the original drafts with contributions from co-authors. N.B., J.S, A.G., M.G., and S.M-A contributed to the writing, revision, and review of this manuscript.

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Conflict of Interest statement

The authors declare none.

Data availability statement

All data used in this study were cited from the literature with appropriate citations, and no data were generated in the preparation of this manuscript.

AI statement

Generative AI (Gemini 3.6) was used solely to assist in creating visual representations of the substrate matrix for Figure 1. All generated graphics were subsequently reviewed, modified, and approved by the authors. No generative AI was used to analyze data or draw scientific conclusions.

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607 Tables

608 Table 1: Eligibility criteria for substrate composition and characteristics, and deployment site
 609 location as was defined in the MCFS methodology by Puro.earth 2025.

	Eligibility criteria	Description
Substrate	<i>Material Composition and Sourcing</i>	Non-toxic, non-hazardous, organic or inorganic material, which includes trace elements (micronutrients) up to 2% of total mass.
Substrate	<i>Chemical Safety</i>	Concentrations of Potentially Toxic Elements (PTEs) (heavy metals, PAHs, PFAS, pesticides) do not exceed the limits defined in the applicable legislation.
Substrate	<i>Micronutrient Characteristics</i>	Must include iron (Fe) in oxide form, and have a zero to low tendency to dissolve. Laboratory-based leaching tests must confirm that trace elements are contained within the substrate.
Substrate	<i>Physical Dimensions and Density</i>	Diameter ranges from 0.5 to 100 mm. Density of the solids must be >0.01 g/cm ³ higher than the density of water.
Substrate	<i>Containment Mechanism</i>	A mechanism (e.g., high porosity, physical entanglement) that minimizes the loss of accumulated phytoplankton and biomass due to physical forces.
Substrate	<i>Floatation and Sinking</i>	Autonomous or controlled sinking mechanism. Maximum floatation period shall not exceed 30 days. Sinking velocity minimum of 20 m/hr (proportional to the substrate-water density difference).
Activity site	<i>HNLC Region Status</i>	Limited to regions with surface nitrate > 8 µM, phosphate > 0.5 µM, iron < 0.2 nM, and chlorophyll a < 1 µg/L.
Activity site	<i>Durability and Deep Ocean Storage</i>	The site must be chosen to ensure that sunken carbon remains out of contact with the atmosphere for hundreds to thousands of years, and no less than 200 years.
Activity site	<i>Seafloor and Ecosystem Stability</i>	Sites must avoid interference with sensitive ecosystems, including those vulnerable to particulate smothering and oxygen depletion, and must not be located in regions subject to seismic or volcanic activity.
Activity site	<i>Phytoplankton Type</i>	The activity shall exclusively rely on growth of local phytoplankton populations. Phytoplankton seeding will be avoided.

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Table 2. Summary of monitored physical, chemical, and biological parameters and the rationale for each parameter’s monitoring, distinguishing between proof of eligibility, quantification of CDR, and environmental impact monitoring. The parameters are defined in the MCFS methodology, as detailed in Puro.earth 2025.

	Parameter	Rationales for monitoring			How evaluated
		Eligibility	Quantification	Environmental monitoring	
Physical	<i>Temperature, Salinity, Density</i>	Site characterization; Baseline	Remineralization rate and sinking efficiency quantification.	Water mass profiles for determining long-term carbon storage stability, enhanced by stratification and colder temperatures.	Historical data (databases and measuring stations); <i>In-situ</i> CTD full water column measurement
	<i>Photosynthetic Active Radiation (PAR)</i>	Euphotic zone depth		Euphotic zone depth required for nutrient depletion assessment	<i>In situ</i> CTD-mounted sensor full water column measurement
	<i>Turbidity</i>	Site characterization; Baseline		Water column transparency monitoring	<i>In situ</i> CTD-mounted sensor full water column measurement
	<i>Seawater Velocities</i>	Site characterization; Baseline		Required for the particle tracking model to project trajectory and seabed deposition densities.	Models and in situ ADCP photic layer measurements
	<i>Surface water retention time</i>	Site characterization; Baseline	Air-Sea Gas Exchange factor		Oceanographic model
	<i>Deep water trajectory</i>	Site characterization; Baseline	Durability, long-term atmospheric reemission		Lagrangian model
Chemical	<i>Dissolved Oxygen</i>	Site characterization; Baseline	Remineralization rate and sinking efficiency.	Oxygen depletion risk analysis	Model and in situ CTD-mounted sensor full water column measurements
	<i>Inorganic macronutrients (N, P, Si)</i>	Site characterization; Baseline; HNLC validation	Effects of downstream nutrient uptake and potential changes to the natural baseline	Macronutrient depletion assessment	<i>In situ</i> full water column discrete sampling
	<i>Trace metals (Fe, Mn)</i>	Site characterization; Baseline; HNLC validation (Iron < 0.2 nM)		Trace element leaching risk assessment	<i>In situ</i> surface water sampling

	Carbonate system (DIC, pH, TA)	Site characterization; Baseline	Estimate if the water are source or sink of CO ₂	Change to the carbonate system	<i>In situ</i> full water column discrete sampling
	CH ₄ , N ₂ O			Project-related enhanced GHG production risk	<i>In situ</i> surface water sampling
	Dimethylsulfoniopropionate (DMSP)			Production of DMS and potential climate co-benefits	<i>In situ</i> surface water sampling
Biological	Chlorophyll <i>a</i>	Site characterization; baseline; HNLC validation (Chl <i>a</i> <1 µg/L)		Project-induced algal bloom risk	<i>In situ</i> full water column sampling
	Community Composition / Biodiversity	Site characterization; Baseline;		Harmful Algal Blooms (HABs) and food web disruption risks	<i>In situ</i> euphotic layer discrete sampling
	Ultraplankton / Microplankton / Bacterial Abundance	Site characterization; Baseline		Changes to the base of the food web risk	<i>In situ</i> euphotic layer discrete sampling
	Algal Toxins			Toxin production risk	<i>In situ</i> euphotic layer discrete sampling
Biological - Organic carbon (water)	Net primary production (NPP)	Site characterization; Baseline	Baseline Net Primary Production.	Local nutrient depletion and impact on natural primary productivity and growth rates risk	<i>In situ</i> euphotic layer discrete sampling
	Total Organic Carbon (TOC/POC, DOC)	Site characterization; Baseline		Changes to organic carbon content in the water column	<i>In situ</i> full water column discrete sampling
Organic carbon (substrate)	Total solids & carbon content	Substrate characterization	Net organic carbon fixed to substrate.		Lab for pristine substrate <i>In situ</i> net sampling
	Remineralization & sinking rate	Substrate characterization	Remineralization rate profile calculation and estimate of sinking efficiency	Slower sinking rates can lead to larger remineralization and effects on oxygen and carbon levels in the water column	<i>In situ</i> net sampling, respiration by incubation measurement, sinking detected by echosounder, and/or ROV

Table 3: Summary of environmental risks, underlying mechanisms, and mitigation measures associated with MCFS operations.

Risk category	Underlying mechanism	Potential environmental impact	Assessment and mitigation
Nutrient depletion and altered phytoplankton growth	Uptake of dissolved macronutrients by biomass associated with deployed substrate, potentially reducing nutrient availability for ambient phytoplankton	Localized suppression of phytoplankton growth	Deployment rates and spatial extent are constrained by operational planning to keep nutrient perturbations within natural variability. In situ measurements of macronutrients (N, P, Si), particulate organic carbon, and net primary production are conducted before, during, and after deployment and at control sites and supported by regional transport modeling
Deep-water oxygen depletion and formation of anaerobic by-products	Microbial remineralization of sinking biomass consumes dissolved oxygen in bottom waters and at the sediment–water interface	Localized oxygen reduction and potential anaerobic pathways producing CH ₄ or N ₂ O	Oxygen drawdown is quantified relative to baseline using a sediment–water interface (multi-box) model coupled to particle-flux estimates. Site selection and areal loading are constrained such that modeled DO reductions remain below a predefined ecological threshold and do not trigger anaerobic conditions. Deployment intervals are spaced to prevent cumulative oxygen demand.
Surface biogeochemical perturbation and trace gas production	Localized enhancement of surface biological activity	Short-lived changes in surface dissolved oxygen and increased trace gas concentrations (N ₂ O, CH ₄ , DMS)	Substrate design immobilizes micronutrients in oxide form, limiting nutrient release to the surrounding water, preventing bloom propagation. Surface-water concentrations of dissolved oxygen, N ₂ O, CH ₄ , and DMSP are measured before, during, and after operation and at control sites to verify that natural background ranges are maintained
Alteration of carbonate system chemistry	Changes in DIC, alkalinity and pH during carbon fixation and remineralization	Short-term, localized shifts in pH and pCO ₂ affect sensitive marine organisms	Deployment rates and locations are constrained to maintain substrate density at a level that keeps the carbonate system parameters within natural background variability. Pre, during, and post-operation measurements and at the control site verify the absence of persistent perturbations
Seawater’s anion adsorption and chemical imbalance	Adsorption of dissolved anions (e.g., phosphate) onto the substrate, altering local nutrient availability	Transient, localized reduction in dissolved phosphate concentrations	Substrate adsorption capacity is characterized <i>ex situ</i> to quantify anion adsorption capacity before deployment, and <i>in situ</i> nutrient concentrations are monitored to verify negligible chemical perturbation. Deployment rates and amounts are constrained to minimize measurable perturbations
Biodiversity alteration and food-web perturbation	Localized changes in primary productivity and organic matter flux alter phytoplankton and microbial community structure	Transient shifts in community structure	Biological indicators are assessed before and after the operation and evaluated relative to intra-seasonal ecosystem variability

Harmful algal bloom development and toxin production	Selective stimulation of opportunistic phytoplankton species under altered local nutrient or surface-water conditions	Localized increases in harmful species or toxins	Assessed via <i>ex situ</i> incubation experiments and <i>in situ</i> monitoring of microbial and micro-phytoplankton community composition using DNA-based methods and microscopy. If DNA analysis reveals an increased abundance of a harmful algal species, the collected water samples will then undergo analysis for specific toxin detection.
Physical interaction with higher trophic-level organisms	Encounter or ingestion of substrate material by marine megafauna or seabirds	Injury or behavioral disturbance	Deployment locations avoid biodiversity hotspots, and substrate properties and distribution minimize exposure and interaction probability. Substrate material properties are characterized <i>ex situ</i> to confirm mechanical stability and the absence of toxic components.
Benthic organism smothering and habitat alteration	Seafloor deposition of substrate material, causing physical coverage or reduced sediment–water exchange	Localized burial or habitat disturbance	Deposition density assessed via <i>ex situ</i> incubation experiments and constrained through site selection, deployment, and dispersion approach, by operational planning. Assessed by modeling to remain below benthic smothering thresholds
Ecotoxicity from trace metals and contaminants	Release or leaching of metals or contaminants	Acute or sub-lethal toxicity	Substrate materials are chemically characterized and toxicity-tested to confirm contaminant concentrations remain below ecotoxicological thresholds (ASTM 1993; USEPA 1987; Williams and Hall 1999)
Turbidity increase and reduced visibility	Temporary suspension of substrates during release and subsequent sinking	Short-term, localized reduction in light penetration	Substrate design promotes rapid sinking, limiting turbidity to brief, localized deviations from background conditions

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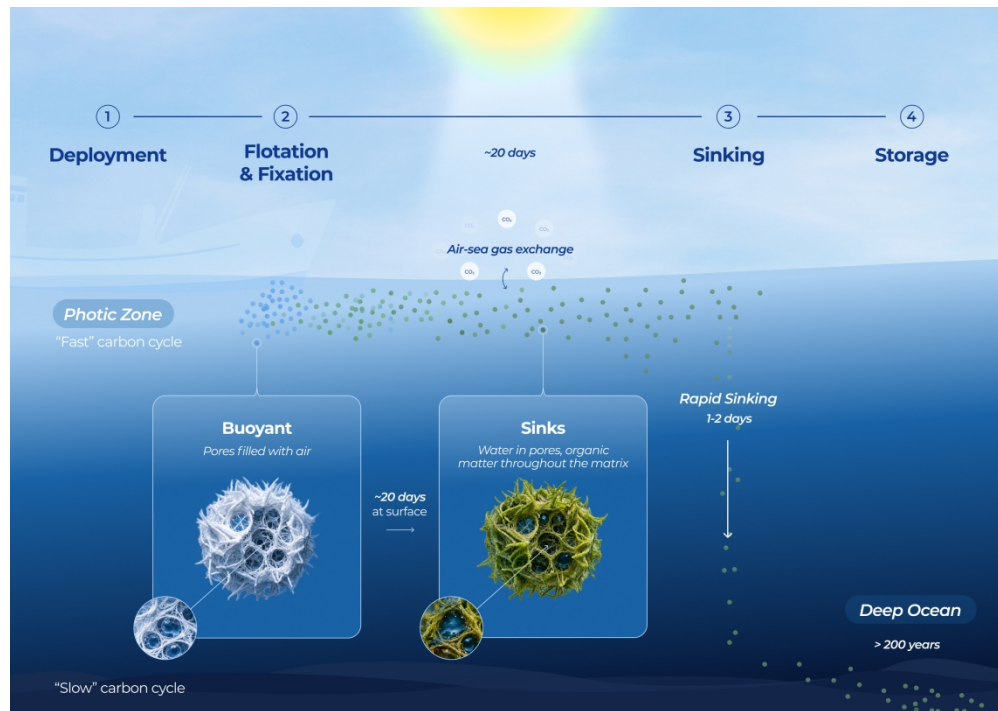
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626 **Figure caption**

627 Figure 1: Conceptual diagram detailing the MCFS pathway employing engineered substrates. The process encompasses four
628 primary stages spanning the “fast” and “slow” carbon cycles. (1) Deployment: Controlled release of pristine substrates at the surface
629 ocean. (2) Flotation and Fixation: Substrates are temporarily retained within the photic zone, allowing local phytoplankton
630 communities to photosynthetically convert dissolved inorganic carbon into biomass directly inside the substrate matrix. Over time, air-
631 sea gas exchange drives net atmospheric CO₂ drawdown to the surface seawater to restore chemical equilibrium across the air-sea
632 interface. Concurrently, trapped air is gradually released from the substrate matrix and replaced by water and accumulating biomass.
633 The lower insets schematically illustrate the physical transition of the substrate over an approximately 20-day surface residence time.
634 The pristine substrate relies on air-filled pores for buoyancy (left inset), which transitions to a negatively buoyant, sinking state once
635 the internal matrix becomes fully saturated with water and organic matter (right inset). (3) Sinking: Density changes trigger
636 autonomous rapid gravitational settling, transporting the fixed organic carbon through the mesopelagic zone while minimizing
637 microbial remineralization. (4) Storage: The biomass-loaded substrates are retained in the deep ocean and benthic sediments,
638 enabling long-term carbon sequestration on timescales of hundreds to thousands of years.
639 (Note: Visual representations of the substrate matrix in buoyant and sinking states were generated using Gemini 3.6 and
640 subsequently reviewed and edited by the authors to reflect pristine and biomass-loaded states.)



Conceptual diagram detailing the MCFS pathway employing engineered substrates. The process encompasses four primary stages spanning the “fast” and “slow” carbon cycles. (1) Deployment: Controlled release of pristine substrates at the surface ocean. (2) Flotation and Fixation: Substrates are temporarily retained within the photic zone, allowing local phytoplankton communities to photosynthetically convert dissolved inorganic carbon into biomass directly inside the substrate matrix. Over time, air-sea gas exchange drives net atmospheric CO₂ drawdown to the surface seawater to restore chemical equilibrium across the air-sea interface. Concurrently, trapped air is gradually released from the substrate matrix and replaced by water and accumulating biomass. The lower insets schematically illustrate the physical transition of the substrate over an approximately 20-day surface residence time. The pristine substrate relies on air-filled pores for buoyancy (left inset), which transitions to a negatively buoyant, sinking state once the internal matrix becomes fully saturated with water and organic matter (right inset). (3) Sinking: Density changes trigger autonomous rapid gravitational settling, transporting the fixed organic carbon through the mesopelagic zone while minimizing microbial remineralization. (4) Storage: The biomass-loaded substrates are retained in the deep ocean and benthic sediments, enabling long-term carbon sequestration on timescales of hundreds to thousands of years.

(Note: Visual representations of the substrate matrix in buoyant and sinking states were generated using Gemini 3.6 and subsequently reviewed and edited by the authors to reflect pristine and biomass-loaded states.)

297x209mm (288 x 288 DPI)