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

Journal:	*Cambridge Prisms: Carbon Technologies*
Manuscript ID	Draft
Manuscript Type:	Perspective
Date Submitted by the Author:	n/a
Complete List of Authors:	Belkin, Natalia; Gigablue Limited, Marine Operations Steinberg, Josh; Gigablue Grossman, Amit; Gigablue Grossowicz, Michal; Gigablue Markus Alford, Sapir; Gigablue
Keywords:	Carbon Sequestration, Carbon Dioxide Removal (CDR), Ocean Storage
Topic:	Biological methods < Carbon capture, Ocean storage < Carbon transportation and storage, Integration < Large-scale implementation
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 adapted, 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.

Impact Statement

Achieving global climate targets requires scalable and durable solutions to remove historical carbon emissions. While the ocean is Earth's largest active carbon reservoir, naturally storing about 60 times more carbon dioxide than the atmosphere, harnessing this capacity safely has been a major challenge. This paper introduces Microalgae Carbon Fixation and Sinking (MCFS), a novel marine Carbon Dioxide Removal (mCDR) methodology. MCFS utilizes formulated, non-toxic substrates that float to promote local microalgae growth, capturing carbon, before rapidly sinking to the deep ocean seabed for secure, long-term storage of 200 years or more.

The wider impact of this methodology lies in its shift from uncontrolled ecological interventions to a highly tailored, process-controlled system. Historically, ocean-based carbon removal efforts have faced concerns regarding environmental risks, such as altering food webs or depleting oxygen, and the inability to accurately measure the carbon stored. MCFS overcomes these hurdles by physically containing nutrients, initiating rapid sinking to minimize biological degradation in the upper ocean, and adhering to strict ecological safety thresholds through controlled, pulsed deployments. By providing a transparent, verifiable, and ecologically constrained framework, MCFS offers a vital blueprint for scaling ocean carbon removal to the gigaton level. This perspective offers a viable, responsible tool to the global climate restoration portfolio, demonstrating that international climate efforts can leverage the ocean's vast carbon sequestration capacity while strictly prioritizing the health and integrity of marine ecosystems.

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

Authors:
Belkin, N.[1]; Steinberg, J[1]; Grossman, A[1]; Grossowicz, M[1]; Markus-Alford, S.*[1]

[1] Gigablue Limited, London, UK

* Corresponding author Belkin N. natasha@gigablue.co

Keywords

- Carbon dioxide removal (CDR)
- Long term sequestration
- Ocean technologies

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 (CO_2) 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 CO_2 removal (mCDR) methodology that offers a distinct, engineered, controlled and measurable solution, which mimics the natural processes of atmospheric CO_2 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 phytoplankton growth 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, and not less than 200 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 CO_2 (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 CO_2 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 CO_2 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. Moreover, ocean fertilization can potentially lead to undesired environmental risks, including alteration of local and far-field food webs and increases in water column oxygen consumption. Ocean fertilization additionally involves challenges to measurability of carbon export and uncertainty in the fate of the fixed carbon (Bach et al. 2025; Buesseler et al. 2020; Jin and Gruber 2003; Keller et al. 2014; Oschlies et al. 2010; Wells et al. 2015; Williamson et al. 2012; Wingenter

et al. 2004).

Active sinking of cultivated biomass is another biotic mCDR approach that has been suggested (commonly known as biomass sinking) 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 (Oschlies 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; Oschlies 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 fix carbon through growth of microalgae within the substrate but also to ensure efficient export of the captured carbon to the deep seabed. 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 must be a non-toxic material, engineered into small (millimetric scale), stable particles, creating a structure that offers an environment specifically designed for the contained growth of phytoplankton, permeable to the surrounding water, allowing exchange of water and macronutrients between the internal and external parts of the substrate. Stable forms of micronutrients, such as iron and manganese oxides, are bound to the substrate but 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. This produces a contained microenvironment, which the natural population of primary producers can colonize and proliferate.

The second design component relates to the substrate's controlled density, where the substrate's lifecycle includes a predetermined flotation period, with a duration optimized to maximize photosynthesis and carbon accumulation, while minimizing remineralization. At the end of the flotation and biomass accumulation period, a mechanism of density increase initiates

substrate rapid sinking, independent of the accumulated biomass. The rapid sinking quickly transports the biomass from the surface into the deep ocean, increasing the export efficiency of the accumulated biomass by minimizing the time that organic matter spends in the upper water column, where biological remineralization would ultimately release the CO_2 back into the atmosphere.

This strategic design (adhering to the eligibility criteria that are defined by Puro.earth MCFS methodology and detailed in Table 1), 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, 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). 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 CO_2 (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, thereby

maximizing net carbon capture (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 dispersed 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.

Monitoring and measurements adhere to standard oceanographic research methodology (parameters detailed in 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 physicochemical 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 detailed in 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, which is essential to evaluate 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 and potential losses. This accounting ensures net, durable carbon is permanently removed from the atmosphere and positive climate impact. The general quantification logic follows:

Net CDR = Carbon stored - Baseline - Losses - Process emissions - Leakage

- Carbon stored: The net total organic carbon (represented in CO2eq units) that has accumulated on the substrates during the fixation phase and settled on the seafloor, quantified via *in-situ* measurements and sampling. The carbon fraction lost to respiration as the substrate sinks through the water column 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 also 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 minimum for the relevant season, 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: Greenhouse gas emissions arising across the project lifecycle, including substrate cultivation and production, material handling and transport, and fuel and energy use 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.

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, which is 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 sediments. 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 µmol/kg DO) must be avoided. This is accomplished through rigorous operational planning utilizing a modelling framework (Breiman 2001; Glasson 2008; Groffman et al. 2006; Vierod et al. 2014). This framework 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 planning utilizing Lagrangian dispersal modelling, 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

Microalgae Carbon Fixation and Sinking represent 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 of careful engineering and methodical oversight ensures that carbon removal is not just effective but also controllable and quantifiable.

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 advanced acoustic tracking, optical sensors, and subsurface sampling systems, will further reduce the costs and uncertainties associated with deep-ocean monitoring.
- High-resolution modeling: The continuous improvement of global ocean ventilation, biogeochemical, and Lagrangian dispersal models will be essential to optimize site selection, accurately predict secondary ecological interactions, and refine air-sea gas exchange 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.

Acknowledgements

We thank Prof. Itay Halevy and Dr. Eyal Rahav for their critical review and constructive feedback during the preparation of this manuscript. We also gratefully acknowledge Dr. Tiia Luostarinen and the rest of the Puro.earth team for fruitful collaboration and the co-development of the MCFS methodology.

Author Contribution statement

S.M-A led the conceptualization of the manuscript with inputs from co-authors. 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.

Financial support. The authors received no financial support for the research presented in this paper, and no funding was contingent on its results.

Conflict of Interest statement

The authors declare non.

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.

References

ASTM (1993) Standard Guide for Conducting Acute Toxicity Tests on Aqueous Effluents with Fishes, Macroinvertebrates and Amphibians E 1192-88. In *Annual Book of ASTM Standards*. Philadelphia, Pa. USA: 853–865: American Society for Testing and Materials.

Bach LT, Tamsitt V, Gower J, Hurd CL, Raven JA and Boyd PW (2021) Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt. *Nature Communications* **12**(1), 2556. https://doi.org/10.1038/s41467-021-22837-2.

Bach LT, Williamson P, House JI and Boyd PW (2025) Natural carbon uptake by ocean biology will not deliver credible carbon credits. *Nature Reviews Earth & Environment* **6**(12), 767–768. https://doi.org/10.1038/s43017-025-00741-3.

Boyd P (2008) Implications of large-scale iron fertilization of the oceans. *Marine Ecology Progress Series* **364**, 213–218. https://doi.org/10.3354/meps07541.

Boyd PW, Bach LT, Hurd CL, Paine E, Raven JA and Tamsitt V (2022) Potential negative effects of ocean afforestation on offshore ecosystems. *Nature Ecology & Evolution* **6**(6), 675–683. https://doi.org/10.1038/s41559-022-01722-1.

Boyd PW, Claustre H, Levy M, Siegel DA and Weber T (2019) Multi-faceted particle pumps drive carbon sequestration in the ocean. *Nature* **568**(7752), 327–335. https://doi.org/10.1038/s41586-019-1098-2.

Breiman L (2001) Random Forests. *Machine Learning* **45**(1), 5–32. https://doi.org/10.1023/A:1010933404324.

Buesseler B, Chai F, Cullen JT, Estapa M, Hawco N, John S, McGillicuddy D, Nawaz S, Nishioka J, Ramakrishna K, Siegel D, Smith SR, Steinberg D, Turk-Kubo KA, Twining BS, Webb R, Wells M, White A and Yoon J-E (2023) *Paths forward for exploring ocean iron fertilization*. Woods Hole Oceanographic Institution. Retrieved from https://hdl.handle.net/1912/67120

Buesseler KO and Boyd PW (2009) Shedding light on processes that control particle export and flux attenuation in the twilight zone of the open ocean. *Limnology and Oceanography* **54**(4), 1210–1232. https://doi.org/10.4319/lo.2009.54.4.1210.

Buesseler KO, Boyd PW, Black EE and Siegel DA (2020) Metrics that matter for assessing the ocean biological carbon pump. *Proceedings of the National Academy of Sciences* **117**(18), 9679–9687. https://doi.org/10.1073/pnas.1918114117.

Buesseler KO, Bianchi D, Burns W, Chai F, Cullen JT, Estapa M, Honda M, John S, Karl DM, Klaas C, Li D, Liu Z, McGillicuddy DJ, Morris PJ, Nishioka J, Omand MM, Ramakrishna K, Roche KM, Siegel DA, Smith SR, Twining BS, Wells M, White A, Xiu P and Yoon J-E (2026) The case for ocean iron fertilization field trials. *Dialogues on Climate Change* 29768659261420631. https://doi.org/10.1177/29768659261420631.

Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne PW, Trisos C, Romero J, Aldunce P, Barrett K, Blanco G, Cheung WWL, Connors S, Denton F, Diongue-Niang A, Dodman D, Garschagen M, Geden O, Hayward B, Jones C, Jotzo F, Krug T, Lasco R, Lee Y-Y, Masson-Delmotte V, Meinshausen M, Mintenbeck K, Mokssit A, Otto FEL, Pathak M, Pirani A, Poloczanska E, Pörtner H-O, Revi A, Roberts DC, Roy J, Ruane AC, Skea J, Shukla PR, Slade R, Slangen A, Sokona Y, Sörensson AA, Tignor M, Van Vuuren D, Wei Y-M, Winkler H, Zhai P, Zommers Z, Hourcade J-C, Johnson FX, Pachauri S, Simpson NP, Singh C, Thomas A, Totin E, Arias P, Bustamante M, Elgizouli I, Flato G, Howden M, Méndez-Vallejo C, Pereira JJ, Pichs-Madruga R, Rose SK, Saheb Y, Sánchez Rodríguez R, Ürge-Vorsatz D, Xiao C, Yassaa N, Alegría A, Armour K, Bednar-Friedl B, Blok K, Cissé G, Dentener F, Eriksen S, Fischer E, Garner G, Guivarch C, Haasnoot M, Hansen G, Hauser M, Hawkins E, Hermans T, Kopp R, Leprince-Ringuet N, Lewis J, Ley D, Ludden C, Niamir L, Nicholls Z, Some S, Szopa S, Trewin B, Van Der Wijst K-I, Winter G, Witting M, Birt A, Ha M, Romero J, Kim J, Haites EF, Jung Y, Stavins R, Birt A, Ha M, Orendain DJA, Ignon L, Park S, Park Y, Reisinger A, Cammaramo D, Fischlin A, Fuglestvedt JS, Hansen G, Ludden C, Masson-Delmotte V, Matthews JBR, Mintenbeck K, Pirani A, Poloczanska E, Leprince-Ringuet N and Péan C (2023) *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.*, First. Intergovernmental Panel on Climate Change (IPCC). Retrieved from https://www.ipcc.ch/report/ar6/syr/

Campbell I, Macleod A, Sahlmann C, Neves L, Funderud J, Øverland M, Hughes AD and Stanley M (2019) The Environmental Risks Associated With the Development of Seaweed Farming in Europe - Prioritizing Key Knowledge Gaps. *Frontiers in Marine Science* **6**, 107. https://doi.org/10.3389/fmars.2019.00107.

Chen S, Strong-Wright J and Taylor JR (2024) Modeling carbon dioxide removal via sinking of particulate organic carbon from macroalgae cultivation. *Frontiers in Marine Science* **11**, 1359614. https://doi.org/10.3389/fmars.2024.1359614.

Chopin T, Costa-Pierce BA, Troell M, Hurd CL, Costello MJ, Backman S, Buschmann AH, Cuhel R, Duarte CM, Gröndahl F, Heasman K, Haroun RJ, Johansen J, Jueterbock A, Lench M, Lindell S, Pavia H, Ricart AM, Sundell KS and Yarish C (2024) Deep-ocean seaweed dumping for carbon sequestration: Questionable, risky, and not the best use of valuable biomass. *One Earth* **7**(3), 359–364. https://doi.org/10.1016/j.oneear.2024.01.013.

Cross JN, Sweeney C, Jewett EB, Feely RA, McElhany P, Carter B, Stein T, Kitch GD and Gledhill DK (2023) *Strategy for NOAA Carbon Dioxide Removal (CDR) Research: A White Paper documenting a potential NOAA CDR Science Strategy as an element of NOAA's Climate Intervention Portfolio* (Special report). Washington DC: National Oceanic and Atmospheric Administration. Retrieved from https://repository.library.noaa.gov/view/noaa/52072

DeVries T (2022) The Ocean Carbon Cycle. *Annual Review of Environment and Resources* **47**(1), 317–341. https://doi.org/10.1146/annurev-environ-120920-111307.

DeVries T and Primeau F (2011) Dynamically and Observationally Constrained Estimates of Water-Mass Distributions and Ages in the Global Ocean. *Journal of Physical Oceanography* **41**(12), 2381–2401. https://doi.org/10.1175/JPO-D-10-05011.1.

Diaz RJ and Rosenberg R (2008) Spreading Dead Zones and Consequences for Marine Ecosystems. *Science* **321**(5891), 926–929. https://doi.org/10.1126/science.1156401.

Doney SC, Wolfe WH, McKee DC and Fuhrman JG (2025) The Science, Engineering, and Validation of Marine Carbon Dioxide Removal and Storage. *Annual Review of Marine Science* **17**(1), 55–81. https://doi.org/10.1146/annurev-marine-040523-014702.

Dunne JP, Sarmiento JL and Gnanadesikan A (2007) A synthesis of global particle export from the surface ocean and cycling through the ocean interior and on the seafloor. *Global Biogeochemical Cycles* **21**(4), 2006GB002907. https://doi.org/10.1029/2006GB002907.

Glasson J (2008) Principles and Purposes of Standards and Thresholds in the EIA Process. In Schmidt M, Glasson J, Emmelin L, and Helbron H (eds), *Standards and Thresholds for Impact Assessment*, Vol. 3. Berlin, Heidelberg: Springer Berlin Heidelberg, 3–17. https://doi.org/10.1007/978-3-540-31141-6_1.

Groffman PM, Baron JS, Blett T, Gold AJ, Goodman I, Gunderson LH, Levinson BM, Palmer MA, Paerl HW, Peterson GD, Poff NL, Rejeski DW, Reynolds JF, Turner MG, Weathers KC and Wiens J (2006) Ecological Thresholds: The Key to Successful Environmental Management or an Important Concept with No Practical Application? *Ecosystems* **9**(1), 1–13. https://doi.org/10.1007/s10021-003-0142-z.

Holligan PM and Robertson JE (1996) Significance of ocean carbonate budgets for the global carbon cycle. *Global Change Biology* **2**(2), 85–95. https://doi.org/10.1111/j.1365-2486.1996.tb00053.x.

Holzer M, Chamberlain MA and Matear RJ (2020) Climate-Driven Changes in the Ocean's Ventilation Pathways and Time Scales Diagnosed From Transport Matrices. *Journal of Geophysical Research: Oceans* **125**(10), e2020JC016414. https://doi.org/10.1029/2020JC016414.

IPCC (2023a) *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st edn. Cambridge University Press. https://doi.org/10.1017/9781009157896.

IPCC (ed) (2023b) Mitigation Pathways Compatible with Long-term Goals. In *Climate Change 2022 - Mitigation of Climate Change*, 1st edn. Cambridge University Press, 295–408. https://doi.org/10.1017/9781009157926.005.

Jin X and Gruber N (2003) Offsetting the radiative benefit of ocean iron fertilization by enhancing N_2O emissions. *Geophysical Research Letters* **30**(24), 2003GL018458. https://doi.org/10.1029/2003GL018458.

Jones DC, Ito T, Takano Y and Hsu W (2014) Spatial and seasonal variability of the air-sea equilibration timescale of carbon dioxide. *Global Biogeochemical Cycles* **28**(11), 1163–1178. https://doi.org/10.1002/2014GB004813.

Keller DP, Feng EY and Oschlies A (2014) Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nature Communications* **5**(1), 3304. https://doi.org/10.1038/ncomms4304.

Kienast StephanieS and Torfstein A (2022) Evaluation of Biological Carbon Pump Metrics in the Subtropical Gulf of Aqaba, Northern Red Sea. *Global Biogeochemical Cycles* **36**(10), e2022GB007452. https://doi.org/10.1029/2022GB007452.

Knap A, Michaels A, Close A, Ducklow H and Dickson A (1996) Protocols for the joint global ocean flux study (JGOFS) core measurements. *JGOFS, Reprint of the IOC Manuals and Guides No. 29* **19**.

Krause-Jensen D and Duarte CM (2016) Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience* **9**(10), 737–742. https://doi.org/10.1038/ngeo2790.

Martin JH, Fitzwater SE and Gordon RM (1990) Iron deficiency limits phytoplankton growth in Antarctic waters. *Global Biogeochemical Cycles* **4**(1), 5–12. https://doi.org/10.1029/GB004i001p00005.

Martin JH, Knauer GA, Karl DM and Broenkow WW (1987) VERTEX: carbon cycling in the northeast Pacific. *Deep Sea Research Part A. Oceanographic Research Papers* **34**(2), 267–285. https://doi.org/10.1016/0198-0149(87)90086-0.

Middelburg JJ (2019) *Marine Carbon Biogeochemistry: A Primer for Earth System Scientists*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-10822-9.

NASEM (2019) *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, D.C.: National Academies Press, 25259. https://doi.org/10.17226/25259.

NASEM (2022) *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*. Washington, D.C.: National Academies Press, 26278. https://doi.org/10.17226/26278.

Nowicki M, DeVries T and Siegel DA (2024) The Influence of Air-Sea CO2 Disequilibrium on Carbon Sequestration by the Ocean's Biological Pump. *Global Biogeochemical Cycles* **38**(2), e2023GB007880. https://doi.org/10.1029/2023GB007880.

Oschlies A, Bach LT, Fennel K, Gattuso J-P and Mengis N (2025a) Perspectives and challenges of marine carbon dioxide removal. *Frontiers in Climate* **6**, 1506181. https://doi.org/10.3389/fclim.2024.1506181.

Oschlies A, Koeve W, Rickels W and Rehdanz K (2010) Side effects and accounting aspects of hypothetical large-scale Southern Ocean iron fertilization. *Biogeosciences* **7**(12), 4017–4035. https://doi.org/10.5194/bg-7-4017-2010.

Oschlies A, Slomp CP, Altieri AH, Gallo ND, Gregoire M, Isensee K, Levin LA and Wu J (2025b) Potential impacts of marine carbon dioxide removal on ocean oxygen. *Environmental Research Letters* **20**(7), 073002. https://doi.org/10.1088/1748-9326/ade0d4.

Primeau F (2005) Characterizing Transport between the Surface Mixed Layer and the Ocean Interior with a Forward and Adjoint Global Ocean Transport Model. *Journal of Physical Oceanography* **35**(4), 545–564. https://doi.org/10.1175/JPO2699.1.

Puro.earth (2025) Microalgae Carbon Fixation and Sinking (MCFS) methodology V1. https://puro.earth/our-blog/343-scaling-ocean-carbon-removal-mcfs-methodology-approved-by-puro-earth-advisory-board

Rabalais NN, Turner RE and Wiseman WJ (2002) Gulf of Mexico Hypoxia, A.K.A. "The Dead Zone". *Annual Review of Ecology and Systematics* **33**(1), 235–263. https://doi.org/10.1146/annurev.ecolsys.33.010802.150513.

Ricart AM, Krause-Jensen D, Hancke K, Price NN, Masqué P and Duarte CM (2022) Sinking seaweed in the deep ocean for carbon neutrality is ahead of science and beyond the ethics. *Environmental Research Letters* **17**(8), 081003. https://doi.org/10.1088/1748-9326/ac82ff.

Ross F, Tarbuck P and Macreadie PI (2022) Seaweed afforestation at large-scales exclusively for carbon sequestration: Critical assessment of risks, viability and the state of knowledge. *Frontiers in Marine Science* **9**, 1015612. https://doi.org/10.3389/fmars.2022.1015612.

Roy-Barman M and Jeandel C (2016) *Marine Geochemistry: Ocean Circulation, Carbon Cycle and Climate Change*, 1st edn. Oxford University PressOxford. https://doi.org/10.1093/acprof:oso/9780198787495.001.0001.

Strand SE and Benford G (2009) Ocean Sequestration of Crop Residue Carbon: Recycling Fossil Fuel Carbon Back to Deep Sediments. *Environmental Science & Technology* **43**(4), 1000–1007. https://doi.org/10.1021/es8015556.

Stukel MR, Irving JP, Kelly TB, Ohman MD, Fender CK and Yingling N (2023) Carbon sequestration by multiple biological pump pathways in a coastal upwelling biome. *Nature Communications* **14**(1), 2024. https://doi.org/10.1038/s41467-023-37771-8.

Truscott J and Brindley J (1994) Ocean plankton populations as excitable media. *Bulletin of Mathematical Biology* **56**(5), 981–998. https://doi.org/10.1016/S0092-8240(05)80300-3.

UNESCO (1988) *The acquisition, calibration, and analysis of CTD data* (Unesco technical papers in marine science, SCOR Working Group 51). Paris, France: Unesco.

USEPA (1987) *Methods for toxicity tests of single substances and liquid complex wastes with marine unicellular algae*. Cincinnati, Ohio: U.S. Environmental Protection Agency.

Vierod ADT, Guinotte JM and Davies AJ (2014) Predicting the distribution of vulnerable marine ecosystems in the deep sea using presence-background models. *Deep Sea Research Part II: Topical Studies in Oceanography* **99**, 6–18. https://doi.org/10.1016/j.dsr2.2013.06.010.

Wells ML, Trainer VL, Smayda TJ, Karlson BSO, Trick CG, Kudela RM, Ishikawa A, Bernard S, Wulff A, Anderson DM and Cochlan WP (2015) Harmful algal blooms and climate change: Learning from the past and present to forecast the future. *Harmful Algae* **49**, 68–93. https://doi.org/10.1016/j.hal.2015.07.009.

Williams RG and Follows MJ (2003) Physical Transport of Nutrients and the Maintenance of Biological Production. In Fasham MJR (ed), *Ocean Biogeochemistry*. Berlin, Heidelberg: Springer Berlin Heidelberg, 19–51. https://doi.org/10.1007/978-3-642-55844-3_3.

Williams E and Hall J (1999) Seasonal and geographic variability in toxicant sensitivity of Mytilus galloprovincialis larvae. *Australasian Journal of Ecotoxicology* **5**(1), 1–10.

Williamson P, Wallace DWR, Law CS, Boyd PW, Collos Y, Croot P, Denman K, Riebesell U, Takeda S and Vivian C (2012) Ocean fertilization for geoengineering: A review of effectiveness, environmental impacts and emerging governance. *Process Safety and Environmental Protection* **90**(6), 475–488. https://doi.org/10.1016/j.psep.2012.10.007.

Wingenter OW, Haase KB, Strutton P, Friederich G, Meinardi S, Blake DR and Rowland FS (2004) Changing concentrations of CO, CH_4 , C_5H_8 , CH_3Br, CH_3I, and dimethyl sulfide during the Southern Ocean Iron Enrichment Experiments. *Proceedings of the National Academy of Sciences* **101**(23), 8537–8541. https://doi.org/10.1073/pnas.0402744101.

Yoon J-E, Yoo K-C, Macdonald AM, Yoon H-I, Park K-T, Yang EJ, Kim H-C, Lee JI, Lee MK, Jung J, Park J, Lee J, Kim S, Kim S-S, Kim K and Kim I-N (2018) Reviews and syntheses: Ocean iron fertilization experiments – past, present, and future looking to a future Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) project. *Biogeosciences* **15**(19), 5847–5889. https://doi.org/10.5194/bg-15-5847-2018.

Zhou M, Tyka MD, Ho DT, Yankovsky E, Bachman S, Nicholas T, Karspeck AR and Long MC (2025) Mapping the global variation in the efficiency of ocean alkalinity enhancement for carbon dioxide removal. *Nature Climate Change* **15**(1), 59–65. https://doi.org/10.1038/s41558-024-02179-9.

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

Authors:
Belkin, N.[1]; Steinberg, J[1]; Grossman, A[1]; Grossowicz, M[1]; Markus-Alford, S.*[1]

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

	Eligibility criteria	**Description**
Substrate	*Material Composition and Sourcing*	Non-toxic, non-hazardous, organic or inorganic material, which includes trace elements (micronutrients) up to 2% of total mass.
Substrate	*Chemical Safety*	Concentrations of Potentially Toxic Elements (PTEs) (heavy metals, PAHs, PFAS, pesticides) do not exceed the limits defined in the applicable legislation.
Substrate	*Micronutrient Characteristics*	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	*Physical Dimensions and Density*	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	*Containment Mechanism*	A mechanism (e.g., high porosity, physical entanglement) that minimizes the loss of accumulated phytoplankton and biomass due to physical forces.
Substrate	*Floatation and Sinking*	Autonomous or controlled sinking mechanism. Maximum flotation period shall not exceed 30 days. Sinking velocity minimum of 20 m/hr (proportional to the substrate-water density difference).
Activity site	*HNLC Region Status*	Limited to regions with surface nitrate > 8 μM, phosphate > 0.5 μM, iron < 0.2 nM, and chlorophyll a < 1 μg/L.
Activity site	*Durability and Deep Ocean Storage*	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	*Seafloor and Ecosystem Stability*	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	*Phytoplankton Type*	The activity shall exclusively rely on growth of local phytoplankton populations. Phytoplankton seeding will be avoided.

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.

		Rationales for monitoring			How evaluated
	Parameter	**Eligibility**	**Quantification**	**Environmental monitoring**	
Physical	*Temperature, Salinity, Density*	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); *In-situ* CTD full water column measurement
	Photosynthetic Active Radiation (PAR)	Euphotic zone depth		Euphotic zone depth required for nutrient depletion assessment	*In situ* CTD-mounted sensor full water column measurement
	Turbidity	Site characterization; Baseline		Water column transparency monitoring	*In situ* CTD-mounted sensor full water column measurement
	Seawater Velocities	Site characterization; Baseline		Required for the particle tracking model to project trajectory and seabed deposition densities.	Models and in situ ADCP photic layer measurements
	Surface water retention time	Site characterization; Baseline	Air-Sea Gas Exchange factor		Oceanographic model
	Deep water trajectory	Site characterization; Baseline	Durability, long-term atmospheric reemission		Lagrangian model
Chemical	*Dissolved Oxygen*	Site characterization; Baseline	Remineralization rate and sinking efficiency.	Oxygen depletion risk analysis	Model and in situ CTD-mounted sensor full water column measurements
	Inorganic macronutrients (N, P, Si)	Site characterization; Baseline; HNLC validation	Effects of downstream nutrient uptake and potential changes to the natural baseline	Macronutrient depletion assessment	*In situ* full water column discrete sampling
	Trace metals (Fe, Mn)	Site characterization; Baseline; HNLC validation (Iron < 0.2 nM)		Trace element leaching risk assessment	*In situ* 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	*In situ* full water column discrete sampling
	CH_4, N_2O			Project-related enhanced GHG production risk	*In situ* surface water sampling
	Dimethylsulfoniopropionate (DMSP)			Production of DMS and potential climate co-benefits	*In situ* surface water sampling
Biological	*Chlorophyll a*	Site characterization; baseline; HNLC validation (Chl a <1 µg/L)		Project-induced algal bloom risk	*In situ* full water column sampling
	Community Composition / Biodiversity	Site characterization; Baseline;		Harmful Algal Blooms (HABs) and food web disruption risks	*In situ* euphotic layer discrete sampling
	Ultraphytoplankton / Microphytoplankton / Bacterial Abundance	Site characterization; Baseline		Changes to the base of the food web risk	*In situ* euphotic layer discrete sampling
	Algal Toxins			Toxin production risk	*In situ* 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	*In situ* euphotic layer discrete sampling
	Total Organic Carbon (TOC/POC, DOC)	Site characterization; Baseline		Changes to organic carbon content in the water column	*In situ* full water column discrete sampling
Organic carbon (substrate)	*Total solids & carbon content*	Substrate characterization	Net organic carbon fixed to substrate.		Lab for pristine substrate *In situ* 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	*In situ* 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_2O	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_2O, 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_2O, 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 *ex situ* to quantify anion adsorption capacity before deployment, and *in situ* 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 *ex situ* incubation experiments and *in situ* 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 ex situ 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 *ex situ* 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