

**Microalgae Carbon Fixation and Sinking -
Distinctions in function and ecological impact from Ocean Iron Fertilization**

10 October 2025

Executive summary

This paper presents the differences between Ocean Iron Fertilization (OIF) and Marine Carbon Fixation and Sinking / Microalgae Carbon Fixation and Sinking (both known as MCFS).

MCFS is a recently developed framework for marine Carbon Dioxide Removal that fosters phytoplankton growth within engineered substrates which sink to sequester carbon. In contrast OIF stimulates direct growth of phytoplankton in the free water column through direct addition of nutrients into the ocean. Subsequent carbon sequestration relies on naturally occurring processes where most of the carbon is lost back to the atmosphere from recycling of biomass in surface or intermediate depths. The key differences between OIF and MCFS are:

- In MCFS the introduced material is a substrate containing micronutrients limited to up to 2% of the total substrate mass and in a form that is insoluble in the ocean. In contrast, in OIF the only ingredient introduced to ocean waters is a highly soluble iron compound that dissolves into surface waters.
- In MCFS primary production is captured by enabling phytoplankton to self-import and culture within a contained nutrient fixed substrate system. In contrast, OIF primary production is driven by phytoplankton blooms produced by the diffuse release of nutrients directly into ocean waters (GESAMP, 2019)
- In MCFS the substrates sink within 30 days to the seabed to minimise recycling of organic matter in the water column. In contrast, OIF stimulated primary productivity drives enhancement of marine food webs and consequent recycling of organic matter into the ocean water column resulting in minimal carbon settling on the seabed.
- In MCFS the export of carbon to the deep ocean is controlled, closely monitored and driven by rapid sinking by the substrate. In OIF any export of carbon is through natural uncontrolled sinking of biological organic matter.

1 Introduction

Microalgae Carbon Fixation and Sinking (MCFS), also known as Marine Carbon Fixation and Sinking, is a recently developed framework for marine Carbon Dioxide Removal (mCDR) in High Nutrient Low Chlorophyll (HNLC) regions (Puro.earth, 2025). mCDR refers to a suite of techniques aimed at removing carbon dioxide (CO₂) from the atmosphere, by leveraging the ocean's natural carbon cycle. MCFS fosters microalgae (phytoplankton) growth within engineered substrates which then sink with attached biomass moving carbon to the slow carbon cycle.

MCFS has been the subject of an independently prepared and reviewed methodology by [Puro.earth](#), a Helsinki-based Nasdaq-owned platform and registry that certifies carbon dioxide removal (CDR) activities. Puro.earth's methodology for MCFS provides specific criteria to differentiate MCFS from OIF. Following scientific and public consultation, the methodology was reviewed and approved by Puro.earth's independent Advisory Board in September 2025.

From a review of the MCFS Puro.earth 2025 methodology this paper clarifies how MCFS differs from Ocean Fertilization by design. For MCFS to provide ongoing assurances that all ecological impacts are being managed it is essential that appropriately scaled and controlled marine scientific research continues.

2 Ocean Iron Fertilization (OIF)

Ocean iron fertilization (OIF) is the Ocean Fertilization technique targeted at oceanic regions with surplus macronutrients where iron is the limiter on primary producers, known as High Nutrient Low Chlorophyll (HNLC) regions. OIF, as currently described, only indirectly leads to carbon sequestration, relying on natural processes in the biological pump for this to occur (GESAMP, 2019; Buesseler et al., 2024). The technique delivers iron in its reduced form, typically as dissolved iron sulphate (FeSO₄), to surface waters to stimulate the primary producers through an algal bloom event. This depletes localised dissolved organic carbon prompting atmospheric drawdown of carbon dioxide into the ocean, with an estimate of about 1% of the original content settling to the deep ocean (Dunne et al, 2007). However, the specific degree of carbon sequestration from enhancement of the biological pump varies considerably between experiments, creating uncertainty around the efficacy of the OIF technique (GESAMP, 2019).

OIF is the principal Ocean Fertilisation method trialled to date, however, other forms of Ocean Fertilisation are also possible, for example, in tropical and sub-tropical waters macronutrients are depleted, particularly nitrogen and phosphorus (GESAMP, 2019). Using the same rationale as for OIF, the addition of macronutrients to deficient regions can stimulate primary productivity and hence indirectly carbon sequestration through the biological pump.

Ocean fertilization is defined in the 2013 amendment of the text of the London Protocol (LP.4(8), 2013) as:

Ocean fertilization is any activity undertaken by humans with the principle [sp] intention of stimulating primary productivity in the oceans. Ocean fertilization does not include conventional aquaculture, or mariculture, or the creation of artificial reefs.

Key aspects of this definition are (1) that the activity involves the **stimulation of primary production in the oceans** – this being interpreted as an activity that enhances the production of organic matter by free-floating phytoplankton drifting in the ocean, and (2) stimulation of primary production in the oceans being the **principal** intent – whereby techniques not solely, or predominantly intended for enhancing the production of organic matter by phytoplankton in ocean water would not be captured under the definition.

The concern about environmental impacts from Ocean Fertilization are emphasised by the definition falling within a broader marine geoengineering definition that highlights that Ocean Fertilization interventions may have:

...the potential to result in deleterious effects, especially where those effects may be widespread, long lasting or severe”.

All thirteen OIF trials conducted to date have followed the same general format of applying dissolved iron to the surface ocean, which has generated large, free floating algal blooms drifting in ocean waters and with some form of monitoring to assess of carbon export to depth (Yoon et al., 2018). However, only one of the thirteen experiments—EIFEX in the Southern Ocean—, where aggregate formation meant natural carbon sinking rates were very rapid demonstrated appreciable carbon export with 50% of the biomass falling below 1000 m (Smetacek et al., 2012; Yoon et al., 2018). Other estimates for carbon export, a key criterion for long-term carbon sequestration are that only about 1% of the carbon content fixed by phytoplankton will settle to deep ocean sediment (Dunne et al, 2007).

3 MCFS

MCFS is a novel mCDR technique developed to mitigate the recognised challenges with Ocean Fertilization though enhancing the export of photosynthetically produced carbon to the deep ocean (US National Academies of Sciences, Engineering, and Medicine Carbon Dioxide Removal - Research Strategy, 2022). MCFS mimics the principles of the biological carbon pump within a substrate, namely: (1) the photosynthetic conversion of carbon dioxide to organic matter; and (2) effective sequestration by organic matter sinking to the ocean floor. These processes in tandem enhance the carbon sequestration to the deep ocean (Martin et al., 1987). In MCFS this process is performed in a controlled manner in two functional stages:

- 1 Fixing and capturing organic carbon of primary producers within a specifically designed substrate by enabling phytoplankton to grow naturally within the substrate, supported through controlled nutrient availability.
- 2 Export of carbon captured within the substrate to the deep ocean through triggered and efficient sinking by the substrate. Long-term carbon removal is facilitated within a MCFS substrate once settled into the low decomposition environment of the cold, high pressure and low oxygen conditions of the deep sea floor (Martin et al., 1987; Puro.earth, 2025).

MCFS uses a chemically and biologically inert substrate containing low-level insoluble micronutrients to allow phytoplankton to self-import, with subsequent growth within the substrate. The MCFS substrate is specifically designed so phytoplankton are retained within the substrate when it sinks, so achieving controlled export of carbon to depth and limiting recycling of the carbon in the surface ocean and water column.

All the established controls and limits on MCFS are reflected in the Puro.earth (2025) methodology eligibility criteria (Chapter 3).

4 Summary of functional differences

Table 1 below summarises the key differences between OIF and MCFS, providing a comparison of materials, application and fate, highlighting unique characteristics and operational approaches of each method.

Table 1: Comparison of the method and functions used in OIF and MCFS techniques.

Aspect	Ocean Iron Fertilization	Marine Carbon Fixation and Sequestration as described by Puro.earth (2025)
Material	Iron (II) as soluble FeSO_4 , dissolved in seawater has been used in all past field studies (Buesseler et al., 2024).	An inert substrate of either non-toxic and non-hazardous organic or inorganic material, containing a micronutrient content of up to 2% of the total mass of the substrate. All micronutrients must be in an oxide form and insoluble under ocean conditions.
Application and fate.	Deployed as water soluble iron direct to surface water (Buesseler et al., 2024). Much of the added iron is quickly converted to particulate or precipitate forms and is lost to sinking before it can be used by phytoplankton (Buesseler et al., 2024).	Deployed as a substrate in well planned transects at a specific rate that floats at the surface waters for up to 30 days the substrate and attached biomass actively sink into the deep ocean and on to the seabed. All components of the substrate, including captured carbon, sink to the deep ocean and there is no intended dissolution of the substrate or nutrients into the water column.
Stimulation of primary production	Uptake of dissolved iron by phytoplankton and uncontrolled growth to bloom conditions (GESAMP, 2019).	Attachment of phytoplankton into the substrate and controlled localised growth
Carbon capture	Enhancement of carbon fixation by free floating primary producers in surface seawater and transfer through the general phytoplankton based food web (GESAMP, 2019).	Enhancement of carbon fixation by primary producers and associated bacteria within the substrate. With the substrate having a mechanism for containment to minimize the physical loss of accumulated phytoplankton and adjacent bacteria (fixed carbon). No intended further transfer of carbon through phytoplankton-based food web.
Carbon sequestration	Natural, spontaneous, gravitational sinking of biological organic matter to the deep ocean. Estimates are that only about 1% of the carbon content fixed by phytoplankton will settle to deep ocean sediment (Dunne et al, 2007). Subject to inherent variation with the vast majority of carbon lost back to the atmosphere from recycling of biomass in surface or intermediate depths (IOC, 2010; GESAMP, 2019).	Controlled sinking of the substrate to the deep ocean and sediment where site selection conditions ensure sequestration for >200 years. Sinking velocity of the substrate is required to be at a minimum of 20 m/hr. Carbon export is designed to exceed natural export efficiency.
Permanence	Some carbon will sink to the deep ocean but there is a low efficiency in reaching this depth, with the carbon flux recycled faster out of the shallower water. (US National Academies of Sciences, Engineering, and Medicine, 2022). Carbon that successfully sinks to the deep ocean can be sequestered for up to hundreds of years, although highly variable depending on the location and the efficacy of the natural biological pump processes (IOC, 2010).	Centuries to thousands of years with a minimum 200-year carbon sequestration.

As identified above the London Protocol definition has two criteria for Ocean Fertilization:

- 1 Does the human activity involve **stimulating primary productivity in the oceans**¹.
- 2 Is stimulating primary productivity in the oceans the **principal intent**?

Neither of these criteria are clearly met for MCFS. With MCFS, as designed and applied in terms of the Puro.earth (2025) methodology, localised growth of phytoplankton occurs as a culture within the substrate and there is no direct stimulation of ocean primary productivity. As a result, other characteristics such as sustaining the food web are not present, nor are free ocean blooms, an identified concern for OIF activities (Puro.Earth, 2025). The MCFS substrate as designed does not facilitate uncontrolled phytoplankton growth, or free-floating growth within surface water.

The principal intent of MCFS is carbon capture and sequestration through the use of managed carbon sinking to the deep ocean for long term sequestration (>200 years; Puro.earth, 2025). The efficacy of the technique leverages off the substrate sinking in the carbon export phase. This results in more efficient capture and sequestration than reliance on the natural sinking rates following an uncontrolled phytoplankton bloom caused by OIF.

5 Summary of environmental risk profiles

The potential for OIF to have deleterious effects, especially effects that are widespread, long lasting or severe, was a significant concern raised in international forums. These concerns were heightened by unintended effects reported in research trials. MCFS when designed and applied in compliance with the Puro.earth (2025) methodology is intended to largely mitigate and/or avoid the negative effects associated with OIF. Consequently, MCFS applied in this way is distinguishable from the risk profile and key areas of environmental concern for OIF as set out in Table 2.

Table 2: Known or anticipated risks for OIF and MCFS, as designed by Puro.earth (2025).

Concern	OIF	MCFS
Control	Research trials have stimulated large ocean blooms covering vast areas (40-300 km ²) of ocean for several weeks. Estimates for full scale deployments require ~10,000km ² area to be fertilized (IOC, 2010).	The substrate must be within a set size range and have an initial buoyancy to allow floating at the surface. After a set time period, no longer than 30 days, buoyancy is lost and the substrate, having a greater density than water sinks at an assured rate of >20m/hr. Extensive and specific pre -and post-deployment monitoring is required.
Hypoxia / oxygen depletion	Modelling indicates that large scale sinking and decomposition of the biomass from fertilizer induced blooms could decrease oxygen levels in sub-surface waters and growth of low-oxygen regions (IOC, 2010). This oxygen depletion could be detrimental to ocean life and nutrient recycling processes.	The substrate is specifically designed for rapid sinking before significant biomass decay and oxygen depletion can occur in surface waters. Pre-deployment assessment for oxygen depletion in deep waters informs the deployment scale which will be moderated to avoid oxygen depletion risk. Extensive and specific pre- -and post-deployment monitoring is required.

¹ The terminology **in the oceans** is used with the definition. Oceans is not further defined under the London Protocol, however the term “sea” is defined as: “all marine waters other than the internal waters of States, as well as the seabed and the subsoil thereof”.

Concern	OIF	MCFS
Increased climate relevant gas production	Climate relevant gases, including nitrous oxide (a greenhouse gas) and dimethyl sulfide (possibly affecting cloud formation) have been observed to have altered concentrations after some field trials (Law and Ling, 2001; Law, 2008; IOC, 2010). Production of more potent greenhouse gases could offset the carbon sequestration, while other gases may have unintended climate impacts.	The substrate is designed for rapid sinking before significant biomass decay can occur to mitigate dimethyl sulfide production. Pre-deployment assessment for oxygen depletion in deep waters also must assess for increased production in climate relevant gas due to increased anaerobic processes, such as methane or nitrous oxide, with this supported by monitoring concentrations of these gases.
Altered phytoplankton communities	Field trials reported the iron addition favoured diatoms, altering surface water species dominance and reducing biodiversity (IOC, 2010; Yoon et al., 2019). Changes in phytoplankton can affect zooplankton and higher trophic levels leading to disruption of food webs. Fertilization could also stimulate blooms of toxin-producing diatom species, such as those producing domoic acid (Trick et al., 2010).	The micronutrients are embedded within the substrate and are required to have controlled solubility reducing their migration and any access by free floating phytoplankton. The substrate must have a contaminant mechanism for accumulated phytoplankton and bacteria to prevent them being physically dislodged. The controlled rate of growth and the short length of floating also means sinking can be modelled to occur before stimulation of phytoplankton grazers and their predators. Genus producing marine toxins could grow within the substrates, however, these would not be present in free floating blooms. Production of extracellular toxins tends not to be considered a concern in the open ocean (Zabaglo et al., 2016). MCSF methodology requires pre- and post-deployment monitoring of surface ocean microbial community composition, and specific analysis for toxin producing species, and if necessary, toxins, in community composition.
Downstream nutrient depletion	Fertilization and creation of blooms may deplete other nutrients in treated waters and so limit transport of these to other regions. (Lauderdale et al., 2020; Tagliabue et al., 2023) Models indicate reduced nutrients could re-distribute or lead to overall decrease in fish populations, and possibly the CO₂ sequestration capacity in downstream regions (IOC, 2010).	A specific and conservative threshold of macronutrient uptake is defined in the MCFS methodology, to ensure no change in the wider ecosystem. Wind/wave dispersion during the floating phase will minimise surface nutrient depletion. Impact assessment for changes to nutrients is required of pre-deployment monitoring and ongoing research on changing nutrient patterns is essential to identify if this risk is realistic.

6 Summary

MCFS is a new mCDR technique designed to offer a safe, controlled, well-monitored and efficient pathway for carbon sequestration. Carbon fixation occurs by colonisation and controlled growth of primary producers within substrates, with the carbon then exported through controlled sinking of the substrate to the deep ocean/seabed in selected areas, where long term (centuries to thousands of years) sequestration can be achieved.

MCFS within the Puro.earth 2025 methodology is distinct from OIF by requiring effective controls to avoid known negative effects of OIF. Based on understanding of the scientific concerns and the different methodological approach, application and aim of activities, MCFS does not align within the established definition for Ocean Fertilization.

For MCFS to provide assurances that all ecological impacts are being managed it is essential that appropriate scale marine research continues to be undertaken.

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